2024 Annual Meeting

Seismological Society of America
Technical Sessions
29 April–3 May • Anchorage, Alaska

The SSA 2024 Annual Meeting will convene at the Dena'ina Civic and Convention Center and feature more than 1069 technical oral and poster presentations as well as plenary sessions, workshops, special interest groups and field trips.

The following schedule of events and abstracts are valid until 23 February, 2024 and subject to change.

Where We are Gathered

The Seismological Society of America and the conference organizers welcome you to the 2024 Annual Meeting in Anchorage, Alaska.

We are gathered in a place that is defined by the environment surrounding us—the Chugach Mountains to the east and Cook Inlet to the west. This resource-rich area has sustained the Dena'ina Athabascan people for the past millennia. Across Alaska, colonization from Russia and then America devastated Alaska Native populations through disease, loss of land and forced integration. Today, the work of reconciling this complex past includes components that are economic, environmental, legal and cultural.

The Dena'ina Center itself is a small but meaningful effort in cultural representation. The meeting rooms carry Athabascan names for essential land and ocean features in this region—features that should resonate with all Earth scientists. And the art that fills the center provides both traditional and modern perspectives on Alaska's indigenous cultures. Other excellent learning resources include the Alaska Native Heritage Center (a 20-minute drive) and the Anchorage Museum (a ten-minute walk).

A sense of place runs deep in all of Alaska. We encourage you to use this meeting to learn and appreciate its land and people.

Annual Meeting Co-Chairs

The Society is grateful to SSA 2024 Co-Chairs Carl Tape and Michael West of University of Alaska Fairbanks for leading the creation of this dynamic week of science.

Contact

info@seismosoc.org

Technical Program

Plenary Sessions

Keynote Address: Learning from Earthquakes—Observations from the Field and the Design Office Following the 2023 Türkiye-Syria Earthquake Sequence

Tuesday, 30 April, 6-7 PM

Ayşe Hortaçsu, Applied Technology Council

With an official death toll of 60,000, an estimated economic loss of over $100 billion, and the immediate loss of housing for 3 million residents, the 6 February earthquakes directly affected the lives of millions of people in Eastern Türkiye and Northern Syria. Following such a major event, while mourning the lives lost and supporting first responders, it is critical for engineers and scientists to conduct focused efforts to learn from the disaster, as no analytical model or test facility can replicate a real earthquake and its effects on built infrastructure. The Earthquake Engineering Research Institute (EERI) established the Learning From Earthquakes (LFE) program in 1973 with a mission to accelerate and increase learning from earthquake-induced disasters that affect the natural, built, social and political environments worldwide. Hortaçsu was deployed to Türkiye one week following the earthquakes as part of the EERI LFE team, and she will summarize her field observations and findings reported by additional teams reported over the past year. The presentation will also include a summary of rebuilding efforts and ongoing initiatives toward improving the way earthquake science and engineering are taught and implemented in Türkiye, and potential implications for the U.S. practice.

Challenges in Geohazards Research in Alaska

Wednesday, 1 May, 6-7 PM

Elena Suleimani, University of Alaska Fairbanks/Alaska Earthquake Center; Rob Witter, U.S. Geological Survey; Jessica Larsen, University of Alaska Fairbanks; Dennis Staley, U.S. Geological Survey

The Pacific-North American plate boundary in Alaska produces a range of geohazards resulting from earthquakes, volcanoes, landslides and tsunamis. The regional scale of geohazards in Alaska, their cascading effects and remoteness of the fieldwork, which is required to investigate them, present many challenges. A panel will share perspectives on these challenges and discuss new frontiers and opportunities to characterize, monitor, detect and prepare for the myriad geohazards in Alaska.

Annual Business and Awards Luncheon

Thursday, 2 May, Noon-2 PM

SSA President Heather DeShon (2024–25) will preside over the awards ceremony and provide an update on the Society. SSA President Ruth Harris (2023–24) will deliver her presidential address.

The 2024 honorees:

- Norman A. Abrahamson, Harry Fielding Reid Medal
- Doyeon Kim, Charles F. Richter Early-Career Award
- Harley M. Benz, Frank Press Public Service Award
- Douglas Scott Dreger, Distinguished Service to SSA Award

Joyner Lecture: Why Seismic Hazard Modeling Has Become a Risky Business

Thursday, 2 May, 6-7 PM

Helen Crowley, Global Earthquake Model (GEM) Foundation

Crowley's Joyner Lecture will look at the role that probabilistic seismic hazard models have historically played in defining actions for seismic design, will review the criticisms that have been placed on these models—especially, but not only, after damaging earthquakes—and will present numerous examples that underline the need for risk assessment to be an integral part of this process going forward.

Special Interest Groups

SSA 2024 offers five special interest group meetings (SIGs).

- The Cascadia Region Earthquake Science Center (CRESCENT)
- Center of Earth Geohazards
- On the Quantification and Treatment of Site Response Modeling Errors
- SZ4D: Status, Progress, Upcoming Activities
- What's Working in Earthquake Public Education? A SIG to Exchange Ideas for Interactive Learning

Workshops

SSA offers workshops for members to help advance their skills.

Data Mining on the Cloud 101

Tuesday 30 April, 10 AM–4 PM

Instructors: Marine Denolle, Yiyu Ni, Qibin Shi, Akash Kharita, Zoe Krauss and Kuan-Fu Feng of University of Washington; and Kaiwen Wang, Theresa Sawi, and Felix Waldhauser of Lamont-Doherty Earth Observatory, Columbia University

This workshop will introduce participants to cloud computing, from concept and best practices to practice, for two main approaches of data mining in seismology: correlation seismology and machine learning.

Seismic Instrumentation

Tuesday 30 April, 10 AM–4 PM

Instructors: Horst Rademacher, Berkeley Seismology Lab (retired); Kasey Aderhold, EarthScope Consortium; Marianne Karplus, University of Texas, El Paso; John Merchant, Sandia Laboratories, Albuquerque; Adam Ringler, Albuquerque Seismology Lab, U.S. Geological Survey

This workshop will discuss seismic instrumentation by explaining different scales and periods of Earth's vibrations and the large selection of instrumentation necessary to cover all aspects of Earth's vibrations. Explore the history of the development of inertial seismometers and what is typically used today. Learn how different kinds of inertial seismometers work and watch a detailed demonstration of a commercial broadband seismometer.

Publishing: How to Review and How to Be Reviewed

Tuesday 30 April, 12:30 PM–4:30 PM

Instructors: Allison Bent, editor-in-chief of Seismological Research Letters (SRL); John Ebel, Boston College and founding editor-in-chief of SRL; Brent Grocholski, editor at Science

Publishing is a key aspect of any academic career. Participants will learn how to review a scientific paper and how to respond effectively to reviews of your own work from three experienced editors. Discussion will also focus on promoting peer-reviewed research to the broader community. This interactive session will combine group discussion with lectures.

Field Seminars

Prince William Sound Field Seminar

Monday, 29 April, 7 AM–6:30 PM

Trip Leaders: Peter Haeussler and Lauren Schaefer of the U.S. Geological Survey; and Summer Ohlendorf, National Oceanic and Atmospheric Administration; Carolyn Parcheta, University of Alaska Fairbanks

This 5.5-hour field seminar cruise on the waters of Prince William Sound departs from Whittier and will include presentations from experts in tectonics, geology, cryo-seismology, tsunamis, landslides and current instrumentation and research efforts in the region. Participants will receive a field guide of the seminar's highlights, including historic earthquakes like the 1964 Great Alaska Earthquake, glacier seismology and local and regional seismic and infrasound networks.

Alaska Geophysics in the Field

Tuesday 30 April, 8 AM–4:30 PM

Trip Leaders: Julie Elliott, Michigan State; Natalia Ruppert, AEC; James Gridley, National Tsunami Warning Center

Where do seismic and GPS data come from? During visits to an active continuous GPS station in Palmer, adjacent to the National Tsunami Warning Center, and an active multi-instrument seismic station in Glacier View, experts will explain the key components of each station, as well as the instruments and components that are unique to Alaska. Participants will learn what it takes to get ground deformation and ground motion from the field to their computers.

SSA Meetings Code of Conduct

SSA is committed to fostering the exchange of scientific ideas by providing a safe, productive and welcoming environment for all SSA-sponsored meeting participants, including attendees, staff, volunteers and vendors. All participants at SSA meetings are expected to be considerate and collaborative, communicating openly with respect for others and critiquing ideas rather than individuals. Behavior that is acceptable to one person may not be acceptable to another, so use discretion to be sure that respect is communicated. For a detailed description of the ethics and code of conduct policies, please visit the SSA website: seismosoc.org/meetings/code-of-conduct.

Technical Sessions

The 2023 USGS National Seismic Hazard Model and Beyond

The USGS National Seismic Hazard Models (NSHMs) are a bridge between best-available earthquake science and public policy. The National Seismic Hazard Model Project (NSHMP) recently published a 50-state update that provided updates to the conterminous U.S., Alaska and Hawaii NSHMs. The USGS plans to update the Puerto Rico and U.S. Virgin Islands (PRVI) NSHM by the end of 2025 and the Guam and Northern Mariana Islands and American Samoa and Neighboring South Pacific Islands NSHMs by the end of 2026. For this session we will present the 2023 NSHMs for Alaska and the conterminous U.S. and progress on the update of the 2025 PRVI NSHM and invite contributions on topics that will influence future seismic hazard models, with an emphasis on Alaska. Topics include, but are not limited to: seismicity catalogs, declustering and smoothed seismicity models, geologic and geodetic deformation models, multi-fault ruptures, improved representation and quantification of epistemic uncertainty, new ground motion models (GMMs) including non-ergodic models, incorporation of physics-based (3D simulation) GMMs, basin effects, site response, directivity and time dependence. We also invite contributions on the use of NSHMs for scenario development, risk assessment for both buildings and infrastructure and other applications of risk mitigation including those within the insurance industry. We are also interested in contributions that highlight potential impacts of hazard modeling uncertainties on downstream applications.

Conveners: Jason M. Altekruse, U.S. Geological Survey (jaltekruse@usgs.gov); Julie A. Herrick, U.S. Geological Survey (jherrick@usgs.gov); Mark D. Petersen, U.S. Geological Survey (mpetersen@usgs.gov); Peter M. Powers, U.S. Geological Survey (pmpowers@usgs.gov); Emel Seyhan, Moody's RMS (Emel.Seyhan@rms.com); Allison M. Shumway, U.S. Geological Survey (ashumway@usgs.gov)

The 2024 Magnitude 7.5 Earthquake and the Associated Earthquake Swarm Beneath the Noto Peninsula, Central Japan

On New Year's Day 2024, a Mw 7.5 (Japanese Metrological Agency-JMA magnitude MJMA 7.6) occurred beneath the Noto Peninsula in Central Japan. The mainshock ruptured along a NE-SW trending thrust fault bilaterally for about 150 km. It was preceded by magnitude 5.5 and 4.6 foreshocks about four and two minutes before, and was followed by 238 M3.5 and larger aftershocks by 6 January 2024. Shaking from the mainshock reached the highest JMA intensity of 7 and produced significant damage and casualties in the Noto Peninsula and surrounding regions. A unique feature of this sequence is that it was preceded by an intense earthquake swarm, which started beneath the Noto Peninsula in November 2020 close to the epicenter of the M7.5 mainshock. The swarm was accompanied by up to 7 cm of uplift over the first two years. The largest event in the swarm sequence prior to the M7.5 mainshock was a M6.2 earthquake on 5 May 2023. Recent studies have shown that the swarm activity migrated from larger depths to shallower depths through a complex fault network, likely driven by upward movement of crustal fluids.

In this late-breaking session, we invite contributions from all disciplines that are relevant to this sequence. These include, but are not limited to: seismological and geodetic studies on the M7.5 mainshock rupture properties, the relationship between the mainshock and the ongoing earthquake swarm, subsurface imaging in the source region beneath the Noto Peninsula, potential remote triggering in Japan and elsewhere around the world, temporal changes in site response and subsurface medium properties tsunami generation, earthquake and tsunami early warning, and potential impact to the building structures. We also welcome submissions on disaster-mitigation strategies based on this earthquake, as well as other interdisciplinary contributions.

Conveners: Dara Goldberg, U.S. Geological Survey (degoldberg@usgs.gov); Sarah Minson, U.S. Geological Survey (sminson@usgs.gov); Takuya Nishimura, Kyoto University (nishimura.takuya.4s@kyoto-u.ac.jp); Zhigang Peng, Georgia Institute of Technology (zpeng@gatech.edu); Dun Wang, Chinese University of Geosciences (wangdun@cug.edu.cn); Suguru Yabe, Geological Survey of Japan (s.yabe@aist.go.jp)

3D Wavefield Simulations: From Seismic Imaging to Ground Motion Modeling

Advances in numerical methods and continued evolution of computer hardware and high-performance computing infrastructures have made it routine to simulate full 3D seismic wave propagation at local, regional and global scales. This capability and the growing efficiency in accomplishing it result in a broad range of applications, from ground motion simulation and scenario earthquakes incorporating 3D models, physics-based fault rupture dynamics simulations, to simulation-based seismic imaging methods such as full-waveform inversion. By taking advantage of ever-growing seismic observations, these applications have considerably expanded our understanding of seismic hazard, earthquake physics and regional and global tectonics. This session invites any seismic contributions that leverage the capabilities of full-wave simulations, including applications related to earthquake ground motion modeling, kinematic and dynamic rupture simulations, ambient noise and seismic imaging at all scales as well as other novel applications.

Conveners: Ebru Bozdag, Colorado School of Mines (bozdag@mines.edu); Bryant Chow, University of Alaska Fairbanks (bhchow@alaska.edu); Andreas Fichtner, ETH Zürich (andreas.fichtner@erdw.ethz.ch); Qinya Liu, University of Toronto (liuqy@physics.utoronto.ca); Erin W. Moriarty, U.S. Geological Survey (emoriarty@usgs.gov); Artie Rodgers, Lawrence Livermore National Laboratory, (rodgers7@llnl.gov)

Advancements in Forensic Seismology and Explosion Monitoring

Geophysical techniques are vital to enhance the detection and characterization of anthropogenic activity. This session calls for abstracts showcasing the latest in geophysical forensic analysis used in global security and monitoring. Topics may encompass observation, modeling and characterization of ground-coupled events such as explosions, mining, collapse and bolides. We also seek to highlight the advancements in source, propagation and signal analysis relating to controlled source experiments. We encourage submissions that integrate multi-modal observations and innovative instrumentation such as distributed acoustic sensing, remote sensing, infrasound and large-N arrays. The aim of this session is to encourage collaboration and discussion among institutional experts to drive innovations in forensic seismology and explosion monitoring.

Conveners: Richard A. Alfaro-Diaz, Los Alamos National Laboratory (rad@lanl.gov); Louisa Barama, Lawrence Livermore National Laboratory (barama1@llnl.gov); Jorge A. Garcia, Sandia National Laboratories (jgarc26@sandia.gov); Carl Tape, University of Alaska Fairbanks (ctape@alaska.edu); Cleat Zeiler, Nevada National Security Site, (ZeilerCP@nv.doe.gov)

Advances in Operational and Research Analysis of Earthquake Swarms

Earthquake swarms are clusters of earthquakes that are localized in space and time but without a distinctive mainshock or characteristic temporal decay of aftershock event rates. While a classic aftershock sequence typically arises due to the adjustment or "settling" of fault stresses after a mainshock, earthquake swarms can be produced from a wide variety of tectonic, structural, geothermal and anthropogenic conditions. Spatiotemporal variations in earthquake rates during swarms tend to depart from traditional mainshock-aftershock sequences resulting in unpredictable swarm durations and spatial extents.

The purpose of this session is to provide a broad overview of work related to earthquake swarms. Potential topics include but are not limited to: operational practices for capturing and forecasting swarms, methods for swarm analysis, geologic and tectonic interpretations and hazard analysis of swarms. Submission of studies at various time and geographic scales and those using both traditional and novel analysis methods are encouraged. This session aims to foster collaboration and the sharing of techniques and data sets to advance the community's capabilities to study and understand these phenomena.

Conveners: Kyren R. Bogolub, Nevada Seismological Laboratory, University of Nevada, Reno (kbogolub@unr.edu); Jeffery L. Fox, Ohio Geological Survey (jeffrey.fox@dnr.ohio.gov); Andrea L. Llenos, U.S. Geological Survey (allenos@usgs.gov); William H. Savran, Nevada Seismological Laboratory, University of Nevada, Reno (wsavran@unr.edu); Daniel T. Trugman, Nevada Seismological Laboratory, University of Nevada, Reno (dtrugman@unr.edu); Elizabeth A. Vanacore, University of Puerto Rico Mayagüez, Puerto Rico Seismic Network (elizabeth.vanacore@upr.edu)

Advancing Seismology with Distributed Fiber Optic Sensing

Distributed fiber optic sensing (DFOS) has emerged as a transformative technology in seismology, offering unparalleled sensing density and cost-effectiveness compared to classical seismic acquisitions, especially in challenging-to-access areas. DFOS enables a wide range of seismic studies, including earthquake detection and location, source focal mechanism and fault rupture process inversions, geo-hazard early warning, microseismic monitoring, subsurface imaging, near-surface and reservoir characterization, urban and environmental monitoring and nondestructive testing. The unused land and subsea telecommunication fiber optic cables, commonly known as 'dark fibers,' have progressively contributed to significant new findings in the Earth sciences.

Moreover, novel sensing techniques and improved instruments are extending the range, enhancing sensitivity and diminishing the noise floor of DFOS, enabling the observation of physical phenomena with an unprecedented resolution. DFOS also makes it possible to integrate multi-physics measurements, such as strain/strain rate (e.g., distributed acoustic sensing or DAS), temperature, electric and magnetic fields, in combination with other point-based sensors, to better constrain subsurface structures and processes and quantify their spatial and temporal variations. Both traditional and novel big-data technologies, including high-performance computing, cloud storage and computing, as well as machine learning, are now successfully employed to effectively manage, process and exploit the vast amounts of data collected by DFOS.

This session aims to explore the latest developments in DFOS technologies, applications and challenges in the integration of DFOS into seismological research. We welcome experts, researchers and practitioners from various disciplines to share, network and exchange innovative ideas to leverage DFOS and advance its applications in seismology and Earth sciences.

Conveners: Ettore Biondi, California Institute of Technology (ebiondi@caltech.edu); Daniel Bowden, ETH Zürich (daniel.bowden@erdw.ethz.ch); Derrick Chambers, Colorado School of Mines (derrickchambers@mines.edu); Julia Correa, Lawrence Berkeley National Laboratory (juliacorrea@lbl.gov); Manuel Mendoza, University of Colorado, Boulder (Manuel.Mendoza@colorado.edu); Krystyna Smolinski, ETH Zürich (krystyna.smolinski@erdw.ethz.ch); Veronica Rodriguez Tribaldos, GFZ Potsdam (verort@gfz-potsdam.de); Shihao Yuan, Colorado School of Mines (syuan@mines.edu)

Anisotropy Across Scales

Mapping the distribution of seismic anisotropy (radial and azimuthal) provides fascinating insights into dynamic processes of Earth (for example, lithospheric deformation, asthenospheric flow pattern, plate boundary dynamics, core-mantle boundary processes and ice dynamics). However, given the complexity of possible anisotropic structures and symmetries, and the different strengths and weaknesses of various measurement techniques, resolving anisotropy in the Earth remains challenging. The growing volume of seismic data and novel analysis methods allow us to characterize anisotropic properties on different scales and attempt to reconcile seismic observables with experimental results and geodynamic models. The aim of this session is to bring together scientists working on different aspects of seismic anisotropy to provide state-of-the-art insights from both an observational and a modeling point of view.

Conveners: Frederik Link, Yale University (frederik.link@yale.edu); Eric Loeberich, Yale University (eric.loeberich@yale.edu); Walid B. Mansour, Washington University in St. Louis (walid@wustl.edu)

Applications and Discoveries in Cryoseismology Across Spatial and Temporal Scales

Polar and mountainous regions are evolving rapidly in response to climate change, carrying significant implications for Earth's cryosphere. These changes impact natural hazards, alter the availability of natural resources, and influence global trade dynamics and additional economic factors. The rapid expansion of data collected by broadband seismometers, nodal instruments, and distributed acoustic sensing (DAS) has led to the emergence of a unique interdisciplinary field at the intersection of glaciology and seismology. Observations from seismic and microseismic signals offer valuable constraints for deducing structures and processes within Earth's cryosphere. As a result, our understanding of the complex interconnections within Earth systems and climate dynamics is further enriched. Seismic techniques used in recent studies have provided in-situ quantitative insights to illuminate the dynamics of various cryospheric systems and environments including glacial flow, retreat, iceberg calving, ice shelves, basal and episodic slip, hydrology and sea ice migration. Active and passive seismic methods allow for analysis and imaging of Earth's structure in polar and mountainous regions, including glaciers, ice sheets, sea ice and permafrost. Furthermore, seismic methods prove useful for monitoring Earth's cryosphere and related phenomena, in a changing world. This session aims to assemble diverse experts to present the latest cryoseismology research and foster collaborations in this emergent field. We welcome a wide range of contributions, encompassing studies that focus on monitoring and analyzing seismicity of tectonic or cryogenic origin, natural hazards, and near-surface processes and structures. We also encourage investigations into tectonic-scale structures and dynamics. Furthermore, we invite submissions that explore the advancement of innovative seismic methods, aiming to enhance monitoring and understanding of Earth's cryosphere. In addition to showcasing excellent science, this inaugural cryoseismology session will help advance SSA's mission of fostering scientific connections and collaborations within an inherently interdisciplinary field.

Conveners: Rick Aster, Colorado State University (rick.aster@colostate.edu); John Cassidy, Natural Resources Canada, Geological Survey of Canada (john.cassidy@nrcan-rncan.gc.ca); Jan Dettmer, University of Calgary (jan.dettmer@ucalgary.ca); Jeremy M. Gosselin, University of Calgary (jeremy.gosselin@ucalgary.ca); Celeste Labedz, University of Calgary (celeste.labedz@ucalgary.ca); John-Morgan Manos, University of Washington (jmanos@uw.edu); Elisa McGhee, Colorado State University (elisa.mcghee@colostate.edu); Stephanie Olinger, Harvard University, (stepholinger@fas.harvard.edu); Rachel Willis, Colorado School of Mines, (rwillis1@mines.edu)

Assessing Seismic Hazard for Critical Facilities and Infrastructure—Insights and Challenges

Critical facilities such as nuclear plants, industrial facilities, dams, tailings dams and waste disposal sites need to remain safe under potential shaking even from large, rare seismic events. Similarly, seismic shaking presents hazards to distributed systems serving power, water, transportation and waste disposal. Hazards are usually assessed through specialized frameworks including PSHA and PFDHA. Challenges in seismic hazard assessment for major structures provide a springboard for research and innovation in the engineering and seismological communities, and lead to cutting-edge solutions and advances. Large national and international projects aimed at critical sites often shape the state-of-the-art, but notable contributions have also come from smaller teams from academia, government and civilian practice. New approaches and innovations are bringing advances in topics such as source, site and ground motion characterization, quantification and refinement of uncertainties.

In this session, we would like to bring together the seismological and engineering communities to discuss advances in any aspect of seismology and engineering seismology where innovation has been driven by the needs of seismic safety and hazard assessment for critical facilities or infrastructure. We welcome contributions from academia and practice, regulating and operating parties, research-led consulting firms, energy and other sectors. We look forward to discussing challenges, insights and best practices from past and current endeavors, with a view to new directions in data, models and methods and potential applications.

Conveners: Céline Beauval, ISTerre, Université Grenoble Alpes (celine.beauval@univ-grenoble-alpes.fr); Glenn Biasi, U.S. Geological Survey (gbiasi@usgs.gov); Olga-Joan Ktenidou, National Observatory of Athen (olga.ktenidou@noa.gr); Andreas Skarlatoudis, AECOM (andreas.skarlatoudis@aecom.com)

Characteristics and Mechanics of Fault Zone Rupture Processes, from Micro to Macro Scales

Fault zones are governed by diverse mechanical processes that hold the key to advancing our understanding of fault rupture behaviors and the related seismic hazards. This session seeks to delve into the interplay of intrinsic fault zone properties, stress regimes and kinematics patterns that dictate rupture mechanics of earthquakes and slow-slip events. Through the lens of advanced multi-geophysical observations from stress accumulation and release to the initiation, propagation and termination of fault ruptures, we are gaining deeper insights into the mechanical processes governing fault zones. However, weaving these insights into a comprehensive understanding remains a challenge. This session invites contributions that focus on the mechanics of fault zone rupture behaviors, from micro to macro scales. We encourage interdisciplinary submissions that synthesize observational, experimental, theoretical and computational insights on the mechanics that control rupture dynamics in the fault zones.

Conveners: Xiaowei Chen, Texas A&M University (xiaowei.chen@tamu.edu); Yifang Cheng, University of California, Berkeley (chengyif@berkeley.edu); Zhe Jia, University of California, San Diego (z5jia@ucsd.edu); Junle Jiang, University of Oklahoma (jiang@ou.edu)

ESC-SSA Joint Session: Climate Change and Environmental Seismology

Climate change and associated environmental impacts will be some of the most pressing global-scale challenges of the coming century. Many of their effects can be observed and evaluated with seismology. With decades of analog seismograms predating the satellite era, an increasing density of seismic networks around the globe and advances in data analysis methods, our science can make significant contributions to understanding climate change and its environmental impacts. This session seeks abstracts showcasing the application of seismology to advancing the observation, modeling and decision-making associated with climate change and other environmental hazards, including how seismology can support the real-time management of natural hazards caused or exacerbated by extreme climate conditions. We welcome seismic and seismoacoustic studies from all domains impacted by climate change. Presentations are also encouraged on the effects of climate change on the practice of seismology, from challenges posed to network operations, to effects on seismic data, to additional data streams needed to improve climate and environmental monitoring capabilities.

This session is jointly organized by the European Seismological Commission and SSA.

Conveners: Robert E. Anthony, U.S. Geological Survey (reanthony@usgs.gov); Allison Bent, Natural Resources Canada (allison.bent@nrcan-rncan.gc.ca); Michael Dietze, Georg-August-University (mdietze@gfz-potsdam.de); Shujuan Mao, Stanford University (sjmao@stanford.edu); Robert Mellors, University of California, San Diego (rmellors@ucsd.edu); Siobhan Niklasson, New Mexico Institute of Mining and Technology (siobhan.niklasson@student.nmt.edu)

Cordilleran Strike-Slip Faults as Seismogenic and Seismological Features

The North American Cordillera extends from southern Mexico to northern Alaska and includes several active fault systems. Strike-slip faults are a major feature in the neotectonic framework of the North American Cordillera and, in many places, coincide with profound geophysical boundaries in the lithosphere. Syntheses of regional geological and geophysical datasets reveal that the crustal-scale architecture of the faults is tied to their geologic evolution, but a number of questions remain regarding the long-term evolution of these structures, leading to the present-day crustal structure and seismogenic behavior. This session seeks to highlight present research relating the long-term geological evolution of Cordilleran strike-slip faults as it relates to the neotectonic, seismological and geophysical signature of the faults.

Conveners: Richard Lease, U.S. Geological Survey (rlease@usgs.gov); Sean Regan, University of Alaska Fairbanks (sregan5@alaska.edu); Sarah Roeske, University of California, Davis (smroeske@ucdavis.edu); Trevor S. Waldien, South Dakota School of Mines and Technology (trevor.waldien@sdsmt.edu)

Creating Actionable Earthquake Information Products

The earthquake science and engineering community can provide leading-edge earthquake impact information to improve mitigation, response and recovery through accessible and actionable communication of earthquake hazard, loss and risk. This session explores and encourages contributions concerning earthquake information tools and their development cycle: science, system and product objectives and design; iterating through end-user engagement and product redesign; and public and professional user information campaigns necessary for their rollout.

We invite presentations highlighting research and applications of earthquake information, particularly those that consider and engage with users to improve earthquake information tools. Example topics include but are not limited to: presenting near-real-time shaking and impact estimates; alerting and follow-up EEW-related information related to earthquake early warnings; tools for communicating hazards and risk, engineering design and mitigation tools; earthquake information apps; and product evaluation and user engagement efforts.

Conveners: Tiegan Hobbs, Geological Survey of Canada (thobbs@eoas.ubc.ca); Sabine Loos, University of Michigan (sloos@umich.edu); Marísa A. Macías, U.S. Geological Survey (mmacias@usgs.gov); Jessie K. Saunders, California Institute of Technology (jsaunder@caltech.edu); David Wald, U.S. Geological Survey (wald@usgs.gov)

Cryptic Faults: Advances in Characterizing Low Strain Rate and Environmentally Obscured Faults

Identifying and characterizing active faults can now be performed almost routinely in places with high strain rates and clear geomorphology. In high strain rate domains, seismicity typically aligns along active fault planes, and slip rates are detectable with GNSS networks. Furthermore, standard methodologies in tectonic geomorphology have developed and matured in arid environments with minimal vegetation, such as in the deserts of the Western United States or Asia.

However, these conditions are not met in all seismically active regions. In low strain rate domains, faults may not produce pronounced geomorphic expressions, and if there are significant ruptures, exceptionally long recurrence intervals contribute to challenges in identifying them. This problem is especially acute in recently glaciated regions where the very young landscapes may not preserve a complete earthquake record. Furthermore, thick vegetation common to many of the same regions (e.g., Western Canada, Alaska), can make remote sensing and field observations of the bare earth difficult. Microseismicity, even when rigorously relocated, often does not align along fault planes, and GNSS networks do not have the necessary precision to measure strain accumulation across faults. Consequently, there is often disagreement between different disciplines about whether there is enough evidence to consider a fault "active" and hazardous. In this session, we solicit abstracts on inconspicuous active faults, and those which are difficult to observe and assess. We hope to hear from a wide variety of practitioners using innovative techniques in paleoseismology, field geology, marine geology, observational seismology, geodesy, remote sensing and modeling to find and characterize these challenging, cryptic faults.

Conveners: Theron Finley, University of Victoria (tfinley@uvic.ca); Tiegan Hobbs, Geological Survey of Canada (tiegan.hobbs@NRCan-RNCan.gc.ca); Barrett Salisbury, Alaska Division of Geological & Geophysical Surveys (barrett.salisbury@alaska.gov); Lydia Staisch, U.S. Geological Survey (lstaisch@usgs.gov)

Detecting, Characterizing and Monitoring Mass Movements

In light of evolving climate patterns and land-use changes, coupled with improved monitoring capabilities, we are witnessing a notable increase in detections of mass movements, such as landslides, debris and snow avalanches, lahars and glacial events. These events can pose significant hazards, and there is a pressing need to better understand, characterize and mitigate them. While these sources are not routinely monitored in real-time like earthquakes, recent advancements in seismoacoustic data and ground-based, airborne and satellite imagery offer opportunities for rapid early warning and post-event detection and analysis. These improved data sources and techniques can also help search for reliable precursors to catastrophic failure and can be used to characterize existing unstable slope instabilities.

This session aims to explore innovative methods to improve our comprehension of these non-earthquake seismic sources and enhance our ability to characterize and monitor them and mitigate associated hazards. We invite presentations that investigate various types of mass movements by leveraging seismoacoustic, geodetic and remote sensing techniques along with the application of machine learning. Topics of interest encompass but are not limited to: source detection, location, characterization, modeling and classification, precursory signal analysis, monitoring and hazard mitigation.

Conveners: Kate Allstadt, U.S. Geological Survey (kallstadt@usgs.gov); Clément Hibert, University of Strasbourg (hibert@unistra.fr); Ezgi Karasozen, University of Alaska Fairbanks/Alaska Earthquake Center (ekarasozen@alaska.edu); Liam Toney, U.S. Geological Survey(ltoney@usgs.gov)

Earth's Structure from the Crust to the Core

This session will cover all aspects of "structural seismology" and highlight new contributions to research of core and mantle dynamics, the role of the mantle transition zone in mantle convection, volcanism in different settings around the world, the structure of subducting slabs, deep lithospheric deformation and processes, and lithosphere-asthenosphere interactions and their feedbacks into geohazards. We encourage submissions that introduce new or new combinations of seismological data types, advances in global and regional-scale seismic tomography, 3D waveform modeling, array- based approaches and the analysis of correlation wavefields.

Conveners: Keith Koper, University of Utah (kkoper@gmail.com); Jeroen Ritsema, University of Michigan (jritsema@umich.edu); Vera Schulte-Pelkum, University of Colorado (vera.schulte-pelkum@colorado.edu)

End-to-End Advancements in Earthquake Early Warning Systems

The field of Earthquake Early Warning (EEW) has expanded and evolved significantly since the first public system came online in Mexico in 1991. Public EEW systems can now be found in many countries around the globe. These systems make use of cutting-edge scientific, technological and social science advancements to deliver alerts as rapidly, accurately and with as much positive impact as possible.

EEW systems comprise various elements that must work together synchronously and seamlessly to deliver useful alerts. These components include world-class seismic and geodetic networks, rapid telecommunications, algorithms that are capable of quickly and correctly detecting earthquakes and technical recipients that are capable of turning alert messages produced by the system into useful warning products. To maximize effectiveness of EEW systems, people must also be educated about how to take safe response actions, such as Drop, Cover and Hold On. To establish the necessary culture of awareness and preparedness, EEW organizations must work with others, including public safety organizations, to ensure a broad, consistent and authoritative EEW education and outreach effort. Such initiatives should include engagement with critical infrastructure operators, and take special care to address vulnerable populations, such as low-income, special needs, new immigrants, indigenous and elderly.

This session welcomes abstracts related to all aspects of innovating, optimizing and maintaining EEW systems including traditional and novel sensor developments, advancements in communications, methodology and algorithmic development, system assessment and abstracts related to education, outreach and engagement for EEW.

Conveners: Ronni Grapenthin, University of Alaska Fairbanks (rgrapenthin@alaska.edu); Angie I. Lux, Berkeley Seismology Laboratory (angie.lux@berkeley.edu); Mouse Reusch, University of Washington (topo@uw.edu); Brian Terbush, Washington State Emergency Management Division (Brian.Terbush@mil.wa.gov); Fabia Terra, Berkeley Seismology Laboratory (terra@berkeley.edu)

From Earthquake Recordings to Empirical Ground-Motion Modeling

The engineering seismology community has made a major effort in recent years to develop advanced ground motion models (GMMs). These developments have been facilitated by the availability of very rich earthquake databases made possible by the expansion of seismological networks around the world and open data policies. However, uncertainties in GMMs remain significant and reducing the epistemic uncertainties is currently one of the main challenges in seismic hazard assessment. In empirical GMMs it is often assumed that the earthquakes are recorded at the free surface of the Earth, that the sensor installation conditions and the seasonal effects can be neglected, and that all instruments provide recordings with reliable amplitudes. In practice, many seismic stations are located at depth (e.g., in borehole, in tunnels) or in an urban environment, errors in the metadata can occur, and detailed site characterization and site-effect assessment are performed only on a limited subset of stations.

With this background, this session welcomes contributions highlighting any effects (from station installation conditions to complex site-effects) that could affect the recorded ground motion, with consequent implications for GMMs, especially at high frequency. Topics of interest include data processing and data quality control, instrument coupling, soil-structure interaction, depth effect (down-going waves), seasonal variations, topography effect, site-effects, site characterization, regional and local attenuation and small-scale heterogeneity and scattering. Studies comparing several techniques at the same site and those integrating a variety of datasets are also encouraged. Studies on improving current practices in earthquake databases and GMMs development, or on the enhanced understanding of the high-frequency content of seismic records are particularly welcome.

Conveners: Carlo Cauzzi, ORFEUS, Swiss Seismological Service, ETH Zürich, (carlo.cauzzi@sed.ethz.ch); Fabrice

Hollender, CEA Cadarache (fabrice.hollender@cea.fr); Vincent Perron, CEA Cadarache (vincent.perron@cea.fr); Zafeiria Roumelioti, University of Patras (zroumelioti@upatras.gr); Paola Traversa, Electricite de France, (paola.traversa@edf.fr)

From Faults to Fjords: Earthquake Evidence in Terrestrial and Subaqueous Environments

Strong ground motion and surface deformation caused by slip on plate boundary, intraslab and crustal faults perturb surficial processes and leave geologic evidence in terrestrial and subaqueous environments. This two-part session explores paleoseismic approaches that use geologic evidence to reconstruct records of past earthquakes. Part one will address earthquake evidence in terrestrial settings. This evidence may be produced by coastal, fluvial and colluvial processes that together shape the ultimate sedimentary and geomorphic response to tectonic surface deformation. Presentations also may focus on ground failure and landslides triggered by earthquake shaking. Part two will feature subaqueous lake bottom and seafloor imprints and processes triggered by earthquakes. These earthquake-triggered responses are governed by the properties of the passing seismic waves (frequency, amplitude, duration) and the geomechanics of the substrate (grain size, composition, shear strength). Presentations may focus on the array of subaqueous sedimentary responses to strong ground motion, including different styles of mass failure, surficial sediment remobilization, soft sediment deformation and/or seismic strengthening.

We invite presentations from Alaska and beyond that highlight paleoseismic records from all depositional environments, laboratory analyses, modeling studies, or syntheses and comparisons of global records. We particularly encourage presentations of: 1) Novel techniques using geophysical survey tools, sediment sampling analyses and remote sensing techniques to quantify tectonic deformation; 2) Studies with high geochronological precision, beyond the limitations of typical radiometric dating; 3) Studies that compare paleoseismic records from adjoining subaqueous and terrestrial environments, pointing out the promises and pitfalls of different approaches; and 4) Experiments that simulate the array of surficial processes that form geologic evidence of earthquakes.

Conveners: Danny Brothers, U.S. Geological Survey (dbrothers@usgs.gov); Tina Dura, Virginia Polytechnic Institute and State University, tinadura@vt.edu); Jenna Hill, U.S. Geological Survey (jhill@usgs.gov); Kristin Morell, University of California, Santa Barbara (kmorell@ucsb.edu); Belle Philibosian, U.S. Geological Survey (bphilibosian@usgs.gov); Derek Sawyer, Ohio State University (sawyer.144@osu.edu); Drake Singleton, U.S. Geological Survey (dsingleton@usgs.gov); Katleen Wils, University of Innsbruck (katleen.wils@uibk.ac.at); Rob Witter, U.S. Geological Survey (rwitter@usgs.gov); Mark Zellman, BGC Engineering (mzellman@bgcengineering.ca)

From Geodynamics to Earthquake Rupture, Models That Cross Time- and Length-Scales

This session brings together researchers in geodynamic modeling and earthquake rupture modeling to exchange ideas in the areas of algorithms, software tools, benchmarks and, of course, scientific results.

The timescales of interest in global geodynamics range from the overturn time of the mantle to the timescale of measurable change of plate motions. This latter timescale becomes increasingly shorter as our capacity to measure deformations reaches sub-millimeter accuracy (driven by the need to understand pressing issues in global climate change, for example). Geodynamic timescales now overlap those associated with surface relaxation times of large earthquakes. Coming from the other direction, models of earthquake rupture run over the seismic cycle and capture the long-term evolution of the surface deformation and capture the accumulated offset along individual faults.

As we approach the computing power and model capacity to attempt to unify long-term geodynamic models with short timescale seismic rupture models, we propose this session to ask: What stands in our way? What algorithm developments are needed? Are there mathematical or physical scale-crossing problems that need to be overcome? Can the geodynamics and earthquake modeling community talk to each other?

Conveners: Matthew Knepley, University at Buffalo (knepley@gmail.com); Louis Moresi, Australian National University (louis.moresi@anu.edu.au)

How Well Can We Predict Broadband Site-Specific Ground Motion and Its Spatial Variability So Far?

Over the past few decades, a large number of studies have focused on the impacts of the shallow geological subsurface structure (within the uppermost one to two km) on the intensity and frequency content of ground motions recorded at the surface. One of the most significant developments in the field is the growing evidence that simplified 1D ground response models have only limited ability to accurately match recorded ground motions. For this reason, very detailed and computationally expensive methods for analysing the ground response are gaining more interest as of late.

In this session, we invite presentations on site characterization and ground motion modeling covering amplification and attenuation in a wide range of frequencies from < 1 Hz (interesting from an engineering perspective) to > 10 Hz (of special interest for the characterization of attenuation). Numerical or empirical studies on the frequency-dependent effects of spatial variability on attenuation and amplification, an often overlooked issue, are specifically welcome. Similarly, contributions about multidimensional ground response analyses are encouraged. Further topics of interest include the use of Artificial Intelligence (AI) to enhance and/or reduce the computational load of very detailed ground response analyses and site characterization as well as other geophysical surveys using active and passive seismic sources. We also invite contributions on the spatial correlation of earthquake intensity measures as well as correlation models for different intensity measures and regions based on empirical data and simulations. This session aims to provide researchers and engineers with an opportunity to discuss different modeling approaches and their required computational effort, and to compare the numerical results against real, observed ground motions over a broadband frequency range.

Conveners: Morteza Bastami, International Institute of Earthquake Engineering and Seismology (m.bastmi@iiees.ac.ir); Mohamad M. Hallal, University of California, Berkeley (mhallal@berkeley.edu); Chunyang Ji, North Carolina State University (cji3@ncsu.edu); Andrés Olivar-Castaño, University of Potsdam (andres.olivar-castano@uni-potsdam.de); Marco Pilz, GFZ Potsdam (pilz@gfz-potsdam.de)

Illuminating Complex, Multiplet Earthquake Sequences at Kahramanmaras (Türkiye), Herat (Afghanistan) and Beyond

Multiplet earthquakes (doublets, triplets, etc.) pose distinct challenges compared to standard mainshock-aftershock sequences, including recurring strong ground motions that can destroy already-damaged buildings and stretch emergency services. The overlapping seismic or surface deformation signals can also complicate the scientific interpretation and response. However, multiplet sequences also have great potential for illuminating earthquake processes such as stress triggering, fault interactions, and rupture nucleation, propagation and arrest. Notable recent examples include the 6 February 2023 Kahramanmaras, Türkiye Mw 7.8 and 7.6 doublet, the October 2023 Herat, Afghanistan Mw 6.3 quadruplet, the 1 July 2022 Mw 6.0 Hormozgan, Iran doublet, the 14 November 2021 Mw 6.2 and 6.3 Fin, Iran doublet, the 2020 Mw 7.8 and 7.6 Shumagin, Alaska doublet, and the 2019 Minandao, Philippines Mw 6.4–6.8 quadruplet, which together offer a wealth of new data to explore. We solicit work on these and other multiplet sequences that involve seismic analyses, remote sensing, geodesy, field observations, numerical modeling or combinations of these approaches. We solicit studies that address the progression of fault slip through time (the kinematics) and/or help explain this sequence of events (the dynamics). We also seek contributions that offer insights into why some fault systems may be more prone to multiplets than others, or perhaps even offer suggestions for how these sequences might be better incorporated into seismic hazard analyses. Through in-depth discussions, we aim to emphasize the significance of enhancing international collaboration, implementing monitoring technologies and establishing disaster preparedness strategies to mitigate the impact of future seismic events.

Conveners: Aybige Akinci, National Institute of Geophysics and Volcanology (aybige.akinci@ingv.it); Pınar Büyükakpınar, GFZ Potsdam (pinar@gfz-potsdam.de); Gareth Funning, University of California, Riverside (gareth@ucr.edu); Alice-Agnes Gabriel, University of California, San Diego (algabriel@ucsd.edu); Mohammadreza Jamalreyhani, SUSTech, China (jamalreyhani@sustech.edu.cn); Edwin Nissen, University of Victoria (enissen@uvic.ca)

Induced Earthquakes: Source Characteristics, Mechanisms, Stress Field Modeling and Hazards

Induced earthquakes triggered by oil and gas production, enhanced geothermal systems, fluid injection for mining and carbon capture have raised significant concerns. The spatial and temporal evolution of induced seismicity is intricately connected to multiple factors, including the poroelastic response of the site, fluid budget, duration of operations and halts, dimension and hydromechanical properties of the substratum and fault-slip modes under undrained/drained conditions. These factors vary between nonproducing unconventional reservoirs and porous conventional reservoirs. The spatiotemporal progression of induced earthquakes appears closely tied to pre-existing tectonic structures, the orientation of faults, the diffusion of pore pressures, stress redistribution over time and poroelastic stress transfer. Multidisciplinary approaches can help to unravel underlying mechanisms, thereby providing insights into the development of multifaceted mitigation strategies.

We invite submissions of case studies that offer insight into the underlying physics of induced earthquakes and the dynamic evolution of stress on host faults. We encourage interdisciplinary studies showcasing source properties of induced earthquakes, 3D imaging of faults, numerical simulations, stress field modeling, InSAR modeling, ground motion prediction models tailored for induced earthquakes, and integrated hydrologic and geo-mechanical modeling linked to production/injection operational data. We welcome contributions that delve into innovative datasets such as deep learning, distributed acoustic sensing and large-N arrays. We also seek computational, laboratory and in-situ experiments to unravel hydromechanical processes governing triggering mechanisms over time.

Conveners: Asiye Aziz Zanjani, Southern Methodist University (aazizzanjani@smu.edu); Farzaneh Aziz Zanjani, University of Miami (fzanjani@earth.miami.edu); Nadine Igonin, University of Texas at Dallas (Nadine.Igonin@utdallas.edu)

Integrative Assessment of Soil-Structure Interaction and Local Site Effects in Seismic Hazard Analysis

In seismically active regions, the execution of reliable site response analyses stands out as a cost-efficient measure during the design phase. The dynamic interactions between structural components and underlying soil layers, known as soil- structure interaction (SSI), impact the overall seismic performance and safety of the structures. The incorporation of SSI is vital during the design of critical infrastructures such as railroad and tunneling systems and power plants.

In this session, we invite researchers and practitioners to contribute to a cohesive understanding of SSI and local site effects, two essential components of the seismic hazard analysis (SHA). This session seeks to foster cutting-edge methodologies and innovative approaches in areas including but not limited to: site response analysis (e.g., nonlinear 2D/3D site effects), kinematic and inertial effects of SSI (e.g., numerical and physical modeling), vertical SSI, role of physics-based simulations in improving our understanding of SRA and SSI, complexities of SSI in urban settings and structures with deeply embedded foundations and large footprints (e.g., nuclear power plants).

Conveners: Swasti Saxena, Pacific Northwest National Laboratory (swasti.saxena@pnnl.gov); Mohammad Yazdi, Mott MacDonald (mohammad.yazdi@mottmac.com); Peiman Zogh, University of Nevada, Reno (pzogh@unr.edu)

Learning Across Geological, Geophysical and Model-Derived Observations to Constrain Earthquake Behavior

Earthquakes are dynamic events, but leave permanent markers of rock deformation and displacement. Geologic field studies identify these permanent markers, often used to determine the magnitude of slip in past earthquakes and combined with dating techniques to determine long-term rates over multiple earthquake cycles. Geophysical methods track ongoing plate motions and earthquake-cycle deformation captured by satellites using techniques involving GPS and InSAR. Analog and numerical models capture long-term geologic deformation and/or short-term dynamic behavior associated with earthquakes. However, in order to best advance both seismic hazard mitigation and earthquake science, the methods and results from these different lines of inquiry should be integrated and well understood by all. This is critical as we face the challenge of accounting for complex fault geometry and ruptures, off-fault damage and distributed deformation, all of which have been revealed as common features in recent earthquakes. Modeling can fill gaps in observational data, target future field sites and help determine the processes responsible for observed deformation features. Likewise, observational data is critical to characterizing earthquake behavior and provides necessary constraints on modeling input and output. This session aims to bring together scientists from these different lines of study to facilitate mutual understanding and collaboration. We encourage submissions that are methods- and/or results-based studies across structural geology, paleoseismology, Quaternary geology, geodesy and modeling of fault behavior and earthquake dynamics.

Conveners: Kimberly Blisniuk, San José State University (kimberly.blisniuk@sjsu.edu); Roland Burgmann, University of California, Berkeley (burgmann@berkeley.edu); Elizabeth Madden, San José State University (elizabeth.madden@sjsu.edu)

Leveraging Cutting-Edge Cyberinfrastructure for Large Scale Data Analysis and Education

The rapid growth of geophysical data, sensing technologies, and computing power has opened new frontiers in seismological research and education. To harness the potential of these resources, seismologists need to adopt advanced cyberinfrastructure and modern numerical methods for data collection, transformation, analysis, storage, and distribution at scale. This session will showcase how cloud computing services, open software frameworks, and high-performance computing (HPC) can enable open, reproducible, and transformative science in seismology. We will also explore how these technologies can support seismology education and training for the next-generation workforce. We invite contributions from researchers, data producers, and data providers who have experience in using or developing cutting-edge cyberinfrastructure for large-scale seismological problems such as dynamic rupture modeling, full waveform simulations and inversions, data mining using large seismic networks and distributed acoustic sensing. We also welcome contributions from educators who have implemented pedagogical approaches to teach seismology using modern cyberinfrastructure. Additionally, we encourage contributions from community efforts that aim to facilitate the adoption of these technologies, such as SCOPED, MTMOD, CRESCENT, SCEC, ChEESE, GeoInquire and Quakeworx.

Conveners: Alice-Agnes Gabriel, University of California, San Diego (algabriel@ucsd.edu); Henry Berglund, EarthScope Consortium (henry.berglund@earthscope.org); Marine A. Denolle, University of Washington (mdenolle@uw.edu); Tim

Dittmann, EarthScope Consortium (tim.dittmann@earthscope.org); Zoe Krauss, University of Washington (zkrauss@uw.edu); Eileen Martin, Colorado School of Mines (eileenrmartin@mines.edu); Amanda Thomas, University of Oregon (amthomas@uoregon.edu); Chad Trabant, EarthScope Consortium (chad.trabant@earthscope.org); Ian Wang, University of Texas at Austin (iwang@tacc.utexas.edu)

Machine Learning for Full Waveform Inversion: From Hybrid to End-to-End Approaches

Machine learning (ML) is quickly changing the landscape of how we approach seismic inverse problems, including full waveform inversion (FWI) where the seismic waveforms are directly used to solve for properties such as seismic velocities, migrated images, source locations and moment tensors. ML can potentially overcome some of the outstanding challenges associated with conventional FWI techniques by increasing computational efficiency, automating to reduce human labor and expertise requirements, mitigating cycle skipping, parameterization and convergence issues, implementing uncertainty quantification through deep learning-based approaches, and reducing the need for a suitable starting model. The wide breadth of ML methods and emerging scientific ML, deep-learning architectures and optimization algorithms that are rapidly expanding warrant a review of current application of these technologies in the seismic inverse domain.

We encourage submissions ranging from ML methods and tools that assist conventional physics-based FWI to full end-to-end deep learning FWI methods that estimate variety of inverted properties. All ML approaches are welcome, including but not limited to: deep neural networks, generative methods, decision trees, unsupervised dimensionality reduction and clustering, physics-informed ML, and application of various learning algorithms including supervised, self-supervised and unsupervised learning.

Conveners: Jennifer L. Harding, Sandia National Laboratories (jlhardi@sandia.gov); Mrinal K. Sen, University of Texas at Austin (mrinal@utexas.edu); Hongkyu Yoon, Sandia National Laboratories (hyoon@sandia.gov)

Marine Seismoacoustics

The depths of oceans, rivers and other water bodies, and the processes occurring within them, continue to be explored through the use of seismic and acoustic observations. Here we invite contributions from the full spectrum of submarine research fields, including geophysical and geodynamical imaging and/or modeling, earthquake/tsunami early warning, interactions at the seafloor interface, water/ice interface, climate induced changes, particularly in polar regions, tracking of marine life and the latest advances in underwater sensors and other related technologies.

Conveners: Kasey Aderhold, EarthScope Consortium (kasey.aderhold@earthscope.org); Helen Janiszewski, University of Hawaiʻi at Mānoa (hajanisz@hawaii.edu); Siobhan Niklasson, Los Alamos National Laboratory (sniklasson@lanl.gov); Charlotte Rowe, Los Alamos National Laboratory (char@lanl.gov).

Multidisciplinary Approaches for Volcanic Eruption Forecasting

Detecting volcanic unrest and forecasting volcanic eruptions, how they will evolve and when they will finish is one of the main challenges in volcanology. The interaction of volcanic systems with their environment during an eruptive process affects many different physical and chemical parameters. Many of these parameters, called observables, are monitored in volcanic systems in near-real time, being the base of alert-level strategies and forecasting protocols. Exploring these observables involves complex data processing, time series analysis and the development of numerical models of volcanic processes, with the goal of improving our understanding of the interaction between subsurface processes and volcanic activity.

Inferring conceptual and numerical models of how volcanoes work requires a multidisciplinary analysis integrating data and methodologies from different disciplines, including geology, seismology, remote sensing and geodesy; as well as physics or chemistry, signal processing and statistical approaches. At present, several promising results have been derived from this joint analysis, improving our knowledge of volcanic unrest and magma ascent, which helps eruption forecasting and decision-making.

This session aims to encourage the multidisciplinary community working in volcanology to submit their most recent results on unrest detection and eruption forecasting. We welcome (but are not limited to) contributions from volcano statistics, event trees analysis, data assimilation techniques, the use of artificial intelligence and machine learning to study volcanic signals, analysis of time series in volcanology, study of the evolution of new seismic parameters/features, development of innovative analytical methods and probabilistic volcanic hazard assessment. We invite researchers to share their valuable work in this session, contributing to the collective knowledge and progress in the field of volcanic forecasting.

Conveners: Alberto Ardid, University of Canterbury (alberto.ardid@canterbury.ac.nz); Francesca Bianco, Istituto Nazionale di Geofisica e Vulcanologia (francesca.bianco@ingv.it); Társilo Girona, Alaska Volcano Observatory, University of Alaska Fairbanks (tarsilo.girona@alaska.edu); Janire Prudencio, Universidad de Granada (janire@ugr.es)

Network Seismology: Recent Developments, Challenges and Lessons Learned

Seismic monitoring is not only an essential component of earthquake response but also forms the backbone of a substantial amount of research into seismic hazards, the earthquake process and seismotectonics. To ensure networks best serve the public, media, government and academic communities, it is important to continue to develop monitoring networks' abilities to accurately and rapidly catalog earthquakes. Due to the operational environment of seismic monitoring, seismic networks encounter many unique challenges not seen by the research community. In this session, we highlight the unique observations and challenges of monitoring agencies and look to developments that may improve networks' ability to fulfill their missions. Seismic operation centers play a crucial role in collecting seismic data, and generating earthquake products including catalogs, warnings and maps of ground shaking. The purpose of the session is to foster collaboration between network operators, inform the wider seismological community of the interesting and challenging problems within network seismology and look to the future on how to improve monitoring capabilities. This session is not only an opportunity for monitoring agencies to highlight new developments in their capabilities, but we also encourage submissions describing new instrumentation, methods and techniques that would benefit network operations for detecting, locating and characterizing earthquakes, particularly in a near real-time environment.

Conveners: Blaine Bockholt, Idaho National Laboratory (blaine.bockholt@inl.gov); Renate Hartog, University of Washington (jhartog@uw.edu); Kristine L. Pankow, University of Utah (pankowseis2@gmail.com); Adam Ringler, U.S. Geological Survey (aringler@usgs.gov); Dmitry Storchak, International Seismological Centre (dmitry@isc.ac.uk)

New Insights into the Development, Testing and Communication of Seismicity Forecasts

The increasing availability and quality of geophysical datasets, including high-resolution earthquake catalogs, fault information and interseismic strain data, has enabled the creation of statistical and physics-based seismicity models, some of which underpin probabilistic seismic hazard analyses. New machine learning (ML) techniques have also improved data acquisition and analysis for seismicity modeling. Forecasts produced by such models can be tested and compared prospectively, e.g., within the framework of the Collaboratory for the Study of Earthquake Predictability, paving the way for potentially more informative earthquake forecasts. In turn, forecast models are being operationalized by public and private agencies to provide a range of audiences with reliable information on the occurrence of earthquakes. This poses communication challenges that require solutions from the social sciences. We welcome contributions that help us elucidate the main advantages and limitations of current seismicity models, identify the most informative forecasting methods, improve our understanding of the earthquake generation process, and facilitate the communication and visualization of earthquake forecasts. Submissions may include models based on ML-derived earthquake catalogs, new hypotheses explaining what controls earthquake potential, quantitative analyses evaluating the predictive skills of seismicity forecasts, or studies on the effective communication of earthquake forecast information.

Conveners: Jose Bayona, University of Bristol (jose.bayona@bristol.ac.uk); Kelian Dascher-Cousineau, University of California, Berkeley (kdascher@berkeley.edu); Leila Mizrahi, Swiss Seismological Service (leila.mizrahi@sed.ethz.ch); William Savran, University of Nevada, Reno (wsavran@unr.edu); Max Schneider, U.S. Geological Survey (mschneider@usgs.gov)

Numerical Modeling in Seismology: Developments and Applications

We equally invite both contributions to numerical-modeling methods/algorithms and applications in any dimension if appropriate. Progress in seismology is unthinkable without continuous developments of theory and numerical-modeling methods. This is well seen in very recent important advances in the discontinuous Galerkin, finite-difference and spectral-element methods as well as in emergence of the new powerful distributional finite-difference method.

Recent developments include faithful rheological and geometrical complexity of the Earth's interior, earthquakes and other important seismological phenomena, time-space discretization, optimizations of computational algorithms and computer codes, optional balance between accuracy and efficiency. Remarkable progress in the finite-difference modeling in seismic exploration poses a useful challenge for numerical modeling in earthquake seismology. New observations and data from local dense networks make it possible for numerical modeling to considerably contribute to our understanding of rupture dynamics, seismic wave propagation, earthquake ground motion including non-linear behavior, seismic noise and earthquake hazard. We especially welcome applications to compelling observational issues in seismology.

Conveners: Alice-Agnes Gabriel, University of California, San Diego (algabriel@ucsd.edu); Martin Galis, Comenius University Bratislava (martin.galis@uniba.sk); Jozef Kristek, Comenius University Bratislava (kristek@fmph.uniba.sk); Peter Moczo, Comenius University Bratislava (moczo@fmph.uniba.sk); Arben Pitarka, Lawrence Livermore National Laboratory (pitarka1@llnl.gov); Wei Zhang, Southern

University of Science and Technology (zhangwei@sustech.edu.cn)

The OSIRIS-REx Sample Return Capsule Reentry: Geophysical Observations

The 24 September 2023 reentry of the NASA's OSIRIS-REx Sample Return Capsule (SRC) was only the fifth reentry from interplanetary space since the end of the Apollo era. It provided a unique opportunity to geophysically observe an "artificial meteor" with known dimensions, speed and mass. A diverse set of institutions utilized nodal seismic arrays, ground and airborne acoustic sensors, distributed acoustic sensing, GPS sounding and ionosphere Doppler sounding to record the object's passage through the atmosphere. Results from these studies have implications for the remote detection and characterization of meteoroids and high-speed artificial objects (e.g., reentry, orbital debris) on Earth and may inform mission concepts for planetary exploration (e.g., Venus, Mars, Titan, Jupiter). We invite contributions that emphasize geophysical observations of the OSIRIS-REx SRC reentry, and discuss their broad scientific implications for remote sensing on Earth and beyond.

Conveners: Chris Carr, Los Alamos National Laboratory (cgcarr@lanl.gov); Brian Elbing, Oklahoma State University (elbing@okstate.edu); Charles Langston, University of Memphis (clangstn@memphis.edu); Richard Lewis, The Defense Threat Reduction Agency (richard.d.lewis1.civ@mail.mil); Yasuhiro Nishikawa, Kochi University of Technology (nishikawa.yasuhiro@kochi-tech.ac.jp); Elizabeth A. Silber, Sandia National Laboratory (esilbe@sandia.gov)

Physics-Based Ground Motion Modeling

Physics-based wave propagation simulations have the potential to quantify the contribution to ground motion estimates from individual features included in the modeling, such as basin edge effects, topographic scattering, nonlinear soil effects, small-scale heterogeneities, source effects and general 3D path effects. Such quantification is useful for understanding wave propagation as well as which features must be included to reproduce observed seismic records. This session welcomes submissions on physics-based numerical modeling of wave propagation, including studies focused on the dynamic or kinematic rupture models as well as development and validation of community seismic velocity models, and quantification of contributions from these model features on simulated ground motions.

Conveners: Evan Hirakawa, U.S. Geological Survey (ehirakawa@usgs.gov); Kim B. Olsen, San Diego State University (kbolsen@mail.sdsu.edu); William Stephenson, U.S. Geological Survey (wstephens@usgs.gov)

Planetary Seismology

This session highlights contributions to seismology focused on planets other than Earth.

Conveners: Isabella Seppi, University of Alaska Fairbanks (irseppi@alaska.edu); Yuan Tian, University of Alaska Fairbanks (ytian4@alaska.edu)

Regional-Scale Hazard and Risk Assessments

Efforts toward improving the resilience of urban environments to seismic hazards and associated geohazards are challenged by spatially variable ground motions and permanent ground deformations (e.g., due to co-seismic landslides or soil liquefaction). Regional-scale probabilistic seismic hazard and risk analyses are often used to evaluate large, distributed infrastructure systems such as pipelines and transportation networks in densely populated cities. While relevant work in the last decade has contributed toward multi-scale probabilistic modeling of regional ground shaking and deformation, important advances to support regional risk and loss assessments, financial loss considerations, and earthquake response tools remain missing. For instance, accurately characterizing the spatial variability of ground motions and their associated effects is important to capture the seismic risk of exposed communities in earthquake-prone areas, which is increasing with urbanization and highly interdependent and aging infrastructure systems.

Even though there are common aspects between site-specific and regional seismic hazard and risk analyses, the characterization of ground motions, geologic conditions, and losses present different challenges to the data collection and modeling efforts. For instance, subduction zones, from the deep inslab environments through the megathrust and shallow crustal faults, present significant challenges when it comes to bridging the gap between earthquake science and application. Thus, this session invites contributions on 1) simulations and analyses of spatiotemporal variations of ground motion and deformation at regional scales, 2) tools developed for earthquake scenarios that capture the spatial correlation of ground motions, 3) advances in earthquake early-warning systems and rapid post-earthquake assessments, 4) methods based on the integration of site-specific data and geospatial analytics, 5) regional-scale approaches to estimate the occurrence and uncertainty of ground failure, 6) regional scale portfolio asset risk analyses and methodologies, 7) regional scale exposure and vulnerability assessments, and 8) specific applications of earthquake science for hazard and loss modeling.

Conveners: Ashly Cabas, North Carolina State University (amcabasm@ncsu.edu); John Cassidy, Geological Survey of Canada (john.cassidy@nrcan-rncan.gc.ca); Rodrigo Costa, University of Waterloo (rodrigo.costa@uwaterloo.ca); Cassie

Gann-Phillips, North Carolina State University (cvgann@ncsu.edu); Mike Greenfield, Greenfield Geotechnical (mike@greenfieldgeotechnical.com); Tiegan E. Hobbs, Geological Survey of Canada (thobbs@eoas.ubc.ca); James Kaklamanos, Merrimack College (kaklamanosj@merrimack.edu); Albert Kottke, Pacific Gas and Electric Company (albert.kottke@pge.com); Sabine Loos, University of Michigan (sloos@umich.edu); Cristina Lorenzo-Velazquez, North Carolina State University (clorenz@ncsu.edu; Andrew Makdisi, U.S. Geological Survey (amakdisi@usgs.gov); Hong-Kie Thio, AECOM (hong.kie.thio@aecom.com); Eric Thompson, U.S. Geological Survey (emthompson@usgs.gov); David Wald, U.S. Geological Survey (wald@usgs.gov); Erin Wirth, U.S. Geological Survey (emoriarty@usgs.gov)

Research Advances in "High-Impact" "Under-Studied" Earthquakes and Their Impacts on Communities

Many regions of the world are at risk of earthquakes with significant human and economic impacts due to regional seismic hazard and lack of earthquake preparedness (termed "high-impact"). The cause of the earthquakes might be poorly understood due to a lack of resources, a low probability of occurrence, a lack of interested seismologists, their remote locations, and/or a lack of awareness of the hazard (termed "under-studied"). The 2023 M6.8 Morocco earthquake serves as a striking example, where high mountains exist with little seismicity a few hundred kilometers from a plate boundary, and which caused shaking-related fatalities and injuries plus large economic losses. This session focuses on "high-impact," "under-studied" (HIUS) earthquakes, and we welcome abstracts across all areas of solid-earth science, earthquake geology and engineering, and social science that study or address HIUS earthquakes. We invite presentations highlighting research from any discipline with the potential to respond to the needs of vulnerable populations that have been historically underserved by current earthquake science, engineering and public policy. Example topics include: 1) community-driven or community-based research results; 2) discoveries advancing our understanding of seismic hazards in areas of low probability but high impact earthquakes (including intraplate and induced earthquakes); 3) strategies for implementing practical, research-inspired solutions for communities; 4) research engaging low-resourced communities or historically marginalized populations; 5) existing efforts to coordinate research and projects for broader community benefits; and 6) integration of social science with seismology. We encourage presenters to highlight strategies and efforts to improve inclusivity, diversity, equity and accessibility in seismology and earthquake science in these regions.

Conveners: Susan Bilek, New Mexico Institute of Mining and Technology (susan.bilek@nmt.edu); Marianne Karplus, University of Texas at El Paso (mkarplus@utep.edu); Zhigang Peng, Georgia Institute of Technology (zpeng@gatech.edu); Elizabeth Vanacore, University of Puerto Rico (elizabeth.vanacore@upr.edu); Aaron A. Velasco, University of Texas at El Paso (aavelasco@utep.edu)

Seismic Cycle-Driven Sea-Level Change Over Decades to Centuries: Observations and Projections

As global sea levels rise, coastal communities worldwide will be forced to adapt or retreat. Projections of relative sea-level change across decades or centuries will become essential planning tools to mitigate the vulnerability of these communities.

In seismically active regions, changes in land elevation associated with the earthquake cycle —including interseismic, coseismic and postseismic deformation, as well as slow-slip events — can either mitigate or exacerbate climate-driven sea-level rise over similar timescales. To ensure accurate projections of relative sea-level change, it is therefore necessary to evaluate the influence of tectonic vertical land movements (VLM) in the relevant analyses.

Estimating and incorporating tectonic VLM into projections of relative sea-level rise requires two key components: 1) Collecting and analyzing geologic and geodetic observations to constrain present and past contributions of VLM to relative sea-level change throughout all phases of the seismic cycle; and 2) Modeling to project observed tectonic VLM decades and centuries into the future.

We welcome contributions that link VLM resulting from the seismic cycle to relative sea-level changes, through data analysis, modeling or a combination of both.

Furthermore, vertical deformation is not always primarily associated with tectonic signals, as nontectonic processes such as sediment loading and glacial isostasy adjustment can also have significant influences on VLM of the lithosphere. Studies that help identify and account for such nontectonic processes to improve VLM projections, and thus relative sea- level projections, are also welcomed.

Conveners: Kate J. Clark, GNS Science (k.clark@gns.cri.nz); Andrew Howell, University of Canterbury (andrew.howell@canterbury.ac.nz); Jeonghyeop Kim, University of Washington (jey.kim@uw.edu);

Seismic Monitoring, Modeling and Management Needed for Geothermal Energy and Geologic Carbon Storage

Emerging subsurface operations (e.g., geothermal energy or carbon storage) are potential pathways to greener or more sustainable energy solutions and will play crucial roles in achieving the net-zero emission goal by 2050. However, concerns around induced earthquakes and the longevity and development of needed reservoirs are a serious impediment to widespread adoption of these emerging energy resources. Thus, tools to identify and de-risk induced seismicity concerns and better characterize the reservoirs will be necessary to reach climate goals. In this session, we invite contributions from research on novel seismic and non-seismic technologies and applications of novel and advanced seismic techniques to better understand and manage the transition to greener energy solutions. We welcome submissions of abstracts on computational, artificial intelligence/machine learning, laboratory experimental and field-scale studies.

We strongly encourage contributions from EGS/geothermal or carbon storage projects. Additionally, we are also interested in lessons learned from induced seismicity caused by other anthropogenic operations (e.g., disposal, production, hydraulic fracturing). Examples can include field test sites that focus on geophysical technologies, such as real-time monitoring and characterization of induced seismicity, distributed acoustic sensing, large-N array, active surface seismic, vertical seismic profiling, seismic imaging of faults and fracture zones, laboratory experiments and novel instrumentation. We also welcome submission of abstracts like laboratory studies that focus on the role that fluids play in fault reactivation, modelling studies at all scales, seismicity forecasting models, hazard/risk analysis, good-practice guidelines and mitigation strategies that would help in reducing commercial costs or enhancing the safety of future projects.

Conveners: Erkan Ay, Shell (Erkan.Ay@shell.com); Kai Gao, Los Alamos National Laboratory (kaigao@lanl.gov); Chet Hopp, Lawrence Berkeley National Laboratory (chopp@lbl.gov; Lianjie Huang, Los Alamos National Laboratory (ljh@lanl.gov); Federica Lanza, ETH Zürich (federica.lanza@sed.ethz.ch); Nori Nakata, Lawrence Berkeley National Laboratory (nnakata@lbl.gov); Annemarie Muntendam-Bos, Delft University of Technology (A.G.Muntendam-Bos@tudelft.nl); Kris Pankow, University of Utah (pankowseis2@gmail.com); Ryan Schultz, ETH Zürich (ryan.schultz@sed.ethz.ch); Nana Yoshimitsu, Kyoto University (yoshimitsu.nana.6i@kyoto-u.ac.jp); Yingcai Zheng, University of Houston (yzheng24@central.uh.edu)

Seismoacoustic, Geodetic and Other Geophysical Investigations of Active Volcanoes

Seismology has long been the primary means through which to study and monitor the movement of magma and other fluids in active volcanic systems. However, despite decades of seismic monitoring at volcanoes, answers to important questions about the ascent of magma, the circulation of fluids within volcanic systems, and how these phenomena are reflected in geophysical signals, remain elusive. In recent decades, improvements in instrumentation and processing techniques have led to the widespread use of additional geophysical tools capable of tracking fluid movement, including infrasound, high-rate GPS, InSAR and gravity. These tools, often used in concert with seismological techniques, have brought forth many new insights that were previously unknown. We seek submissions that showcase the breadth of interdisciplinary geophysical monitoring and study of active volcanoes using any of the methods described above or other interdisciplinary approaches. We encourage contributions that emphasize advances in numerical modeling or machine learning, feature new instrumentation or analytical methods and/or provide novel insights into the physical processes controlling fluid movement or other volcanic signals.

Conveners: Josh Crozier, U.S. Geological Survey (jcrozier@usgs.gov);Ricardo Garza-Giron, Colorado State University (rgarzagi@ucsc.edu); Margaret Glasgow, U.S. Geological Survey (mglasgow@usgs.gov); Alicia Hotovec-Ellis, U.S. Geological Survey (ahotovec-ellis@usgs.gov); John J. J. Lyons, U.S. Geological Survey (jlyons@usgs.gov); Diana Roman, Carnegie Science (droman@carnegiescience.edu)

Seismology in the Oceans: Pacific Hemisphere and Beyond

The ocean realm provides a clear, relatively pristine view into many of the fundamental tectonic and geodynamical processes that form our planet, including rifting, volcanism and hydrothermal processes at mid-ocean ridges; the origin and nature of mid-plate and hot-spot volcanism, transform-fault earthquake dynamics, hydration of oceanic lithosphere and the nature of multi-scale convection and its relationship to plate evolution, to name a few. The Pacific basin provides a natural laboratory for studying these processes, and it has been the focus of a number of experiments exploiting recent advances in marine-seismic instrumentation, including those affiliated with the multinational grassroots collaboration PacificArray. We invite contributions from scientists using active- and passive-source marine-seismic datasets to investigate fundamental Earth-science processes in the Pacific and other ocean basins.

Conveners: James Gaherty, Northern Arizona University (james.gaherty@nau.edu); Jianhua Gong, Indiana University (gongjian@iu.edu); HyeJeong Kim, University of Utah (hyejeong.kim@utah.edu); YoungHee Kim, Seoul National University (younghkim@snu.ac.kr); Joshua Russell, Syracuse University (jbrussel@syr.edu); Lindsay Worthington, University of New Mexico (lworthington@unm.edu)

Six Decades of Tsunami Science: From the Source of the 1964 Tsunami to Modern Community Preparedness

Tsunami science has evolved significantly in the 60 years since the 1964 Great Alaska Earthquake. There have been important advances in tsunami source characterization, propagation and runup modeling, tsunami warning and forecasting and probabilistic tsunami hazard assessment. After the recent tsunami disasters of 2004 and 2011, tsunami science has encompassed new fields of research that include studies of survivability, resilience, loss estimates and recovery potential of coastal communities. Translating tsunami hazards into potential risk estimates, educating the public, counteracting disaster amnesia and preserving the memories of tsunamis for future generations are all important tasks that the tsunami community will be working on for decades.

We welcome both focused and multidisciplinary contributions to this session covering any of the following: analytical and numerical modeling of different tsunami generation mechanisms, including submarine and subaerial landslides, volcanic eruptions and air-pressure disturbances; mapping tsunami inundation and evacuation zones; paleotsunami studies; regional and local studies that deal with hazard, risk, vulnerabilities and exposure; tools and procedures for more efficient forecast and warning; studies of community preparedness and human behavior; and best practices in public education and outreach.

Conveners: Dmitry Nicolsky, University of Alaska Fairbanks (djnicolsky@alaska.edu); Anthony Picasso, Alaska Division of Homeland Security & Emergency Management (anthony.picasso@alaska.gov); Barrett Salisbury, Alaska Division of Geological & Geophysical Surveys (barrett.salisbury@alaska.gov); Elena Suleimani, University of Alaska Fairbanks (ensuleimani@alaska.edu)

Special Applications in Seismology

This session presents a range of applications that record unique data or analyze data that contribute in novel ways. This includes studies on noise reduction, improved earthquake detection and characterization, low frequency and triggered earthquakes and applications in urban areas.

Conveners: Carl Tape, University of Alaska Fairbanks (ctape@alaska.edu); Michael West, University of Alaska Fairbanks (mewest@alaska.edu)

Structure and Behavior of the Alaska-Aleutian Subduction Zone

The Alaska-Aleutian subduction zone is one of the most seismically and volcanically active plate boundaries in the world. Over the past decade, it has ruptured in several large interplate and intraplate earthquakes and produced notable volcanic eruptions and non-eruptive activity. It exhibits profound along-strike variations in geodynamics, lithospheric configuration, locking, rupture history of the megathrust and other fault systems, slow-slip events and magmatic processes. The Alaska-Aleutian subduction zone is thus an excellent place to address fundamental questions regarding subduction zone processes and associated earthquake and volcanic activity. The availability of new geophysical datasets on land and off shore and the occurrence of a series of recent, well-characterized large earthquakes in the Alaska-Aleutian subduction zone have enabled a plethora of new results and insights into subduction processes. We invite a wide spectrum of contributions that focus on the Alaska-Aleutian subduction zone, including investigations using newly available geophysical imaging and monitoring datasets, paleoseismology and geological studies and numerical and experimental studies.

Conveners: Grace Barcheck, Cornell University (grace.barcheck@cornell.edu); Julie Elliott, Michigan State University (ellio372@msu.edu); Ronni Grapenthin, University of Alaska (rgrapenthin@alaska.edu); Donna Shillington, Northern Arizona University (donna.shillington@nau.edu); Xiaotao Yang, Purdue University (xtyang@purdue.edu)

Structure, Seismicity and Dynamics of the Queen Charlotte-Fairweather Fault System

The Queen Charlotte - Fairweather Fault System (QC-FW) is a transform plate boundary that spans >1000 kilometers of the western edge of North America between the Cascadia and Alaska convergent margins. In the last 100 years, the QC-FW has hosted several major earthquakes, including the 1949 magnitude (M 8.1) Queen Charlotte earthquake, the 1958 (M 7.9) on the Fairweather Fault, and the 2012 Haida-Gwaii (M 7.8) and 2013 Craig (M 7.5) earthquakes. The tectonics of the QC-FW are variable along its length, including oblique convergence in the south at Haida Gwaii, comparably simple shear offshore Southeast Alaska, and oblique collision with the Yakutat microplate in the north. The QC-FW is similar in length and in slip rate (~4-5 cm/yr) to the San Andreas fault system. However, the remote location of the QC-FW, largely offshore hugging the North American continental shelf and slope, leaves major gaps in our understanding of its structure, seismicity and dynamics. We welcome abstracts that explore the QC-FW system, including but not limited to: its natural hazards, earthquakes, subsurface properties, structure and tectonics. We encourage a large range of methods and seek perspectives that compare the QC-FW with other plate boundary systems.

Conveners: Collin Brandl, University of New Mexico (cbrandl@unm.edu); Andrew Gase, Western Washington University (gasea@wwu.edu); Emily Roland, Western

Washington University (rolande2@wwu.edu); Lindsay Worthington, University of New Mexico (lworthington@unm.edu)

Tectonics and Seismicity of Stable Continental Interiors

Earthquakes in stable continental interiors far from active plate boundaries, such as in central and eastern North America, northern Europe, western and southern Africa, Australia and parts of Asia, are perhaps the least understood. Nevertheless, advances in intraplate seismicity are being achieved through a variety of approaches. Examples include local- and national-scale seismic monitoring efforts that increase completeness of earthquake catalogs, detection algorithms that identify ever-smaller earthquakes from existing data, imaging of subsurface faults using relocated seismicity, seismic tomography and other geophysical methods, studies that constrain historical slip on such faults, quantification of geodetic, geomorphologic and elevation changes and through improved measurements of local stresses. In parallel with these efforts, ongoing ground motion studies continue to improve our understanding of source, path and site response characteristics unique to intraplate regions.

This session seeks diverse contributions related to intraplate earthquake hazards with goals of improving earthquake catalogs, identifying and characterizing active faults and/or deformation in stable continental interiors, deciphering long-term earthquake histories, statistical analyses of seismicity, assessing potential ground motion impacts, constraining models of kinematics and geodynamic properties and understanding the mechanisms that cause enigmatic intraplate earthquakes. Contributions regarding recent intraplate earthquake sequences are especially welcome.

Conveners: Oliver Boyd, U.S. Geological Survey (olboyd@usgs.gov); Jessica Thompson Jobe, U.S. Geological Survey (jjobe@usgs.gov); William Levandowski, TetraTech (will.levandowski@tetratech.com); Zhigang Peng, Georgia Institute of Technology (zpeng@gatech.edu); Anjana K. Shah, U.S. Geological Survey (ashah@usgs.gov)

Towards Advancing Earthquake Forecasting and Nowcasting: Recent Progress Using AI-Enhanced Methods

New technologies like advanced machine learning (ML) of big data (BD) and artificial intelligence (AI), together with signal-processing tools that emerged in the past decade, have brought a wave of intensified studies of earthquake forecasting and nowcasting. In addition, fast-expanding datasets due to the installation of dense-sensing networks, diversified observations (e.g., acoustic, elastic, satellite observations), injection-induced seismicity from around the world and high-resolution ML-based catalogs provide more resources and constraints for studying the earthquake nucleation mechanism. These methods also allow the exploration of physical earthquake precursors and call for advanced computing architectures and data management plans in their effective usage. These new methods and datasets open the door to multidisciplinary collaboration in a seamless way. In this session, we welcome contributions from a wide spectrum of advances in the field of earthquake forecasting and nowcasting, including but not limited to: new data-driven or physics-based ways for forecasting/nowcasting earthquakes; machine learning and AI-enhanced methods to boost accuracy, verification and reliability; earthquake forecasting/nowcasting from laboratory to field; breakthrough real case studies; cross-disciplinary studies of earthquake forecasting/nowcasting; and new sensing and processing technologies for capturing the precursor signals.

Conveners: Yangkang Chen, University of Texas at Austin (yangkang.chen@beg.utexas.edu); Katsumi Hattori, Chiba University (khattori@faculty.chiba-u.jp); Lisa G. Ludwig, University of California, Irvine (lgrant@uci.edu); Dimitar Ouzounov, Chapman University (ouzounov@chapman.edu); John Rundle, University of California, Davis (john.b.rundle@gmail.com)

Translating Seismic Imaging into Geodynamic Understanding

Seismic imaging provides valuable information about the subsurface of the Earth. Travel times and waveforms from natural and controlled sources can be used to construct 2D and 3D velocity, attenuation and anisotropy models of the Earth's interior from the core to the crust. These seismically determined quantities are subsequently interpreted into physical properties and integrated into geodynamic models to explore a wide range of dynamical processes to understand Earth's past, present and future evolution.

This session seeks to increase the exchange between seismic and geodynamic model communities to better understand data and model uses and limitations. Contributions that explore applications of seismic imaging results in computational models that increase our understanding of Earth dynamics, model uncertainty and data resolution, and software tools used to construct model data are welcome. This includes but is not limited to: dynamics of the deep Earth including core-mantle interaction, mantle convection and mantle plumes; dynamics of the lithosphere including subduction zones, rifting and glacial isostatic adjustment; and dynamics of the crust including fault, geothermal and volcanic systems.

Conveners: Ebru Bozdag, Colorado School of Mines (bozdag@mines.edu); Rebecca Fildes, University of California, Davis (rfildes@ucdavis.edu); Menno Fraters, University of Florida (menno.fraters@ufl.edu); Lorraine J. Hwang, University of California, Davis (ljhwang@ucdavis.

edu); Andrew Lloyd, Lamont-Doherty Earth Observatory, Columbia University (andrewl@ldeo.columbia.edu); Brandon VanderBeek, Università di Padova (brandonpaul.vanderbeek@unipd.it)

Understanding and Quantifying the Variability in Earthquake Source Parameter Measurements

Earthquake source parameters such as stress drop, magnitude and moment tensors are fundamental terms used to describe earthquakes. They are also key ingredients in earthquake ground motion modeling, rupture simulation, source physics analysis and statistical seismology. For this reason, the estimation of these parameters is often the first step in any analysis of earthquakes, but due to variability in site characterization, network capability and resources different procedures and methods are often used in their estimation. These issues and uncertainties depend on length scale, and therefore vary across magnitudes. For example, high frequency (>10 Hz) shallow site effects will strongly affect smaller earthquakes (M<3), while larger events are more strongly affected by issues at lower frequencies. This variability in method and inconsistencies across magnitude scales can yield artifacts which mask physical trends, leading to contrasting interpretations of earthquake scaling relationships and earthquake dynamic rupture processes. For example, catalog magnitude estimation varies regionally and by event size and network capability, producing artifacts that can influence important statistics like magnitude exceedance probabilities. Source parameters quantifying stress and energy release are fundamental to understanding fault strength and dynamic rupture propagation but can vary by orders of magnitude among studies. Estimating these parameters accurately, or at least uniformly, is needed to understand earthquake mechanics and ground motion hazard.

We seek all interested researchers to compare and validate source parameter estimates for any magnitude. We encourage studies that aim to quantify the uncertainties of these measurements, comparative studies of multiple methods and those that focus on reliable interpretation of results.

Conveners: Rachel E. Abercrombie, Boston University (rea@bu.edu); Shanna Chu, U.S. Geological Survey (schu@usgs.gov); Sydney Gable, University of Michigan (gablesyd@umich.edu); Gene Ichinose, Lawrence Livermore National Laboratory (ichinose1@llnl.gov); Colin N. Pennington, Lawrence Livermore National Laboratory (pennington6@llnl.gov)

Overview of Technical Program

Monday 29 April

7:00 AM–6:30 PM
Prince William Sound Field Seminar

Tuesday 30 April

8:00 AM–4:30 PM
Alaska Geophysics in the Field

10:00 AM–4:00 PM
Data Mining on the Cloud 101 Workshop
Tikahtnu Ballroom C, Third Level

10:00 AM–4:00 PM
Seismic Instrumentation Workshop
Tikahtnu Ballroom E/F, Third Level

12:30–4:30 PM
Publishing: How to Review and How to Be Reviewed Workshop
Kahtnu 1, Second Level

3:00–7:30 PM
Registration
Lobby

4:30–6:00 PM
Opening Reception and Exhibits
Exhibit Hall

6:00–7:00 PM
Plenary
Tikahtnu Ballroom A/B, Third Level

Wednesday 1 May

7:00 AM–5:00 PM
Registration
Lobby

8:00–9:15 AM
Technical Sessions

9:15–10:30 AM
Poster Break
Exhibit Hall

10:30–11:45 AM
Technical Sessions

11:45 AM–2:00 PM
Lunch Break

Noon–1:00 PM
Newcomer's Welcome Lunch*
Exhibit Hall

2:00–3:15 PM
Technical Sessions

3:15–4:30 PM
Poster Break
Exhibit Hall

4:30–5:45 PM
Technical Sessions

6:00–7:00 PM
Plenary
Tikahtnu Ballroom A/B, Third Level

7:00–8:00 PM
Student/Early-Career Reception*
Exhibit Hall

Thursday 2 May

7:00 AM–5:00 PM
Registration
Lobby

7:15–8:00 AM
GR Briefing
Exhibit Hall

8:00–9:15 AM
Technical Sessions

9:15–10:30 AM
Poster Break
Exhibit Hall

10:30–11:45 AM
Technical Sessions

Noon–2:00 PM
Annual Business and Awards Luncheon
Exhibit Hall

2:00–3:15 PM
Technical Sessions

3:15–4:30 PM
Poster Break
Exhibit Hall

4:30–5:45 PM
Technical Sessions

6:00–7:00 PM
Joyner Lecture
Tikahtnu Ballroom A/B, Third Level

7:00–8:00 PM
Joyner Reception
Tikahtnu Ballroom Foyer, Third Level

Friday 3 May

7:00 AM–5:00 PM
Registration
Lobby

8:00–9:15 AM
Technical Sessions

9:15–10:30 AM
Poster Break
Exhibit Hall

10:30–11:45 AM
Technical Sessions

11:45 AM–2:00 PM
Lunch Break

2:00–3:15 PM
Technical Sessions

3:15–4:30 PM
Poster Break
Exhibit Hall

4:30–5:45 PM
Technical Sessions

* Invite only

Wednesday, 1 May

Oral Sessions

Time	*K'enakatnu 6/ Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom A/B*	*Tikahtnu Ballroom C*
8:00–9:15 AM	From Faults to Fjords: Earthquake Evidence in Terrestrial and Subaqueous Environments	How Well Can We Predict Broadband Site-Specific Ground Motion and Its Spatial Variability So Far?	Induced Earthquakes: Source Characteristics, Mechanisms, Stress Field Modeling and Hazards	The 2023 USGS National Seismic Hazard Model and Beyond	Creating Actionable Earthquake Information Products
9:15–10:30 AM	Poster Break				
10:30–11:45 AM	From Faults to Fjords: Earthquake Evidence in Terrestrial and Subaqueous Environments	How Well Can We Predict Broadband Site-Specific Ground Motion and Its Spatial Variability So Far?	Induced Earthquakes: Source Characteristics, Mechanisms, Stress Field Modeling and Hazards	The 2023 USGS National Seismic Hazard Model and Beyond	Creating Actionable Earthquake Information Products
11:45 AM–2:00 PM	Lunch Break				
2:00–3:15 PM	From Faults to Fjords: Earthquake Evidence in Terrestrial and Subaqueous Environments	How Well Can We Predict Broadband Site-Specific Ground Motion and Its Spatial Variability So Far?	Induced Earthquakes: Source Characteristics, Mechanisms, Stress Field Modeling and Hazards	The 2023 USGS National Seismic Hazard Model and Beyond	Network Seismology: Recent Developments, Challenges and Lessons Learned
3:15–4:30 PM	Poster Break				
4:30–5:45 PM	From Faults to Fjords: Earthquake Evidence in Terrestrial and Subaqueous Environments	Planetary Seismology	The OSIRIS-REx Sample Return Capsule Re-entry: Geophysical Observations		Network Seismology: Recent Developments, Challenges and Lessons Learned
6:00–7:00 PM	Plenary: Challenges in Geohazards Research in Alaska				
7:00–8:00 PM	Student/Early-Career Reception				

Poster Sessions

- The 2023 USGS National Seismic Hazard Model and Beyond
- Creating Actionable Earthquake Information Products
- Cryptic Faults: Advances in Characterizing Low Strain Rate and Environmentally Obscured Faults
- From Faults to Fjords: Earthquake Evidence in Terrestrial and Subaqueous Environments
- How Well Can We Predict Broadband Site-Specific Ground Motion and Its Spatial Variability So Far?
- Induced Earthquakes: Source Characteristics, Mechanisms, Stress Field Modeling and Hazards
- Learning Across Geological, Geophysical & Model-Derived Observations to Constrain Earthquake Behavior
- Marine Seismoacoustics
- Network Seismology: Recent Developments, Challenges and Lessons Learned
- Numerical Modeling in Seismology: Developments and Applications
- The OSIRIS-REx Sample Return Capsule Re-entry: Geophysical Observations
- Special Applications in Seismology
- Structure, Seismicity and Dynamics of the Queen Charlotte-Fairweather Fault System
- Towards Advancing Earthquake Forecasting and Nowcasting: Recent Progress Using AI-Enhanced Methods
- Translating Seismic Imaging into Geodynamic Understanding

Time	*Tikahtnu Ballroom E/F*	*Tubughnenq' 3*	*Tubughnenq' 4*	*Tubughnenq' 5*
8:00–9:15 AM	Earth's Structure from the Crust to the Core	Cryptic Faults: Advances in Characterizing Low Strain Rate and Environmentally Obscured Faults	Numerical Modeling in Seismology: Developments and Applications	Learning Across Geological, Geophysical & Model-Derived Observations to Constrain Earthquake Behavior
9:15–10:30 AM	Poster Break			
10:30–11:45 AM	Earth's Structure from the Crust to the Core	Cryptic Faults: Advances in Characterizing Low Strain Rate and Environmentally Obscured Faults	Numerical Modeling in Seismology: Developments and Applications	Learning Across Geological, Geophysical & Model-Derived Observations to Constrain Earthquake Behavior
11:45 AM–2:00 PM	Lunch Break			
2:00–3:15 PM	Earth's Structure from the Crust to the Core	Towards Advancing Earthquake Forecasting and Nowcasting: Recent Progress Using AI-Enhanced Methods	Numerical Modeling in Seismology: Developments and Applications	Learning Across Geological, Geophysical & Model-Derived Observations to Constrain Earthquake Behavior
3:15–4:30 PM	Poster Break			
4:30–5:45 PM	Marine Seismoacoustics	Special Applications in Seismology	Translating Seismic Imaging into Geodynamic Understanding	Structure, Seismicity and Dynamics of the Queen Charlotte-Fairweather Fault System
6:00–7:00 PM	Plenary: Challenges in Geohazards Research in Alaska			
7:00–8:00 PM	Student/Early-Career Reception			

Thursday, 2 May

Oral Sessions

Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom A/B*
8:00–9:15 AM	3D Wavefield Simulations: From Seismic Imaging to Ground Motion Modelling	Illuminating Complex, Multiplet Earthquake Sequences at Kahramanmaras (Turkiye), Herat (Afghanistan), and Beyond	Detecting, Characterizing and Monitoring Mass Movements	Seismic Monitoring, Modelling and Management Needed for Geothermal Energy and Geologic Carbon Storage
9:15–10:30 AM	Poster Break			
10:30–11:45 AM	3D Wavefield Simulations: From Seismic Imaging to Ground Motion Modelling	Illuminating Complex, Multiplet Earthquake Sequences at Kahramanmaras (Turkiye), Herat (Afghanistan), and Beyond	Detecting, Characterizing and Monitoring Mass Movements	Seismic Monitoring, Modelling and Management Needed for Geothermal Energy and Geologic Carbon Storage
Noon–2:00 PM	Annual Business and Awards Luncheon			
2:00–3:15 PM	3D Wavefield Simulations: From Seismic Imaging to Ground Motion Modelling	Six Decades of Tsunami Science: From the Source of the 1964 Tsunami to Modern Community Preparedness	Detecting, Characterizing and Monitoring Mass Movements	Seismic Monitoring, Modelling and Management Needed for Geothermal Energy and Geologic Carbon Storage
3:15–4:30 PM	Poster Break			
4:30–5:45 PM	Applications and Discoveries in Cryoseismology Across Spatial and Temporal Scales	Special Applications in Seismology	New Insights into the Development, Testing and Communication of Seismicity Forecasts	
6:00–7:00 PM	Joyner Lecture: Why Seismic Hazard Modeling Has Become a Risky Business			
7:00–8:00 PM	Joyner Reception			

Poster Sessions

- 3D Wavefield Simulations: From Seismic Imaging to Ground Motion Modelling
- Advancements in Forensic Seismology and Explosion Monitoring
- Applications and Discoveries in Cryoseismology Across Spatial and Temporal Scales
- Characteristics and Mechanics of Fault Zone Rupture Processes, from Micro to Macro Scales
- Cordilleran Strike-Slip Faults as Seismogenic and Seismological Features
- Detecting, Characterizing and Monitoring Mass Movements
- Earth's Structure from the Crust to the Core
- From Earthquake Recordings to Empirical Ground-Motion Modelling
- Illuminating Complex, Multiplet Earthquake Sequences at Kahramanmaras (Turkiye), Herat (Afghanistan), and Beyond
- Leveraging Cutting-Edge Cyberinfrastructure for Large Scale Data Analysis and Education
- Multidisciplinary Approaches for Volcanic Eruption Forecasting
- New Insights into the Development, Testing and Communication of Seismicity Forecasts
- Seismic Monitoring, Modelling and Management Needed for Geothermal Energy and Geologic Carbon Storage
- Seismology in the Oceans: Pacific Hemisphere and Beyond
- Six Decades of Tsunami Science: From the Source of the 1964 Tsunami to Modern Community Preparedness

Time	*Tikahtnu Ballroom C*	*Tikahtnu Ballroom E/F*	*Tubughnenq' 3*	*Tubughnenq' 4*	*Tubughnenq' 5*
8:00–9:15 AM	Characteristics and Mechanics of Fault Zone Rupture Processes, from Micro to Macro Scales	Advancements in Forensic Seismology and Explosion Monitoring	Seismology in the Oceans: Pacific Hemisphere and Beyond	From Earthquake Recordings to Empirical Ground-Motion Modelling	Network Seismology: Recent Developments, Challenges and Lessons Learned
9:15–10:30 AM	Poster Break				
10:30–11:45 AM	Characteristics and Mechanics of Fault Zone Rupture Processes, from Micro to Macro Scales	Advancements in Forensic Seismology and Explosion Monitoring	Seismology in the Oceans: Pacific Hemisphere and Beyond	From Earthquake Recordings to Empirical Ground-Motion Modelling	Network Seismology: Recent Developments, Challenges and Lessons Learned
Noon–2:00 PM	Annual Business and Awards Luncheon				
2:00–3:15 PM	Regional-Scale Hazard, Risk and Loss Assessments	Advancements in Forensic Seismology and Explosion Monitoring	Multidisciplinary Approaches for Volcanic Eruption Forecasting	From Earthquake Recordings to Empirical Ground-Motion Modelling	Network Seismology: Recent Developments, Challenges and Lessons Learned
3:15–4:30 PM	Poster Break				
4:30–5:45 PM	Regional-Scale Hazard, Risk and Loss Assessments	Advancements in Forensic Seismology and Explosion Monitoring	Multidisciplinary Approaches for Volcanic Eruption Forecasting	Leveraging Cutting-Edge Cyberinfrastructure for Large Scale Data Analysis and Education	Cordilleran Strike-Slip Faults as Seismogenic and Seismological Features
6:00–7:00 PM	Joyner Lecture: Why Seismic Hazard Modeling Has Become a Risky Business				
7:00–8:00 PM	Joyner Reception				

Friday, 3 May

Oral Sessions

Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom A/B*
8:00–9:15 AM	Advancing Seismology with Distributed Fiber Optic Sensing	Physics-Based Ground Motion Modeling	Seismoacoustic, Geodetic and Other Geophysical Investigations of Active Volcanoes	Structure and Behavior of the Alaska-Aleutian Subduction Zone
9:15–10:30 AM	Poster Break			
10:30–11:45 AM	Advancing Seismology with Distributed Fiber Optic Sensing	Physics-Based Ground Motion Modeling	Seismoacoustic, Geodetic and Other Geophysical Investigations of Active Volcanoes	Structure and Behavior of the Alaska-Aleutian Subduction Zone
11:45 AM–2:00 PM	Lunch Break			
2:00–3:15 PM	Advancing Seismology with Distributed Fiber Optic Sensing	Assessing Seismic Hazard for Critical Facilities and Infrastructure—Insights and Challenges	Seismoacoustic, Geodetic and Other Geophysical Investigations of Active Volcanoes	Structure and Behavior of the Alaska-Aleutian Subduction Zone
3:15–4:30 PM	Poster Break			
4:30–5:45 PM	From Geodynamics to Earthquake Rupture, Models That Cross Time- and Length-Scales	Assessing Seismic Hazard for Critical Facilities and Infrastructure—Insights and Challenges	Machine Learning for Full Waveform Inversion: From Hybrid to End-to-End Approaches	Structure and Behavior of the Alaska-Aleutian Subduction Zone

Poster Sessions

- The 2024 Magnitude 7.5 Earthquake and the Associated Earthquake Swarm Beneath the Noto Peninsula, Central Japan
- Advances in Operational and Research Analysis of Earthquake Swarms
- Advancing Seismology with Distributed Fiber Optic Sensing
- Anisotropy Across Scales
- Assessing Seismic Hazard for Critical Facilities and Infrastructure—Insights and Challenges
- End-to-End Advancements in Earthquake Early Warning Systems
- ESC-SSA Joint Session: Climate Change and Environmental Seismology
- From Geodynamics to Earthquake Rupture, Models That Cross Time- and Length-Scales
- Integrative Assessment of Soil-Structure Interaction and Local Site Effects in Seismic Hazard Analysis

Time	*Tikahtnu Ballroom C*	*Tikahtnu Ballroom E/F*	*Tubughnenq' 3*	*Tubughnenq' 4*	*Tubughnenq' 5*
8:00–9:15 AM	The 2024 Magnitude 7.5 Earthquake and the Associated Earthquake Swarm Beneath the Noto Peninsula, Central Japan (See Supplemental Material)	End-to-End Advancements in Earthquake Early Warning Systems	Understanding and Quantifying the Variability in Earthquake Source Parameter Measurements	Anisotropy Across Scales	Tectonics and Seismicity of Stable Continental Interiors
9:15–10:30 AM	Poster Break				
10:30–11:45 AM	The 2024 Magnitude 7.5 Earthquake and the Associated Earthquake Swarm Beneath the Noto Peninsula, Central Japan (See Supplemental Material)	End-to-End Advancements in Earthquake Early Warning Systems	Understanding and Quantifying the Variability in Earthquake Source Parameter Measurements	Anisotropy Across Scales	Tectonics and Seismicity of Stable Continental Interiors
11:45 AM–2:00 PM	Lunch Break				
2:00–3:15 PM	ESC-SSA Joint Session: Climate Change and Environmental Seismology	End-to-End Advancements in Earthquake Early Warning Systems	Understanding and Quantifying the Variability in Earthquake Source Parameter Measurements	Advances in Operational and Research Analysis of Earthquake Swarms	Tectonics and Seismicity of Stable Continental Interiors
3:15–4:30 PM	Poster Break				
4:30–5:45 PM	ESC-SSA Joint Session: Climate Change and Environmental Seismology	End-to-End Advancements in Earthquake Early Warning Systems		Advances in Operational and Research Analysis of Earthquake Swarms	Tectonics and Seismicity of Stable Continental Interiors

- Machine Learning for Full Waveform Inversion: From Hybrid to End-to-End Approaches
- Physics-Based Ground Motion Modeling
- Regional-Scale Hazard, Risk and Loss Assessments
- Research Advances in “High-Impact”, “Under-Studied” Earthquakes and Their Impacts on Communities
- Seismic Cycle-Driven Sea-Level Change Over Decades to Centuries: Observations and Projections
- Seismoacoustic, Geodetic and Other Geophysical Investigations of Active Volcanoes
- Structure and Behavior of the Alaska-Aleutian Subduction Zone
- Tectonics and Seismicity of Stable Continental Interiors
- Understanding and Quantifying the Variability in Earthquake Source Parameter Measurements

Wednesday, 1 May 2024—Oral Sessions

Presenting author is indicated in bold.

Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom A/B*
	From Faults to Fjords: Earthquake Evidence in Terrestrial and Subaqueous Environments (see page 1296).	**How Well Can We Predict Broadband Site-Specific Ground Motion and Its Spatial Variability So Far? (see page 1311).**	**Induced Earthquakes: Source Characteristics, Mechanisms, Stress Field Modeling and Hazards (see page 1322).**	**The 2023 USGS National Seismic Hazard Model and Beyond (see page 1194).**
8:00 AM	Effect of Marine Reservoir Variations on the Temporal Correlation of Earthquake Evidence on the Central and Southern Hikurangi Subduction Zone. **Clark, K. J.**, Pizer, C., Howarth, J., Litchfield, N., Howell, A.	STUDENT: Site Response Characteristics from Ambient Noise Data Recorded on Degrading Warm Permafrost in Bethel, Alaska. **Goozen, A.**, Zhao, Y., Dutta, U., Yang, Z.	INVITED: Structural Controls on Induced Earthquake Sequence's Growth and Slip Behavior. **Pennington, C. N.**, Chen, X.	Recommendations on Best Available Science for the United States National Seismic Hazard Model. **Anderson, J. G.**, Atkinson, G. M., Baker, J. W., Campbell, K. W., DeShon, H. R., *et al.*
8:15 AM	INVITED: An 8000-Year Holocene Earthquake Record From the Northern Cascadia Forearc: Evidence for Multiple Sources at Lake Crescent, Washington. **Leithold, E. L.**, Wegmann, K., Colip, G. D.	Improving the Performance of the SSRh Site-Response Assessment Techniques on a Dense Array in the Koutavos Basin (Greece). **Perron, V.**, Rischette, P., Theodoulidis, N., Roumelioti, Z., Hollender, F., *et al.*	Seismic Hazard Analysis for Hydraulic-Fracture Triggered Earthquakes in Oklahoma. **Walter, J.**, Ogwari, P. O., Thiel, A., Woelfel, I., Mace, B., *et al.*	The 2023 U.S. 50-State National Seismic Hazard Model: Overview and Implications. **Petersen, M. D.**, Project Team, N.
8:30 AM	Variations in Mass Transport Deposits That Record Strong Ground Motion Events in Western Prince William Sound, Alaska. **Singleton, D. M.**, Brothers, D. S., Haeussler, P. J., Witter, R. C., Hill, J. C., *et al.*	A Simple Way of Estimating Site Effect With Respect to a Distant Rock-Reference Site: Application of the Standard Spectra Ratio Technique Based on Coda Waves. **Grendas, I.**, Hollender, F., Perron, V., Theodoulidis, N., Buscetti, M., *et al.*	Undocumented Cases of Induced Seismicity in Oklahoma and Texas. **Grigoratos, I.**, Savvaidis, A.	The 2023 Alaska National Seismic Hazard Model. **Powers, P. M.**, Altekruse, J. M., Development Team, N.

Time	*Tikahtnu Ballroom C*	*Tikahtnu Ballroom E/F*	*Tubughnenq' 3*	*Tubughnenq' 4*	*Tubughnenq' 5*
	Creating Actionable Earthquake Information Products (see page 1251).	**Earth's Structure from the Crust to the Core (see page 1268).**	**Cryptic Faults: Advances in Characterizing Low Strain Rate and Environmentally Obscured Faults (see page 1256).**	**Numerical Modeling in Seismology: Developments and Applications (see page 1369).**	**Learning Across Geological, Geophysical & Model-Derived Observations to Constrain Earthquake Behavior (see page 1331).**
8:00 AM	INVITED: STUDENT: Improving Rapid Earthquake Characterization for Tsunami Early Warning for Aotearoa New Zealand and the Southwest Pacific. **Lacoua, L. Z.**, Fry, B., Gorman, A., Liao, Y. M., Foundotos, L., *et al.*	STUDENT: A High-Resolution Body Wave Tomography Super-Virtual Interferometry of the Rio Grande Rift. **Barman, D.**, Pulliam, J.	INVITED: STUDENT: An Ongoing Search for Active Faults in Major Seismic Zones of Québec, Eastern Canada. **Gourdeau, A.**, Wang, K., Laly, M., Prush, V. B., Rowe, C., *et al.*	STUDENT: Reflection and Transmission of Inhomogeneous Plane Waves in Thermoporoelastic Media with Two-temperature Equations of Heat Conduction. **Hou, W.**, Fu, L., Carcione, J.	Strain Accommodation Along the Northeast Altyn Tagh Fault System and the Potential for a Future Large-Magnitude, Multi-Fault Rupture. **Yang, H.**, Yang, X., Cunningham, D., Huang, X.
8:15 AM	Site-Specific, Extended Shakemaps for Earthquake Engineering Applications. **Thompson, E. M.**, Hearne, M., Worden, C. B., Quitoriano, V., Cunningham, A. E., *et al.*	INVITED: The Poisson's Raio Surrounding the Subduction Megathrust. **Mann, M.**, Abers, G. A., Fulton, P. M.	Timescales of Surface Faulting Preservation in Stable Continental Regions From Landscape Evolution Modeling and the Geomorphic and Historical Record. **Thompson Jobe, J. A.**, Reitman, N.	STUDENT: Dynamic Rupture Simulation of Caldera Collapse Earthquakes: Effects of Wave Radiation, Magma Viscosity, and Evidence of Complex Nucleation at Kīlauea 2018. **Wang, T. A.**, Dunham, E. M., Krenz, L., Abrahams, L. S., Segall, P.	Partitioning of Oblique Convergence During Simultaneous Rupture of a Megathrust and Splay Fault: Observations From the Western Nepal Fault System. **Bemis, S.**, Curtiss, E. R., Murphy, M. A., Taylor, M. H., Styron, R., *et al.*
8:30 AM	INVITED: Geonet's Shaking Layer Tool: Understanding and Incorporating User Needs into Shaking Layers for Aotearoa, New Zealand. **Charlton, D.**, Houltham, J., Horspool, N., Goded, T., Kaiser, A., *et al.*	Improving the Salt Lake Basin Velocity Model Using Multi-Year Nodal Geophone Arrays. **Kim, H.**, Lin, F., Pechmann, J. C., McKean, A. P., Hardwick, C. L., *et al.*	The 2018 Kaktovik, Alaska Earthquakes and Their Context: Insights From Seismotectonics, Insar Geodesy, and Static Stress Changes. **Rollins, C.**, Freymueller, J. T., Xue, X., Holtkamp, S. G., Logan, T. A., *et al.*	What Is the Principal Accuracy Limit of a Seismic Wavefields Simulated by a Finite-Difference Method?. Valovcan, J., **Moczo, P.**, Kristek, J., Kristekova, M., Galis, M.	STUDENT: Architecture of an Active Tsunamigenic Splay Fault: Outcrop to Micro-Scale Structure of the Patton Bay Fault, Montague Island, Alaska. **Fintel, A.**, Tobin, H., Haeussler, P.

Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom A/B*
	From Faults to Fjords: Earthquake Evidence (continued)	**How Well Can We Predict Broadband Site-Specific Ground (continued)**	**Induced Earthquakes: Source Characteristics, Mechanisms (continued)**	**The 2023 USGS National Seismic Hazard Model and Beyond (continued)**
8:45 AM	STUDENT: Long Lacustrine Sedimentary Records in South-Central Chile Evaluate the Spatiotemporal Variability of Megathrust Earthquakes. **Niederstätter, M.**, Moreno, V., Wils, K., Van Daele, M., Konzett, J., *et al.*	CD-VAE-GMG: Conditional Dynamic Variational Autoencoder for Earthquake Ground Motion Generation. **Ren, P.**, Naiman, I., Lacour, M., Nakata, R., Nakata, N., *et al.*	Regional Moment Tensors for Texas. **Herrmann, R. B.**, Benz, H. M.	Another Look at Time-Dependent Hazard and its Implications to Seismic Design in Southeastern Alaska. **Wong, I.**, Lewandowski, N., Thomas, P.
9:00 AM	Quantitative Calibration of the Lacustrine Seismograph Using Sedimentary Imprints of Recent Megathrust Earthquakes in South-Central Chile. **Wils, K.**, Montalva, G., Moernaut, J., Van Daele, M., De Batist, M.	Euro-Mediterranean Hard-Rock Reference Ground Motion Model by Git-Based Site Response Deconvolution. Shible, H., **Hollender, F.**, Traversa, P., Baumont, D., Ameri, G., *et al.*	Cross-Examining Methods for Determining Source Mechanisms for Induced Earthquakes in the Permian Basin. **Aziz Zanjani, F.**, Savvaidis, A., Huang, G. D., Domino, J., Chen, Y.	USGS 2025 Puerto Rico and the U.S. Virgin Islands National Seismic Hazard Model Update. **Shumway, A. M.**, Aagaard, B. T., Altekruse, J. M., Briggs, R. W., Field, E. H., *et al.*
9:15–10:30 AM	Poster Break			
	From Faults to Fjords: Earthquake Evidence in Terrestrial and Subaqueous Environments (see page 1296).	**How Well Can We Predict Broadband Site-Specific Ground Motion and Its Spatial Variability So Far? (see page 1311).**	**Induced Earthquakes: Source Characteristics, Mechanisms, Stress Field Modeling and Hazards (see page 1322).**	**The 2023 USGS National Seismic Hazard Model and Beyond (see page 1194).**
10:30 AM	Seismic Imaging Beneath Iceberg Lake, Alaska: Sediment Characteristics and Fundamental Site Response Parameters Beneath a Drained Lake With an Alaskan-Aleutian Subduction Zone Paleoseismic Record. **Liberty, L. M.**, Haeussler, P. J., Otheim, L. T., Singleton, D. M., Wesson, R. L., *et al.*	Observed Strong Motions and Site Effects During the Jan. 1, 2024 Noto-Hanto Earthquake in Japan and Its Reproduction Based on a Priori Information. **Kawase, H.**, Ito, E., Sun, J.	Spatiotemporal Evolution of Induced Earthquakes in the Southern Delaware Basin, Reeves-Pecos, West Texas. **Aziz Zanjani, A.**, DeShon, H. R., Savvaidis, A.	Next Steps for USGS Earthquake Rupture Forecast Developments. **Field, E. H.**

Time	*Tikahtnu Ballroom C*	*Tikahtnu Ballroom E/F*	*Tubughnenq' 3*	*Tubughnenq' 4*	*Tubughnenq' 5*
	Creating Actionable Earthquake (continued)	**Earth's Structure from the Crust to the Core (continued)**	**Cryptic Faults: (continued)**	**Numerical Modeling in (continued)**	**Learning Across Geological, (continued)**
8:45 AM	Improved Rapid Source and Shaking Characterization Using Large Seismic Array Observations. **Wang, D.**, Chen, W., Wald, D.	Seismic Structure of Northern Alaska From Ambient Noise Adjoint Tomography. **Chow, B.**, Tape, C.	Deciphering Low-Rate Faulting on the Landscape Above the Marsh Creek Anticline in Arctic Alaska. **Bender, A. M.**, Craddock, W., Connors, C. D., Gooley, J., Lease, R. O.	Modeling the Seismic Noise Horizontal-to-Vertical Spectral Ratio in Laterally Irregular Configurations Using the Diffuse Field Assumption. **Sanchez-Sesma, F. J.**, Weaver, R. L., Baena-Rivera, M. E., Pardo-Dañino, J. C., Arciniega-Ceballos, A.	INVITED: Paleoseismic Investigations of Quaternary Active Faults in the Forearc and Backarc of the Central Pacific Northwest, U.S.A. **Streig, A. R.**, Dunning, A., Bennett, S. E., Madin, I., Wells, R. E., *et al.*
9:00 AM	A Growing Catalogue of Short-Period Earthquake Rupture Histories From Multi-Array Back-Projection. Vera Sanhueza, F., **Tilmann, F.**, Saul, J.	Using Local and Regional Travel Time Data From the ISC to Estimate Lithospheric Velocity Structure. **Pasyanos, M. E.**	STUDENT: Utilising UAV Lidar to Investigate Potential Late Quaternary Surface Ruptures Along the San Juan Fault on Vancouver Island, BC. **Salomon, G. W.**, Finley, T., Nissen, E.	The Ongoing Development of Distributional Finite-difference Modeling in Global Seismology. **Lyu, C.**, Masson, Y., Awan, M., Romanowicz, B.	Coseismic Temperature Proxies and their Applications to Understanding Earthquake Rupture and Seismic Hazard. **Coffey, G. L.**, Savage, H. M., Polissar, P. J., Cox, S. E., Hemming, S. R., *et al.*
9:15–10:30 AM	Poster Break				
	Creating Actionable Earthquake Information Products (see page 1251).	**Earth's Structure from the Crust to the Core (see page 1268).**	**Cryptic Faults: Advances in Characterizing Low Strain Rate and Environmentally Obscured Faults (see page 1256).**	**Numerical Modeling in Seismology: Developments and Applications (see page 1369).**	**Learning Across Geological, Geophysical & Model-Derived Observations to Constrain Earthquake Behavior (see page 1331).**
10:30 AM	Visual Communication of Aftershock Forecasts Driven by User Needs. **Schneider, M.**, Wein, A. M., van der Elst, N., McBride, S. K., Becker, J., *et al.*	Intraplate Volcanism in Northeast China Controlled by the Underlying Heterogeneous Lithospheric Structures. **Chen, Q.**, Fan, X., Ai, Y.	INVITED: Late Pleistocene and Protohistoric Earthquakes on Forelimb Thrusts Within the Seattle Fault Zone: Implications for Independent Hanging Wall Deformation Rates. **Angster, S.**, Sherrod, B. L., Staisch, L., Pearl, J. K., Johns, W.	Numerical Simulation of Strong Ground Motion for the Mw 6.0 Jishishan Earthquake of 18 December 2023 in Gansu Province, China. **Zang, N.**, Zhang, W., Chen, X.	Inter-Seismic Slip in Caldera Collapse Earthquake Cycles. **Crozier, J. A.**, Anderson, K. R., Segall, P.

Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom A/B*
	From Faults to Fjords: Earthquake Evidence (continued)	**How Well Can We Predict Broadband Site-Specific Ground Motion (continued)**	**Induced Earthquakes: Source Characteristics, Mechanisms, (continued)**	**The 2023 USGS National Seismic Hazard Model and Beyond (continued)**
10:45 AM	The Subaerially Exposed Iceberg Lake Sediments: A ~1000 Yr Long Paleoseismic Record From the Eastern Edge of the Alaska Subduction Zone. **Van Daele, M.**, Vercruysse, P., Witter, R. C., Loso, M., Singleton, D., *et al.*	Exploring the Spatial Correlation of Ground Motions During the 2019 Ridgecrest Earthquake Sequence. **Cochran, E. S.**, Parker, G. A., Minson, S. E., Baltay, A. S.	Seismicity Triggering in the North Delaware Basin, West Texas, USA. **Savvaidis, A.**, Lomax, A., Huang, G., Chen, Y., Alvarez, N., *et al.*	Earthquake Geology Contributions Across the U.S. Geological Survey 2023 50-State National Seismic Hazard Model. **Hatem, A. E.**, Briggs, R., Thompson Jobe, J. A., Gold, R., Collett, C., *et al.*
11:00 AM	The Great Salt Lake as a Recorder of Sublacustrine Surface Rupture and Strong Shaking in the Wasatch Front Region, Utah. **DuRoss, C. B.**, Brothers, D. S., Thompson Jobe, J. A., Briggs, R. W., Singleton, D. M., *et al.*	STUDENT: Use of Weak Motion Data to Constrain Site-Specific Ground Motion Estimates. **Anbazhagan, B.**, Rodriguez-Marek, A., Vantassel, J., Kottke, A.	INVITED: Potential Poroelastic Triggering of the 2020 M 5.0 Mentone Earthquake in the Delaware Basin, Texas, by Shallow Injection Wells. **Lui, S.**, Tan, X.	Continued Work on a Geodetic Strain Rate and Slip Deficit Rate Model for New Zealand. **Rollins, C.**, Wallace, L. M., Johnson, K. M., Maurer, J., Hamling, I., *et al.*
11:15 AM	Sediment Shear Strength Development Within Terminal Basins of the Japan Trench and Lower Slope: Insights Into Seismic Strengthening and Earthquake Paleoseismology From R/V Sonne Expedition SO251 (Eager-Japan) and IODP Expedition 386. **Sawyer, D. E.**, Strasser, M.	Ergodic and Non-Ergodic Ground-Motion Models for Small Magnitude Earthquakes in the San Francisco Region. **Lacour, M.**, Abrahamson, N. A., Nakata, R., Nakata, N., Ren, P.	Using Converted Phases to Investigate Induced Seismicity in the Midland Basin, Texas. **DeShon, H. R.**, Rosenblit, J., Huang, G., Savvaidis, A.	Correlation of Epistemic Uncertainties in Seismic Hazard Models: An NSHM23 Case Study for Western U.S. Faults. **Milner, K. R.**
11:30 AM	STUDENT: Beyond the Waves: Integrating Rock Physical Properties for Deeper Seismic Understanding. **Castillo, R.**, Sawyer, D. E., Srasser, M., Keep, M.	Comparison of the Spatial Correlation of Non-Ergodic Terms in GMMs Utilizing Empirical and Simulation Data From Diverse Regions. **Sung, C.**, Abrahamson, N. A.	STUDENT: Fault Reactivation During Induced Seismicity Sequences in Southern Kansas. **Ries, R.**, Beroza, G., Ellsworth, W.	Enhancing Decision-Making Stability in Model Updates Through Explicit Consideration of Epistemic Uncertainty in Seismic Hazard and Risk Assessments. **Lee, Y.**
11:45 AM–2:00 PM	Lunch Break			

Time	Tikahtnu Ballroom C	Tikahtnu Ballroom E/F	Tubughnenq' 3	Tubughnenq' 4	Tubughnenq' 5
	Creating Actionable Earthquake (continued)	**Earth's Structure from the Crust to the Core (continued)**	**Cryptic Faults: Advances (continued)**	**Numerical Modeling in Seismology (continued)**	**Learning Across Geological, (continued)**
10:45 AM	Tomorrow's Cities: An Interdisciplinary Decision Support Environment for Risk Sensitive Urban Planning and Design. **Galasso, C.** and the Tomorrow's Cities Programme Working Group	Seismic Evidence for a Melt-Rich Lithosphere-Asthenosphere Boundary Along the Base of Young Slab at Cascadia. **Wang, X.**, Chen, L., Wang, K., Chen, Q., Zhan, Z., *et al.*	Recurrence of Large Upper-Plate Earthquakes in the Salish Lowland, Washington State, USA. **Sherrod, B. L.**, Styron, R.	A Detailed Analysis of Body Waves Simulated in Homogenized Media. **Cupillard, P.**, Mulder, W., Anquez, P., Mazuyer, A., Zakari, M., *et al.*	INVITED: The Influence of Preexisting Geologic Structures on Coseismic Surface Deformation During the 2019 M7.1 Ridgecrest, California, Earthquake. **Nevitt, J. M.**, Brooks, B., Baden, C., Hardebeck, J., Aagaard, B. T., *et al.*
11:00 AM	Exploring the Ethical Tensions and Communication Challenges of Publicly Available Global Aftershock Forecasting From Science Agencies. **McBride, S. K.**, Michael, A. J., Schneider, M., Hardebeck, J., Wein, A. M., *et al.*	STUDENT: Mantle Upwelling, Continental Sutures, and LAB Structure Identified From a Suite of Seismic Data Types in the Eastern United States. **Brunsvik, B. R.**, Eilon, Z., Lynner, C.	Towards Improved Understanding of Regional Tectonics and Faulting at the Mendocino Triple Junction from Geomorphic Investigation. **DeLong, S. B.**, Vermeer, J., Patton, J. R., Sion, B., Hammer, M., *et al.*	Efficient Lossy Compression of Simulated 4d Seismic Wavefields. **Zhang, W.**, Wang, W., Tang, Y., Lei, T.	STUDENT: Bayesian Dynamic Source Inversion of the 2004 Parkfield Earthquake: Insights From Linked 3D Dynamic Rupture and Afterslip Modeling Constrained by Gps and Strong Motions. **Schliwa, N.**, Gabriel, A. A., Premus, J., Gallovič, F.
11:15 AM	STUDENT: Development of Rapid Earthquake Damage Estimation System to Expedite Rescue Efforts in the Post-Disaster Phase. **Patchett, M.**, Hobbs, T. E.	STUDENT: Crustal Structure of Eritrea from Receiver Function Analysis. **Gauntlett, M. Z.**, Stephenson, S. N., Kendall, J., Ogden, C., Hammond, J. O. S., *et al.*	Geophysical Validation of Tidally Calibrated Strains From the Novel Alto Tiberina Near Fault Observatory Strainmeter Array (TABOO-NFO-STAR). **Hanagan, C. E.**, Mandler, E., Bennett, R. A., Chiaraluce, L., Gottlieb, M., *et al.*	STUDENT: Effects of Dip Angle on Rupture Propagation Along Branch Fault Systems. **Marschall, E.**, Douilly, R.	Multi-Cycle Evolution of Seismicity and Fault Zone for a Fault Network. Mia, M., Abdelmeguid, M., **Elbanna, A. E.**
11:30 AM	Improving the Usability of Near-Real-Time Earthquake Information for Equity-Focused Decision-Making Through Earthquake Scenario Exercises. **Macías, M. A.**, Loos, S., Reddy, E., Wald, D. J., Knodel, E. J., *et al.*	Surface-Wave Diffraction Stripes: Measurement, Observables, Explanation, Modeling and Inversion. **Kolínský, P.**, Belinić Topić, T., Vecsey, L., Working Group, t.	The Parguera Fault: Quaternary Reactivation of a Fault in Southwest Puerto Rico. **Thompson Jobe, J. A.**, Briggs, R., Ortega Diaz, V., Hughes, K., López-Venegas, A., *et al.*	Insight From 3D Deterministic Ground Motion Simulations in Central Italy. **Akinci, A.**, Pitarka, A., De Gori, P., Artale Harris, P., Buttinelli, M.	Bayesian Inference of Rheological Parameters From Observations Before and After the Tohoku Earthquake. Marsman, C., Vossepoel, F., D'Acquisto, M., van Dinther, Y., **Govers, R.**
11:45 AM–2:00 PM	Lunch Break				

Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom A/B*
	From Faults to Fjords: Earthquake Evidence in Terrestrial and Subaqueous Environments (see page 1296).	**How Well Can We Predict Broadband Site-Specific Ground Motion and Its Spatial Variability So Far? (see page 1311).**	**Induced Earthquakes: Source Characteristics, Mechanisms, Stress Field Modeling and Hazards (see page 1322).**	**The 2023 USGS National Seismic Hazard Model and Beyond (see page 1194).**
2:00 PM	Repeated Coseismic Uplift of Coastal Lagoons Above the Patton Bay Splay Fault System, Montague Island, Alaska, USA. **DePaolis, J.**, Dura, T., Witter, R. C., Haeussler, P. J., Bender, A., *et al.*	Toward an Alternative Approach for Using VS Profiles in Estimating Seismic Site Response. **Pretell, R.**, Katuwal, S.	Detailed Analysis of Microseismic Activity Associated with Shutdowns of the San Emidio Geothermal Plant, Nevada. **Thurber, C. H.**, Guo, H., Cunningham, E., Roecker, S. W., Hampton, J., *et al.*	Subduction Ground Motion Models for Cascadia in the 2023 USGS National Seismic Hazard Model. **Rezaeian, S.**, Powers, P. M., Altekruse, J., Ahdi, S. K., Petersen, M. D., *et al.*
2:15 PM	Re-Examination of the 1958 Huslia Earthquake Sequence and Regional Tectonics of the Northwestern Koyukuk Basin, Alaska in Light of Post-1974 Seismicity, Mapped Faults and Geophysical Data. **Doser, D. I.**, Baker, M. R., Haeussler, P. J.	Resonance vs Shape of Sedimentary Basins. **Castellaro, S.**, Musinu, G.	Source Characteristics of Microseismicity Occurring During Operational Shut-in Periods at the Coso Geothermal Field, California. **Holmgren, J. M.**, Kaven, J., Oye, V.	Ground-Motion Characterization of Puerto Rico and the U.S. Virgin Islands for the 2025 Update of the USGS National Seismic Hazard Model. **Aagaard, B. T.**, Smith, J. A., Moschetti, M. P., Stephenson, W. J., Ahdi, S. K.
2:30 PM	Confirmation of Late Quaternary Surface Faulting and Preliminary Slip Rates for the Iditarod-Nixon Fork Fault and the Boss Creek and Holitna Sections of the Denali Fault in West-Central Alaska. **Zellman, M.**, Duckworth, W., Koehler, R. D., Zaleski, M. P., Ostenaa, D. A., *et al.*	Impact of Shallow Subsurface Stratigraphic Architecture on Shear-Wave Velocity Prediction: Examples From the Po Plain and Other Coastal Lowlands of Italy. **Amorosi, A.**, Di Martino, A.	STUDENT: Double-Pair Double-Difference Relocation for Dense Network Improves Depth Precision of Induced Seismicity, Leading to a Detailed 3D Fault Geometry Model. **Biegel, K.**, Dettmer, J., Igonin, N., Eaton, D.	STUDENT: Development of Ground Motion Models in Central and Eastern United States for Use in the Coastal Plain Using Sediment Thickness. **Akhani, M.**, Davatgari Tafreshi, M., Pezeshk, S.

Time	*Tikahtnu Ballroom C*	*Tikahtnu Ballroom E/F*	*Tubughnenq' 3*	*Tubughnenq' 4*	*Tubughnenq' 5*
	Network Seismology: Recent Developments, Challenges and Lessons Learned (see page 1353).	**Earth's Structure from the Crust to the Core (see page 1268).**	**Towards Advancing Earthquake Forecasting and Nowcasting: Recent Progress Using AI-Enhanced Methods (see page 1443).**	**Numerical Modeling in Seismology: Developments and Applications (see page 1369).**	**Learning Across Geological, Geophysical & Model-Derived Observations to Constrain Earthquake Behavior (see page 1331).**
2:00 PM	ISC: Collaborating With Seismic Networks Worldwide. **Storchak, D.**, Harris, J., Di Giacomo, D., Garth, T., Gallacher, R., *et al.*	STUDENT: The Continental Collision and Rifting in East North America Margin Revealed by Full Waveform Tomography. **Lei, T.**, Wang, K., He, B., Du, N., Liu, T., *et al.*	Towards Deep-Learned Picking at the USGS National Earthquake Information Center. **Wells, D.**, Yeck, W., Cole, H., Patton, J., Shelly, D., *et al.*	STUDENT: The 2022 Mw 6.6 Menyuan Earthquake, Qinghai, China: An Early-terminated Runaway Rupture Revealed by the Dynamic Rupture Simulations. **Xu, D.**, Li, Z., Zhang, Z., Yu, H., Chen, X.	Surveying Active Fault Zones in California Using Quakes-I Wide-Swath Airborne Stereoimagery. **Zinke, R.**, Donnellan, A., Applegate, R., Padgett, C.
2:15 PM	The International Monitoring System Sustainment: A Technical Strategy. **Pérez-Campos, X.**, Sid Ahmed, Y., Kramer, A., Zampolli, M., Woods, V. T., *et al.*	STUDENT: P-Wave Attenuation Structure and Melting Processes of the Tonga-Lau Mantle Wedge. **Zhang, Y.**, Wei, S., Byrnes, J. S., Tian, D., Wang, F., *et al.*	Evaluating the Application of Machine Learning in Seismic Site Classification: A Case Study of Vs30 Development in Po Plain, Italy. **Mitra, D.**, Sethi, S.	Using a Dynamic Earthquake Simulator to Explore Three-Dimensional Multicycle Dynamics of Stepover Faults. **Duan, B.**	Improvements to Fault Displacement Models: Examples From the 2023 M7.8 Pazarcık, Türkiye Earthquake. **Mason, H. B.**, Lavrentiadis, G., Asimaki, D., Hatem, A. E., DuRoss, C. B., *et al.*
2:30 PM	The Chilean Seismic Network: An Update. **Barrientos, S. E.**, Bravo, F., Koch, P., Baez, J. C., Rivet, D., *et al.*	INVITED: Illuminating Earth's Inner Core Fine-Scale Heterogeneity With Small Aperture Arrays. **Wu, S.**, Pang, G., Koper, K.	An AI-Assisted Real-Time Earthquake Forecasting Case Study in China. **Chen, Y.**, Saad, O., Chen, Y., Savvaidis, A., Fomel, S., *et al.*	Entropy Approach to the 2021 Alaska 8.2 Earthquake. **Vogel, E. V.**, Saravia, G., Pasten, D., Posadas, A., Aguilera, M.	Characterizing Surface Fault Displacement Uncertainty and Its Effects on Probabilistic Fault Displacement Hazard. Example From the 2023 M7.8 Pazarcık, Türkiye Earthquake. **Lavrentiadis, G.**, Mason, H. B., Asimaki, D., Hatem, A. E., DuRoss, C. B., *et al.*

Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom A/B*
	From Faults to Fjords: Earthquake Evidence (continued)	**How Well Can We Predict Broadband Site-Specific Ground… (continued)**	**Induced Earthquakes: Source Characteristics… (continued)**	**The 2023 USGS National Seismic Hazard Model and Beyond (continued)**
2:45 PM	INVITED: A New Generation of High-Precision Dating Techniques for Coseismically-Killed or Damaged Trees. **Black, B.**	Near-Surface Attenuation Estimated With Coda Waves: Insights From Numerical Simulations and Empirical Observations. **Ji, C.**, Cabas, A., Pilz, M., Kottke, A.	Multi-Sensor Microseismic Monitoring of the Quest CCS site, Alberta, Canada. **Langet, N.**, Goertz-Allmann, B. P., Baird, A., Iranpour, K., Kühn, D. K., *et al.*	New Ground-Motion Model With Long-Period Non-Ergodic Path Effects From the Cybershake Simulations in the Southern California Region. **Sung, C.**, Abrahamson, N. A., Lacour, M., Meng, X.
3:00 PM	Precisely Dating Seismically Triggered Debris Avalanches in the Northern California Coast Range. Pearl, J. K., **Kelsey, H.**, Angster, S., Caldwell, D., Pryor, I., *et al.*	Site-Specific Response Spectra Estimation at Designated Seismic Stations of the Puerto Rico Strong Motion Program Seismic Network. **Huerta-López, C. I.**, Suarez-Colche, L. E., Martínez-Cruzado, J. A.	Advanced InSAR Analysis of Groningen's Subsurface Deformation: Enhancing Understanding of Reservoir Rheology and Induced Seismicity Modeling. **Li, Y.**, Acosta, M., Sirorattanakul, K., Bourne, S., Avouac, J.	An Updated Version of the New Empirical Source-Scaling Laws for Crustal Earthquakes Incorporating Fault Dip and Seismogenic-Thickness Effects. **Huang, J.**, Abrahamson, N. A., Sung, C., Chao, S.
3:15– 4:30 PM	Poster Break			
Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom C*
	From Faults to Fjords: Earthquake Evidence in Terrestrial and Subaqueous Environments (see page 1296).	**Planetary Seismology (see page 1381).**	**The OSIRIS-REx Sample Return Capsule Re-entry: Geophysical Observations (see page 1374).**	**Network Seismology: Recent Developments, Challenges and Lessons Learned (see page 1353).**
4:30 PM	STUDENT: Diatom-Based Coseismic Subsidence Estimates Spanning a ~4,500 Year History of Cascadia Subduction Zone Ruptures Along the Southcentral Coast of Oregon. **Bruce, D.**, Dura, T., Witter, R., Kelsey, H., Hemphill-Haley, E.	Near Surface Excitation of the Martian Ground as Measured by Insight. **Pou, L.**, Panning, M. P., Kedar, S., Stahler, S. C., Dahmen, N. J., *et al.*	First-Ever Detection of a Re-Entry Capsule With Distributed Acoustic Sensing (DAS): Initial Results and Data Comparison With Co-Located Seismic and Infrasound Sensors. **Carr, C.**, Donahue, C., Viens, L., Beardslee, L., McGhee, E., *et al.*	INVITED: Why Non-Seismic Sensors Are Actually Valuable to Network Seismology: Examples From Alaska. **West, M. E.**, Ruppert, N., Grapenthin, R., Mohler, M.
4:45 PM	Constraints on Cascadia Subduction Zone Paleoearthquakes from Terrestrial Shaking Proxies and Coseismic Land-level Change. **Grant, A.**, Wirth, E., Dunham, A., LaHusen, S., Maurer, B., *et al.*	Evaluation of Lunar Seismicity Parameters Based on Analysis of Newly Discovered Shallow Moonquakes in the Apollo Seismic Data. **Onodera, K.**	Array Data From the University of Memphis Seismo-Acoustic Coupling Experiment Fielded at the Eureka County Airport, Nevada. **Langston, C. A.**, Bazargan, S., Horton, S., Mitra, I., Islam, S.	Seismic Network Station Infrastructure as the Basis for Multi-Disciplinary Geophysical Stations. **Perlin, M.**

Time	*Tikahtnu Ballroom C*	*Tikahtnu Ballroom E/F*	*Tubughnenq' 3*	*Tubughnenq' 4*	*Tubughnenq' 5*
	Network Seismology: (continued)	**Earth's Structure from the Crust to the Core (continued)**	**Towards Advancing Earthquake (continued)**	**Numerical Modeling (continued)**	**Learning Across Geological, (continued)**
2:45 PM	Geophysical and Sea Level Monitoring in Puerto Rico. **Huerfano, V. A.**	STUDENT: Waveform Changes Due to Moving Scatterers - Application to the Inner Core. **Wang, R.**, Vidale, J.	Now-Casting With Real-Time Strong-Motion Response Spectra. **Franke, M.**, Lindquist, K., Vernon, F.	STUDENT: On the Dynamic of Peierls Creep at Subduction Zones: Implication for Intermediate-Depth Lower Plane Earthquakes. **Zhang, R.**, Yang, J., Zhao, L.	Relating Large-Volume Landslides and Potentially Active Faults Using Geotechnical Analyses in the Pocuro Fault System, Central Andes (32°-33°s). **Sepúlveda, S. A.**, Urrejola-Sanhueza, J. T., Pinto, L., Moreiras, S. M.
3:00 PM	Retrospective of the USGS National Earthquake Information Center Strategic Plan, 2019-23: How We Did and Future Directions. **Earle, P.**, Hayes, G., Yeck, W., Goldberg, D., Wald, D., *et al.*	2020-2030. A Golden Decade for Very Broad Band Planetary Seismology and Seismic Imaging of Mars and Moon Interiors. **Lognonné, P. H.**, Panning, M. P., Banerdt, W. B., Ceylan, S., Clinton, J., *et al.*	Abnormal Low-Magnitude Seismicity Preceding the M6.4–M7.1 2019 Ridgecrest (California) Sequence and the M7.1 2018 Anchorage (Alaska) Earthquake. **Girona, T.**, Drymoni, K.	STUDENT: Quadrangular Adaptive Mesh for Elastic Wave Simulation in Smooth Anisotropic Media. **Rapenne, M.**, Caumon, G., Cupillard, P., Gouache, C.	Measuring Gaps Between Geodetic, Geologic, and Seismic Moment Rates Across the Western U.S.: How to Determine a Budget for Earthquake Rates?. **Hatem, A. E.**, Briggs, R., Pollitz, F., Reitman, N., Tan, M.
3:15– 4:30 PM	Poster Break				

Time	*Tikahtnu Ballroom E/F*	*Tubughnenq' 3*	*Tubughnenq' 4*	*Tubughnenq' 5*
	Marine Seismoacoustics (see page 1344).	**Special Applications in Seismology (see page 1420).**	**Translating Seismic Imaging into Geodynamic Understanding (see page 1445).**	**Structure, Seismicity and Dynamics of the Queen Charlotte-Fairweather Fault System (see page 1432).**
4:30 PM	STUDENT: Rupture Behavior of Large Strike-Slip Earthquakes at Equatorial Atlantic Oceanic Transform Faults: Constraints From Hydroacoustic Data. Sampaio **de Melo, G.**, Grevemeyer, I., Metz, D., Lange, D., Kopp, H.	STUDENT: Is Dynamically Triggered Seismicity Comparable to Background Seismicity?. **DeSalvio, N. D.**, Fan, W., Barbour, A. J.	INVITED: Integration of Geophysical Constraints in Global Mantle Flow Models for Insights Into Plate Tectonics. **Saxena, A.**, Dannberg, J., Gassmoeller, R., Fraters, M.	Aftershock Regions of Mw > 6.7 Earthquakes on the Queen Charlotte–Fairweather Plate Boundary, 1929 to 2013. **Tape, C.**, Lomax, A.
4:45 PM	STUDENT: Waveform Modeling of Hydroacoustic Teleseismic Earthquake Records from Autonomous Mermaid Floats. **Pipatprathanporn, S.**, Simons, F. J., Simon, J. D.	Ligabue—Large Induced Ground Amplitudes by Urban Excitations, as Recorded by a 7c-Station. **Braun, T.**, Famiani, D., Govoni, A., Keil, S., Wassermann, J.	STUDENT: Immersive Insights: Visualization of Earth's Interior in VR and Dome Theaters. **Hoyle, A. M.**, Orsvuran, R., Ghosh, A., Yu, K., Peter, D., *et al.*	Kinematics of the Fairweather-Queen Charlotte Transform System and Deformation Across the Broad Pacific-North America Plate Boundary Zone. **Elliott, J.**

Wednesday, 1 May (*continued*)

Time	K'enakatnu 6/Boardroom	Kahtnu 1	Kahtnu 2	Tikahtnu Ballroom C
	From Faults to Fjords (continued)	**Planetary Seismology (continued).**	**The OSIRIS-REx Sample Return Capsule Re-entry (continued)**	**Network Seismology (continued)**
5:00 PM	Student: A Cycle of Memory Creation, Erasure, and Solid to Fluid-Like State Transitions Encoded Within Granular Assemblages Sheared by Faults. **Dasent, J.**, Kilburn, R., Wright, V., Scharer, K., Manga, M.	A Novel Statistical Technique to Distinguish Lunar Impacts From Shallow Moonquakes. **Turner, A. R.**, Gulick, S. P. S., Trugman, D. T., Civilini, F., Onodera, K.	Infrasound From the Osiris-Rex Src Re-Entry Observed Near the Nevada-Utah Border. **Elbing, B. R.**, Wilson, T. C., Spillman, K., Fox, D., KC, R. J., *et al.*	Small Aperture Seismic Arrays for Offshore Out-of-Network Events. **Perry, H.**, Crane, S., Eisermann, A. S., Ziv, A., McCormack, D. A., *et al.*
5:15 PM	Lost and Found: Evidence of the Penultimate Earthquake on the Hebgen and Red Canyon Faults, Montana. **Hecker, S.**, Stenner, H. D., Schwartz, D. P., Costa, C. H., Hamilton, J. C.	A Reference Marsquake Catalogue. **Clinton, J.**, Ceylan, S., Dahmen, N. J., Staehler, S., Horleston, A., *et al.*	Invited: Direction-Finding Observation of Vlf Radio Emission Upon the Reentry of Osiris-Rex Sample Return Cuspule on 24 September 2023. **Watanabe, T.**, Kobayashi, M., Katoh, Y.	Student: Determining the Feasibility of DAS for Urban Earthquake Monitoring in Athens, Greece. **Smolinski, K. T.**, Bowden, D. C., Lentas, K., Melis, N. S., Simos, C., *et al.*
5:30 PM	Unveiling Seismic Hazards: Paleoseismic Insights From the La Venta Fault in the Forearc Mountains, Mexico. **Ramírez-Herrera, M.**, Gaidzik, K., Dominguez, L. A., Coca, O., Vargas E., V. H.		Invited: Airborne Acoustic Observations of the OSIRIS-REx Reentry. **Bowman, D. C.**, Krishnamoorthy, S., Silber, E. A., Popenhagen, S. K., Garces, M. A.	Towards the Inclusion of Distributed Acoustic Sensing in Earthquake Monitoring and Early Warning Operations. **Biondi, E.**, Saunders, J. K., Tepp, G., Yu, E. C., Bhadha, R., *et al.*
6:00–7:00 PM	Plenary: Challenges in Geohazards Research in Alaska			

Poster Sessions

Network Seismology: Recent Developments, Challenges and Lessons Learned (see page 1358).

1. Student: Picking Regional Earthquake Waveforms With Neural Networks. **Aguilar, A. L.**, Beroza, G. C.
2. Student: Moment Magnitude Estimation Using Machine Learning Algorithms for Western United States. **Alidadi, N.**, Pezeshk, S.
3. Student: National Strong Motion Project's Advancements in Station Health and Integration to the Earthquake Early Warning System in the San Francisco Bay Area. **Amador, V. S.**, Schleicher, L. S., Carrasco Rodriguez, V., Childs, D. M., Luna, E., *et al.*
4. Building an Operational Low-Cost Seismic Network in Ukraine. **Amashukeli, T.**, Malatesta, L., Farfuliak, L., Haniiev, O., Kuplovskyi, B., *et al.*
5. Automated and Efficient Installation of AQMS. **Antolik, L.**, Friberg, P.
6. Enhancing Data Resiliency With Dual-Feed Telemetry. **Bhadha, R.**, Black, M. L., Hoggro, C., Hirata, T., Husker, A. L., *et al.*
7. Next Generation In-Vault Power Distribution to Increase Network Reliability and Remote Ops Capability. **Blom, L.**, Helmericks, J., Dalton, S.
8. Evaluation of Station Performance of the Idaho National Laboratory Seismic Monitoring Network Using Network Detection Thresholds. **Bockholt, B.**, Sandru, J.
9. Field Evaluation of Seismic Sensors for Monitoring Earthquakes, Tsunamis, Volcanoes, and Geodesy. **Bodin, P.**, Venkateswara, K., Wilcock, W., Tobin, H., Paros, J.
10. Performance of Raspberry Shake vs. Kentucky Seismic and Strong-Motion Network Instruments. Schmidt, J. P., **Carpenter, S.**, Wang, Z., Kalinski, M.
11. Access to Seismic Waveform Data, Services and Products in the Euro-Mediterranean Region and Beyond: Status and

Time	Tikahtnu Ballroom E/F	Tubughnenq' 3	Tubughnenq' 4	Tubughnenq' 5
	Marine Seismoacoustics (continued)	**Special Applications (continued).**	**Translating Seismic Imaging (continued)**	**Structure, Seismicity… (continued)**
5:00 PM	INVITED: STUDENT: Decoding the Submarine Ambient Noise Field with Distributed Acoustic Sensing. **Fang, J.**, Williams, E. F., Yang, Y., Biondi, E., Zhan, Z.	STUDENT: #Utequake: An Outreach Project Combining Real-Time Large Crowd Seismology and Football. **Rabade, S.**, Farrell, J., Hale, J. M., Blycker, W., Morton, E., *et al.*	STUDENT: Investigating the Seismic Signature of Galápagos Mantle Flow Models. **Autumn, K. R.**, Hooft, E. E. E., Ito, G., Faccenda, M., VanderBeek, B. P., *et al.*	The Making of a Future Accreted Terrane: Plate Tectonics of the Queen Charlotte Fault System and the Development of the Queen Charlotte Terrace Adjacent to Haida Gwaii. **Furlong, K. P.**, Rohr, K. M. M., Riedel, M.
5:15 PM	Ocean Bottom Turbulence Evolution Observed by Arrayed Obs, Dpg, and a Temperature String. **Chi, W.**, Yang, C., van Haren, H.	Enhancing Classification Reliability With Anomaly Detection for Operational Monitoring of Continuous Seismic Data. **van Dinther, C.**, Malfante, M., Chiasson-Poirier, L., Gaillard, P., Cano, Y.	First Steps Towards Imaging the Antarctic's 3D Viscosity Structure Using GPS Observations. **Lloyd, A.**, Hollyday, A. E., Powell, E., Mitrovica, J. X., Gomez, N., *et al.*	STUDENT: Slope Evolution and the Accommodation of Oblique Convergence From the Central to the Northern Queen Charlotte Fault. **Adedeji, O.**, Worthington, L. L., Brandl, C. C., Walton, M. A. L., Roland, E., *et al.*
5:30 PM	STUDENT: Searching for Low-Amplitude Shallow Tectonic Tremor in Cascadia Using Buried Ocean Bottom Seismometers. **Krauss, Z.**, Wilcock, W., Creager, K.	Towards the Automatic Relocation of Intermediate-Depth Earthquakes Using Adaptive Teleseismic Arrays. **Craig, T. J.**, Blackwell, A., Rost, S.	Instantaneous 3D Tomography-Based Convection and Melt Generation Beneath the Rungwe Volcanic Province, East Africa. **Njinju, E. A.**, Stamps, D., Atekwana, E. A., Rooney, T., Rajaonarison, T. A.	A Spectral Perspective on Fault Geometry and Strike-Slip Rupture at Plate-Boundary Scales Along the Queen Charlotte Fault. **Miller, N.**, Brothers, D. S.
6:00–7:00 PM	Plenary: Challenges in Geohazards Research in Alaska			

Outlook of Orfeus Coordinated Programs. **Cauzzi, C.**, Clinton, J., Crawford, W., Custódio, S., D'Amico, S., *et al.*

12. From Dense Seismic Monitoring to Mass-Movement Hazards and Their Impacts: Demonstrating an Operational Workflow and Associated Data Services. **Cauzzi, C.**, Böse, M., Clinton, J., Danciu, L., Kästli, P., *et al.*
13. Evolution of Volcano Hazards Monitoring of the Cascades Chain in Washington and Oregon: Cascades Volcano Observatory. **Darold, A. P.**
14. Seismic Network Modernization and Expansion in Ukraine. **Farfuliak, L.**, Amashukeli, T., Aderhold, K., Chiang, A., Mackey, K., *et al.*
15. Hydrothermal Monitoring Site in Norris Geyser Basin, Yellowstone National Park, Wyoming, United States of America. **Forbes, N. M.**, Farrell, J., Hale, J. M., Trow, A. J., Alexander, J., *et al.*
16. Improving Earthquake Monitoring Capabilities in Ohio With Low-Cost Robust Posthole Vaults. **Fox, J. L.**
17. Near Real-Time Earthquake Catalog for the Endeavour Segment of the Juan De Fuca Ridge: Integrating Community Code Into Ocean Networks Canada's Ocean 3.0 Data Portal. **Heesemann, M.**, Hutchinson, J., Ferguson, E., Biffard, B., Krauss, Z., *et al.*
18. AdriaArray—a Passive Seismic Experiment to Study the Geodynamics and Geohazards in Central Mediterranean. **Kolínský, P.**, Meier, T., Seismology Group, t.
19. Northern California Earthquake Data Now Available in AWS Cloud. **Marty, J.**, Zuzlewski, S., Taira, T., Thompson, S., Allen, R.
20. Assessment of Data Quality for the Alaska Geophysical Network. **McFarlin, H.**, Ruppert, N., Murphy, N., Holtkamp, S., Heslop, J.
21. A Review of Recent IDA Sensor Performance. **Mellors, R. J.**, Ebeling, C. W., Davis, P., Berger, J.
22. High Frequency Ground Motion and Electrical Calibrations of Seismometers Used at IMS Stations. **Merchant, B. J.**, Bloomquist, D. K., Slad, G. W.

23. Student: Machine Learning Earthquake Catalog Performance for Characteristic Alaska Settings. **Noel, S. K.**, West, M. E., Ruppert, N. A.
24. Monitoring Induced Microseismicity (M>-1) With the Local Network at the Utah Frontier Observatory for Research in Geothermal Energy (FORGE). **Pankow, K. L.**, Whidden, K., Rutledge, J., Petersen, G., Niemz, P., *et al.*
25. Seismic Data Compression and Telemetry Bandwidth Considerations for EEW. **Perlin, M.**
26. Sensor Corrections for Multi-Component Monitoring of Seismic Translation and Rotation. **Rossi, Y.**, Guattari, F., Bernauer, F., Lin, C.
27. Comparative Analysis of Seismic Instrument Installations: Surface Vaulted Pier Mount, Direct Burial, and Bore Hole, Considering Noise Models. **Sandru, J.**
28. Applying Machine Learning Salves to Network Build-Out "Growing Pains" at the Pacific Northwest Seismic Network. **Stevens, N. T.**, Hartog, R., Ni, Y., Hutko, A., Denolle, M., *et al.*
29. System Monitoring, Telemetry Quality Control, and Planning Tools for Scsn. **Stubailo, I.**, Bhadha, R., Watkins, M., Husker, A. L., Yu, E. C., *et al.*
30. Quick Look at the Reoccupation and Installation of Seismic Stations at the NNSS. **Turley, R.**, Scalise, M., Zeiler, C. P., Gochenour, J., White, R., *et al.*
31. A Decade of the Seattle Liquefaction Array. **Williams, E. F.**, Denolle, M., Bodin, P., Steidl, J. H.
32. Improving Automatic Post-Processing at the Southern California Seismic Network With Machine Learning Algorithms. Tepp, G., **Yu, E. C.**, Zhu, W., Jaski, E., Newman, Z., *et al.*
33. Güralp SMART Sensors - A Comparison of Next Generation Mid-Band Seismometers and Traditional Sensor Technologies. **Lindsey, J. C.**, Watkiss, N., Hill, P., O'Neill, J.

Marine Seismoacoustics **(see page 1345).**

34. Pushing Boundaries With Ocean Bottom Seismometers (Obs) With a Pool-Ready System: Güralp Aquarius. **Lindsey, J. C.**, Watkiss, N., Hill, P., Nedimović, M., Cairns, G.
35. Student: Probing Further the Cascadia Initiative Data to Detect New Offshore Events. **Bito, H.**, Denolle, M. A., Ni, Y., Shi, Q., Krauss, Z.
36. Noise on Ocean Bottom Seismometers: Observations and New Directions. **Janiszewski, H. A.**, Russell, J., Hoots, C., Maso, E.
37. Student: Changing Ambient Noise Patterns in the Beaufort Sea. **Niklasson, S.**, Rowe, C., Bilek, S.
38. RBRquartz³ APT: Innovative Instrumentation for Enhanced Marine Seismic Monitoring on Ocean Networks Canada's NEPTUNE Cabled Observatory. **Schlesinger, A.**, Heesemann, M., Sun, T., Davis, E., Dexter, J., *et al.*
39. Observations From the Seafloor: Ultra-Low-Frequency Ambient Ocean-Bottom Nodal Seismology From the Gulf of Mexico. **Shragge, J. C.**, Girard, A. J.
40. High-Resolution Acoustic Seabed Quantification with an Autonomous Underwater Vehicle. **Sonnemann, T.**, Dettmer, J., Holland, C. W., Dosso, S. E.
41. Implementation Plan for the Cascadia Offshore Subduction Zone Observatory. **Wilcock, W. S. D.**, Harrington, M. J., Schmidt, D. A., Kelley, D. S., Tobin, H. J., *et al.*
42. CHIRP Acoustic Reflection Imaging: Toward Improved Signal Processing in Extant Glacial Lakes. **Woller, K. L.**, McGlue, M. M., Thigpen, J. R., Yeager, K. M., Woolery, E. W.

From Faults to Fjords: Earthquake Evidence in Terrestrial and Subaqueous Environments **(see page 1301).**

43. Lacustrine Paleoseismic Evidence From Two Large Lakes in Cascadia: Preliminary Comparisons of Post-Glacial Sediment Records From Ozette and Whatcom Lakes, Washington. **Brothers, D. S.**, Hill, J., Singleton, D., Derosier, B., Sherrod, B. L., *et al.*
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53. Cataloging the Date of Last Event (DOLE) Across the Western U.S. **Hatem, A. E.**, Briggs, R., Tan, M.
54. Tectonic Oversteepening, Sediment Accretion, and Lower Slope Failure in the Cascadia Subduction Zone—A Recipe for Abyssal Seismoturbidites and Insights Into Earthquake History. **Hill, J. C.**, Brothers, D. S., Watt, J. T., Paull, C. K., Caress, D., *et al.*
55. Marine Seismoturbidites in the Cascadia Subduction Zone: Filling the Gaps and Refining the Offshore Records of Earthquake Shaking. **Hill, J. C.**, Watt, J. T., Paull, C. K., Caress, D., Brothers, D. S., *et al.*
56. Urban Paleoseismology of the Taylorsville Fault - New Data and Challenges from one of the Last Remaining Trench Sites on the West Valley Fault Zone, Utah. **Hiscock, A. I.**, Kleber, E. J., McDonald, G. N., Hylland, M. D., McLean, J. H., *et al.*
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58. Chirp Correlation and Acoustic Characterization of Lacustrine Turbidite Deposits in Lake Ozette, Wa Using Ct-Derived Density, Synthetic Seismograms, and Advanced Chirp Processing. **Kluesner, J.**, Brothers, D. S., Snyder, G., La Selle, S., Singleton, D., *et al.*
59. How Do Large Lakes in the Seattle Area Respond to Different Sources of Seismic Shaking? Revisiting Lake Washington and Lake Sammamish With New High-Resolution Data. **Kluesner, J.**, Hill, J., Brothers, D. S., Sherrod, B. L., Conrad, J., *et al.*
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62. Ground Surface Rupture Complexity on the Northern Alpine Fault, Aotearoa New Zealand. La Greca, J., **Quigley, M.**, Langridge, R., Morgenstern, R., Kulesza, O.
63. Using Modern Fires to Estimate Charcoal Age Inheritance at Paleoseismic Sites in California. **Scharer, K.**, McPhillips, D., Leidelmeijer, J., Kirby, M.
64. Refined Timing and Estimates of Coseismic Subsidence at the Southern Cascadia Subduction Zone: Combining Modern Dendrochronology, Age Modeling, and Relative Sea-level Reconstruction Techniques in the Eel River Valley, CA. **La Selle, S.**, Padgett, J. S., Black, B. A., Kelsey, H. M., Witter, R. C., *et al.*
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67. Temporal Clues Point to an Along-Strike Cascadia Megathrust Rupture Sequence Between 680–950 Years Ago. **Witter, R.**, Staisch, L., Nelson, A., Kelsey, H., Padgett, J.

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68. Infrasound Analysis of the OSIRIS-REx Reentry at the NVIAR Array. **Clarke, J.**, Arrowsmith, S., Park, J., Anderson, D.
69. Observation of Osiris-Rex via Shock Wave: Temporary Observation Network Utilizing Portable Infrasound Sensors and Comparative Analysis With Hayabusa and Hayabusa2. **Nishikawa, Y.**, Yamamoto, M., Hasumi, Y.
70. Leveraging Infrasound Detections of Sample Return Space Missions Towards Characterization of Meteors: A Review. **Silber, E. A.**, Bowman, D., Albert, S. A.
71. The Utility of Infrasound Towards Detection and Characterization of Bolides. **Silber, E. A.**
72. Infrasound Detection of the OSIRIS-REx Re-Entry: Signal Characteristics. **Silber, E. A.**, Bowman, D. C.
73. The OSIRIS-REx Sample Return Capsule Re-Entry: Initial Results From a Historic Geophysical Recording Campaign Against an 'Artificial Meteor'. **Silber, E. A.**, Bowman, D. C., Krishnamoorthy, S., Carr, C., Haaser, R. A., *et al.*
74. The First Detection of an 'Artificial Meteor' by a Large N Acoustic Array. **Silber, E. A.**, Bowman, D. C., Eisenberg, D. P.

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75. Post-Earthquake Liquefaction Mapping by Semi-Supervised Machine Learning Using Partially Labeled Imagery. **Asadi, A.**, Baise, L. G., Sanon, C., Koch, M., Chatterjee, S., *et al.*
76. Investigating Different Methodologies for a Sar Coherence Change Detection Product. **Burgi, P. M.**
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78. Integration of Seismic Monitoring and Involvement of Civil Protection Volunteers for an Effective Post-Earthquake Response. Camassi, R., **Faenza, L.**, Ercolani, E., Brunelli, M., Pondrelli, S., *et al.*
79. Applying ShakeCast to Monitor Earthquake Hazards for Pipeline Infrastructure. **Hille, M.**, Zellman, M., Modney, T., Widmann, B., Duckworth, W., *et al.*
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81. Global Structural Health Monitoring via MyShake: An Economical and Accessible Smartphone-Based Approach. **Kumar, U.**, Marcou, S., Patel, S., Allen, R.
82. ShakeCast: Pivoting USGS Products to Respond to User Needs. **Lin, K.**, Cheeck, L., Smith, K. K., Thompson, E. M., Wald, D.
83. Guidelines on Using (Uncertain) Macroseismic Data in ShakeMap. **Quitoriano, V.**, Wald, D. J., Worden, C. B., Thompson, E. M.
84. Creating Earthquake Early Warning Post-Alert Information Products: Harnessing Existing Earthquake Information Tools to Depict Alerting Efficacy. **Saunders, J. K.**, Wald, D. J.
85. A Framework for Implementing a New Intensity Metric for USGS's Shakemap: Cumulative Absolute Velocity (CAV). **Smith, K.**, Thompson, E. M., Worden, C. B., Wald, D.

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87. Geologic and Geomorphic Evidence for Possible Reactivation Along the Dry Creek Fault Zone and Hoadley Fault, Cryptic Faults in the Northern Sacramento Valley and Surrounding Areas. **von Dassow, W.**, Klinger, R., Besana-Ostman, G., Reedy, T.
88. Constraints on Late-Quaternary Fault Displacement and Tectonic Hazards in the Sacramento–San Joaquin Delta, Northern California, From Shallow Sediment Cores Across the Pittsburg–Kirby Hills Fault System. **Trexler, C.**, Vermeer, J., Hammer, M., Doyle, M., Williams, T.
89. Characterization of Slip Rates Across the Buffalo Valley, Buena Vista Valley, and Southern Shoshone Faults, Central Nevada. **Koehler, R. D.**, Stirling, M. W.
90. Late Pleistocene Kinematics of the Great Southern Puerto Rico Fault Zone, Puerto Rico. **Lynch, E. M.**, Thompson Jobe, J. A., Briggs, R., Ortega Diaz, V. G.
91. Student: A Comprehensive Search for Evidence of Active Faulting in the Southern Coast Mountains of British Columbia, Canada: Progress and Preliminary Results. **Mendoza, R.**, Hobbs, T. E., Salomon, G., Finley, T., Nissen, E., *et al.*
92. Student: Investigating Holocene-Active Faulting in the Strait of Georgia, British Columbia Through Archived Seismic Reflection Data. **Podhorodeski, A.**, Douglas, K., Hobbs, T., Leonard, L., Schaeffer, A.
93. Steps Toward Linking the Kaltag and Tintina Faults in Interior Alaska. **Salisbury, B.**
94. Student: A Detailed Earthquake Catalog for Interior Alaska Fault Zones. **Sims, N. E.**, Tape, C.
95. Spatial Patterns of Tectonic Deformation at the Mendocino Triple Junction Inferred From River Terraces and Landscape Morphology. **Vermeer, J.**, DeLong, S., Hammer, M., Patton, J. R., Trexler, C., *et al.*

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97. A 3-Dimensional P-Wave Tomography Model of the Pecos, Texas Region of the Delaware Basin. **Faith, J. L.**, Karplus, M. S., Doser, D. I., Savvaidis, A.
98. Student: Pore Pressure Effect on Coulomb Stress Change and Triggering of Earthquakes in Raton Basin, Colorado—New Mexico Region. **Fuentes, F. A.**, Mendoza, M. M., Brown, M. R. M., Ge, S., Sheehan, A. F.
99. The Minimal Effect of Solid-Earth Tides on Earthquake Rate in Oklahoma and Kansas. **Glasgow, M. E.**, Rubinstein, J. L., Hardebeck, J.
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101. Quake-Dfn, A Software for Simulating Sequences of Induced Earthquakes in a Discrete Fault Network. **Im, K.**, Avouac, J.
102. Crustal Rheological Layering Revealed in Multiscale Signals of Natural and Anthropogenic Processes at Pawnee, Oklahoma. **Jiang, J.**, Bodunde, S., Walter, J., Carpenter, B., Viteri Lopez, J.
104. Fluid-Induced Aseismic Slip May Explain the Non-Self-Similar Source Scaling of the Induced Earthquake Sequence Near the Dallas-Fort Worth Airport, Texas. **Lui, S.**, Jeong, S., Tan, X.
105. DC or Non-DC? Exploring Uncertainties and Resolution Limitations for Source Mechanism Studies in a Complex EGS Environment. **Niemz, P.**, Rutledge, J., Petersen, G., Finger, C., Pankow, K. L.
106. Wastewater Disposal and Hydraulic Fracturing Interaction Propagating Seismicity in Oklahoma. **Ogwari, P. O.**, Walter, J. I., Allen, B., Thiel, A., Woelfel, I., *et al.*

107. Student: Centroid Full Moment Tensor Analysis Reveals Geological and Injection Related Constraints of Induced Seismicity at the Experimental Otaniemi EGS Site, Helsinki Region, Finland. **Rintamäki, A. E.**, Hillers, G., Heimann, S., Dahm, T., Korja, A.
108. Inferring Maximum Magnitudes From the Ordered Sequence of Large Earthquakes. **Schultz, R.**
109. Constraining the Non-Double-Couple Components of Local Events Recorded by Dense Nodal Array. Yang, L., **Wang, R.**
110. Student: Unraveling the Subsurface Mosaic: Implications of Tectonic Structures and Fault Orientations on Induced Seismicity. **Wangari, V. N. N.**
111. On Delayed Triggering of Earthquakes by Anthropogenic Activities. **Yang, H.**, Zi, J., Yang, Y.
112. Student: Source Mechanisms Inversion of Induced "Seismicity" During Laboratory Hydraulic Fracturing. **Yuan, H.**, Gu, C., Zhong, Y., Wu, P., Chen, Z., *et al.*
113. How Induced Earthquakes Response to Pre-Existing Fractures and Hydraulic Fracturing Operations? a Case Study in South China. Li, D., **Zhang, M.**, Zheng, J., Peng, S.

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116. Passive Source Detection Technology Based on Short-Period Dense Seismic Array. **Gamez, R.**, Zou, L., Shen, J., Zhou, B.
117. Student: Effects of Bimaterial Interface on Rupture Along Strike-Slip Branch Faults. **Marschall, E.**, Douilly, R., Kame, N.
118. New Constraints on the Seismic Crustal Structure of the Southern Apennines (Italy): Numerical Modeling of P- and S- Body Waves for Moderate Earthquakes at Regional Scale. **Scarponi, M.**, Di Luccio, F., Piromallo, C., Sun, D.

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122. Inversion of Earthquake-HVSR in the Anchorage Basin, Alaska, for Delineation of Shallow Sedimentary Structures. **Dutta, U.**, Thornley, J., Yang, Z., Zhao, Y., Stephenson, W.
123. Measuring Shallow Seismic Attenuation in the Pacific Northwest of the United States Using Ambient Noise Seismology. **Feng, K.**, Denolle, M., Ni, Y.
124. Relating Peak and Cumulative Ground Motions for Earthquakes in the San Francisco Bay Area. **Hirakawa, E. T.**, Parker, G. A., Baltay, A. S.
125. A Comparative Study Between the Resonance Frequency by Hvsr Analysis and Bedrock Depth in Western Busan, Korea. **Kang, S.**, Kim, K., Lee, S.
126. Student: Preliminary Site Characterization for Earthquake Hazard Assessment Using Ambient Vibration Techniques in Haines Junction, Yukon. **Leishman, T.**, Gosselin, J. M., Dettmer, J., Cassidy, J., Kang, T.
127. Influence of Buried Geometries on Ground Response Analysis: The Case of the Pescara Paleovalley System. **Di Martino, A.**, Sgattoni, G., Purri, F., Amorosi, A.
128. Influence of Seasonal Frozen Soil on High-Frequency Attenuation (κ0). Haendel, A., **Pilz, M.**, Cotton, F.
129. Combining Simulated and Empirical Nonergodic Ground Motion Models for Southern California. **Smith, J.**, Engler, D. T., Moschetti, M. P., Parker, G. A., Thompson, E. M., *et al.*
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131. Constraining Shear-Wave Velocity Profiles in Anchorage, Alaska, Through Inversion of Microtremor Horizontal-to-Vertical Spectral Ratios. **Stephenson, W. J.**, Dutta, U., Lindberg, N. S., Leeds, A., Goozen, A., *et al.*
132. Student: Seismic Site Characterization of Sikkim Himalaya Using HVSR. **Uthaman, M.**, Singh, C., Singh, A., Bose, S.

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135. Conterminous U.S. Site Parameter Maps for Ground Motion Models. **Boyd, O. S.**, Smith, J. A., Moschetti, M. P.
136. Recurrence Model for Puerto Rico Subduction Zone Interface and Muertos Thrust Belt Earthquakes. **Briggs, R.**, ten Brink, U., Thompson Jobe, J. A., Hatem, A. E., Pratt, T., *et al.*

137. Seismic Hazard, Lithosphere Hydration, and Double-Verging Structure of the Puerto Rico Subduction Zone: A Seismic Reflection and Refraction Perspective. **Canales, J.**, Han, S., ten Brink, U., Vanacore, E., Harmon, N., *et al.*
138. Deploying the USGS National Seismic Hazard Models. **Clayton, B.**, Powers, P.
139. USGS Earthquake Hazard Toolbox. **Girot, D. L.**, Powers, P. M., Clayton, B. S.
140. The 2023 Alaska National Seismic Hazard Model: Inputs and Implications. **Herrick, J. A.**, Rukstales, K. S., Altekruse, J. M., Powers, P. M., Team, N.
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142. Gridded Seismicity Models for the 2025 USGS National Seismic Hazard Model for Puerto Rico and the U.S. Virgin Islands. **Llenos, A. L.**, Michael, A. J., Shumway, A. M., Haynie, K. L.
143. A Seismological Method for Estimating the Long-Period Transition Period Tl in the Seismic Building Code. **Pezeshk, S.**, Assadollahi, C.
144. Why Seismic Hazard Models Appear to Overpredict Historical Shaking Observations: An Intensely Simple Answer. **Salditch, L.**, Stein, S., Gallahue, M., Neely, J., Abrahamson, N. A.
145. Hybrid Empirical Ground-Motion Models for the Island of Hawaii Based on an Updated Strong Ground Motion Database. **Davatgari Tafreshi, M.**, Pezeshk, S., Haji-Soltani, A.
146. Empirical Models for Fourier Amplitude Spectrum of Ground-Motion Calibrated on Data From the Iranian Plateau. **Davatgari Tafreshi, M.**, Pezeshk, S., Singh Bora, S.
147. Methods to Evaluate and Improve the Modeling of Rupture Directivity in Assessment of Seismic Hazard. **Withers, K.**, Kelly, B., Bayless, J., Moschetti, M.
148. A Fault-Based Crustal Deformation Model With Buried Dislocation Sources for Slip-Rate Inversion of the Alaska Faults. **Zeng, Y.**

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149. Short-Term Earthquake Forecast Using Precursor Phenomena. **Hattori, K.**
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151. Student: Study of the b-Value Change Preceding the 2024 Noto Peninsula Earthquake M7.6, Japan. **Li, W.**, Yoshino, C., Hattori, K.
152. The January 1, 2024, Noto Hanto, Japan, Mw 7.6 Earthquake as a Plausible 'Dragon King' Event. **Liu, Y.**, Zhang, Y., Wu, Z.
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155. Local Earthquake Monitoring of the Central Queen Charlotte Fault With an Ocean-Bottom Seismic Array. **Gase, A. C.**, Roland, E., Worthington, L. L., Walton, M. A. L., Bostock, M., *et al.*
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157. Student: Crustal Velocity Structure of the 2013 m7.5 Craig Earthquake Source Region With Joint Ocean-Bottom Seismometer and Streamer Tomography. **Martin, E. C.**, Gase, A., Roland, E., Garza, L., Worthington, L. L., *et al.*
158. Crustal Structure Crossing the Queen Charlotte Fault and Trough in the Region of the Haida Gwaii 2012 m7.9 Thrust Earthquake Using P-Wave Tomography. **Roland, E.**, Worthington, L. L., Gase, A., Walton, M. A. L., Nedimovic, M.
159. Crustal Architecture Across the Queen Charlotte Fault Zone North of Haida Gwaii, British Columbia From 2d Tomography. **Walton, M. A. L.**, Worthington, L. L., Roland, E., Gase, A., Garza, L., *et al.*
160. New Constraints on Crustal Structure and Fault Zone Architecture in the m7.8 2012 Haida Gwaii Earthquake Source Region, Offshore British Columbia. **Worthington, L. L.**, Brandl, C. C., Roland, E., Walton, M. A. L., Nedimovic, M., *et al.*

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161. Guiding Deep Earthquake Investigation with Subduction Modeling: Is Thermal Shear Instability Viable in the Deep Slab?. **Fildes, R. A.**, Billen, M. I., Thielmann, M.
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163. Image of Crust and Upper Mantle of Ne India Based on Surface Wave Tomography. **Mukhopadhyay, S.**, Kumar, N., Kumar, A., Chanu, M. N.
164. Student: Transdimensional Mt. Etna Volcano P-Wave Anisotropic Seismic Imaging. **Del Piccolo, G.**, Lo Bue, R., VanderBeek, B. P., Faccenda, M., Cocina, O., *et al.*
165. Ecoman 2.0: An Open-Source Software for Exploring the Consequences of Mechanical Anisotropy in the Mantle. Faccenda, M., **VanderBeek, B. P.**, de Montserrat, A., Yang, J.

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166. Sub-Daily Gnss Denoising Using Graph Neural Network. **Bachelot, L.**, Thomas, A. M., Melgar, D., Searcy, J.
167. Analysis of Characteristic Repeating Earthquakes in the Tehuantepec Triple Junction, Mexico. **Dominguez, L. A.**, Taira, T.
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169. Student: Machine Learning as a Tool to Build a Comprehensive Seismic Catalog for the Island of Hispaniola. **Muñoz, L. F.**, Walter, J., Pulliam, J., Leonel, J., Polanco Rivera, E.
170. Assessment of Atmospheric-Driven Ground Noises for Dragonfly's Seismic Observation on Titan. **Onodera, K.**, Kawamura, T., Nishida, K., Shiraishi, H., Tanaka, S., *et al.*
171. Ground Deformation Caused by Atmospheric Gravity Waves on Mars: An Independent Assessment of Martian Crustal Rigidity. **Onodera, K.**, Nishida, K., Widmer-Schnidrig, R., Kawamura, T., Spiga, A., *et al.*
172. Student: Efficient Cataloging of Low-Frequency Earthquakes With Deep-Learning Model and Template Matching. **Papin, L.**, Thomas, A. M., Lin, J., Hawthorne, J.

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173. Student: Rupture Geometry and Static Stress Changes of the 2022 Mw 7.0 and Mw 6.4 Earthquakes in Abra, Philippines. **Catugas, S. A.**, Aurelio, M. A., Dianala, J. B.
174. Student: Investigating Early Earthquake Rupture Characteristics With Borehole Strainmeters. **Dybing, S. N.**, Melgar, D., Barbour, A. J., Canitano, A., Goldberg, D. E.
175. Student: Hybrid Model: A Tool for Combining Fault and Area Sources in Seismic Hazard Assessment. **Gamboa-Canté, C.**, Rivas-Medina, A., Ornelas-Agrela, A., Benito, B.
176. A New View on Interseismic Locking of the Hikurangi Megathrust Along the North Island of New Zealand. **Govers, R.**, Bijlsma, E., Vos, S.
177. Geological Constraints on the Seismic Activity of the Mid-section of the Minjiang Fault in the Eastern Margin of the Tibet Plateau. **Han, Z.**, Guo, P., Zhou, C., Niu, P., Li, J.
178. Seismic Structure, Lithospheric Deformation and Seismicity of the Indian Plate in Sikkim Himalaya. Singh, A., Uthaman, M., **Jana, N.**
179. Earthquake Rate Modelling Tools to Explore Uncertainties in Fault Source Parameters The Case of the Alboran Sea. Perea, H., Gómez-Novell, O., **Jiménez, M.**, García, M., Lozano, L., *et al.*
180. Mapping Finite-Fault Slip in 3D From Spatial Correlation Between Seismicity and Point-Source Coulomb Stress Change. **Lomax, A.**
181. Student: Microseismicity and Fault Structure in the Daliangshan Subblock Within the Southeastern Tibetan Plateau. **Ma, J.**, Xiao, Z., Li, L., Ai, Y.
182. Student: Mapping Outerrise Normal (and other) Dip-slip Fault Parameters using Semi-automated and Newly Developed Python Toolbox. **Nielson, Q.**, Losasso, E., Newman, A.
183. Student: Diatom Evidence of Tsunami Inundation Extent Following the Great Ca. 1700 Ce Earthquake(s) at the Salmon River Estuary, Oregon, USA. **Priddy, M.**, Dura, T., Hawkes, A., Kelsey, H., La Selle, S., *et al.*
184. Moment Tensor Analysis for Earthquakes in Armenia. **Sahakyan, E.**, Babayan, G., Sargsyan, L., Gevorgyan, M., Nabelek, J.
185. Preliminary Constraints on Quaternary Fault Activity in the Malawi Rift from New High-resolution Bathymetry and Seismic Data. **Shillington, D. J.**, Scholz, C. A., Chindandali, P. R. N., Wood, D., Greenlee, J. M., *et al.*
186. Student: Constraining Earthquake Nucleation using Response of Seismicity to Transient Slow-slip Event and Hydrological Surface Load. **Sirorattanakul, K.**, Avouac, J.
187. Student: Towards Systematic Kinematic Source Models of Historically Large Earthquakes. **Solares-Colón, M. M.**, Melgar, D., Bato, M. G.
189. Study on the Latest Activity and the Maximum Potential Earthquake in the Middle Section of the Minjiang Fault. **Zhou, C.**, Han, Z., Guo, P., Niu, P.

Thursday, 2 May 2024—Oral Sessions

Presenting author is indicated in bold.

Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom A/B*
	3D Wavefield Simulations: From Seismic Imaging to Ground Motion Modelling (see page 1201).	**Illuminating Complex, Multiplet Earthquake Sequences at Kahramanmaras (Turkiye), Herat (Afghanistan), and Beyond (see page 1318).**	**Detecting, Characterizing and Monitoring Mass Movements (see page 1262).**	**Seismic Monitoring, Modelling and Management Needed for Geothermal Energy and Geologic Carbon Storage (see page 1393).**
8:00 AM	INVITED: High Frequency (2+ Hz), 3D Wavefield Simulations of Large Earthquakes on the Southern Whidbey Island Fault, Washington State. **Stone, I.**, Wirth, E., Grant, A., Frankel, A.	The October 2023 Herat, Afghanistan Earthquake Quadruplet - Aftershock Locations and Moment Tensors. **Braunmiller, J.**, Ghods, A.	Infrasound Array Analysis of Rapid Mass Movements in Mountain Regions. **Johnson, J.**, Marchetti, E.	DOE's Best Practices for Addressing Induced Seismicity Associated With Enhanced Geothermal Systems. Majer, E., Robertson-Tait, A., Nelson, J., Savy, J., **Wong, I.**
8:15 AM	3D Kinematic Models of Ground Motions of Cascadia Megathrust Earthquakes: Preliminary Results and Comparison to Paleoseismic Subsidence Data. **Dunham, A.**, Wirth, E., Kim, J., Schmidt, D., Grant, A., *et al.*	STUDENT: Long-Term Seismicity of the East Anatolian Fault System and Its Relationship With the 2023 Mw 7.8 & 7.6 Kahramanmaraş (Se Türkiye) Earthquake Doublet. **Zhou, Y.**, Ding, H., Ghosh, A., Ge, Z.	The Mount Rainier Lahar Detection System: Risk Mitigation for an Unlikely, but Potentially Catastrophic, Event. **Moran, S. C.**, Thelen, W. A., Iezzi, A. M., Kramer, R. L., Pauk, B., *et al.*	Geophysical Monitoring of Anthropic Underground Operations in Italy: An Operative Center for Risk Mitigation. **Saccorotti, G.**, Anderlini, L., Anselmi, M., Braun, T., Caciagli, M., *et al.*
8:30 AM	Broadband Ground Motion Simulations for a Türkiye-like Earthquake "Doublet" on the Hayward and Calaveras Faults. **Graves, R.**, Wang-Connelly, J., Thompson, E., Quitoriano, V., Wald, D., *et al.*	STUDENT: The Kahramanmaras (Turkey) Earthquake Multiplet Sequence Revealed by Deep Learning Computer Vision. **Tan, F.**, Nissen, E., Kao, H.	Characterization of a Debris Flow at Mount Rainier via Seismoacoustics and a Novel Usage of a Laser Rangefinder. **Iezzi, A.**, Thelen, W. A., Bryant, E., Gabrielson, C., Moran, S. C., *et al.*	An Open-Source Tool for Operational Forecasting of Induced Seismicity (Orion). **Kroll, K.**, Sherman, C. S., Geffers, G., Wang, C., He, D. J., *et al.*

Time	Tikahtnu Ballroom C	Tikahtnu Ballroom E/F	Tubughnenq' 3	Tubughnenq' 4	Tubughnenq' 5
	Characteristics and Mechanics of Fault Zone Rupture Processes, from Micro to Macro Scales (see page 1244).	**Advancements in Forensic Seismology and Explosion Monitoring (see page 1208).**	**Seismology in the Oceans: Pacific Hemisphere and Beyond (see page 1410).**	**From Earthquake Recordings to Empirical Ground-Motion Modelling (see page 1292).**	**Network Seismology: Recent Developments, Challenges and Lessons Learned (see page 1353).**
8:00 AM	Temporally-Varying Creep Behavior on the East Anatolian Fault and the End of the 2023 Pazarçik Rupture. **Funning, G. J.**, Hofstetter, C., Özarpacı, S.	INVITED: Seismology in Support of Negotiation, Implementation, and Verification of Nuclear Test Ban Treaties and Science Diplomacy: Where It Started and DOS R&D Challenges. **Jih, R.**	Structure of the Cascadia Margin Offshore Northern Oregon (44.5-46deg N) From Casie21-OBS Wide-Angle Seismic Profiles. **Canales, J.**, Jian, H., Mann, M., Miller, N., Carbotte, S., *et al.*	From Satellites to Soil Response: Analyzing Body Wave locity Variations at Shallow Depths in Sync With Satellite Soil Moisture. Kyriou, A., **Roumelioti, Z.**, Hollender, F.	Making Phase-Picking Neural Networks More Consistent and Interpretable. **Park, Y.**, Delbridge, B. G., Shelly, D. R.
8:15 AM	STUDENT: Modeling Rupture Propagation Into Creeping Faults by Thermal Pressurization. Stephenson, O., **Vescu, V.**, Lapusta, N.	Three-dimensional Nonlinear Calculations of Explosions at the Novaya Zemlya Nuclear Test Site. **Stevens, J. L.**, O'Brien, M. S.	STUDENT: A Newly Identified Mass-Transport Deposit in the Guaymas Basin, Gulf of California: Implications for Regional Tectonics and Continental Slope Stability. **Piña, A.**, Stock, J., Lizarralde, D., Berndt, C., González-Fernández, A., *et al.*	INVITED: Seeking for Dependencies of the High-Frequency "Kappa" Parameter of Earthquake Spectrum on Weather/climate Conditions. **Grendas, I.**, Roumelioti, Z., Hollender, F.	Evaluation of Deep Learning Phase Picking Models. **Parikh, N.**, Myren, S., Rael, R., Flynn, G., Casleton, E.
8:30 AM	Across-Slab Propagation and Low Stress Drops of Deep Earthquakes in the Kuril Subduction Zone. **Turner, A. R.**, Ferreira, A. M. G., Brantut, N., Faccenda, M., Kendall, E., *et al.*	Discriminating Collapses From Explosions and Earthquakes. **Walter, W. R.**, Pasyanos, M. E., Ichinose, G., Price, A., Pennington, C., *et al.*	Implications of Multi-Layer High-Vp/Vs Seafloor Sediments Characterized Using Passive Ocean Bottom Seismic Data: Toward Improving Crustal and Mantle Structure Analysis. **Kim, H.**, Kawakatsu, H., Akuhara, T., Takeuchi, N.	Beyond Site Response: On the Importance of Installation Depth on the Quality of Seismic Recordings - Example of Measurements Carried Out at Epos-France Seismological Network Stations. **Hollender, F.**, Iacobucci-Jund, H., Douste-Bacqué, I., Rischette, P., Buscetti, M., *et al.*	A Comparison of Machine Learning Methods of Association. **Pennington, C. N.**, McBrearty, I., Kong, Q., Walter, W. R.

Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom A/B*
	3D Wavefield Simulations: (continued)	**Illuminating Complex, Multiplet Earthquake (continued)**	**Detecting, Characterizing and Monitoring (continued)**	**Seismic Monitoring, Modelling (continued)**
8:45 AM	Toward High-Frequency Three-Dimensional Green's Function Databases. **Modrak, R. T.**, Kintner, J. A., Nelson, P., Gao, K., Zhou, R., *et al.*	Surface Expression of the Narlı and East Anatolian Fault Rupture Intersection in the 2023 M7.8 Pazarcık, Türkiye Earthquake. **DuRoss, C. B.**, Reitman, N. G., Hatem, A. E., Mason, H., Lavrentiadis, G., *et al.*	INVITED: STUDENT: Identification of Lahar Signals: A Supervised Learning Model Applied to Monitoring Data of Volcan De Fuego, Guatemala. **Bejar, G.**, Waite, G. P., Escobar-Wolf, R., Johnson, J. B., Bosa, A., *et al.*	Forecasting the Next Largest Earthquake During EGS Stimulations. **Grigoratos, I.**, Kwiatek, G., Wiemer, S.
9:00 AM	STUDENT: Iterative Global 3D Centroid Moment Tensor Inversions Using Stored Global Green Functions From Glad-M25. **Sawade, L.**, Ekström, G., Ding, L., Peter, D., Liu, Q., *et al.*	Seismic Analysis of the 2023 Earthquake Sequence in Southeast Türkiye: Insights From Mainshocks and Aftershocks. **Büyükakpınar, P.**, Petersen, G., Vera Sanhueza, F., Metz, M., Cesca, S., *et al.*	Lahar Early Warning at Volcano Santiaguito: A Classical and a Deep Learning Approach. **Jozinović, D.**, Massin, F., Roca, A., Clinton, J.	INVITED: Stress-Based Forecasting of Seismicity Induced by Geothermal Operations and CO2 Storage. **Avouac, J.**
9:15–10:30 AM	Poster Break			
	3D Wavefield Simulations: From Seismic Imaging to Ground Motion Modelling (see page 1201).	**Illuminating Complex, Multiplet Earthquake Sequences at Kahramanmaras (Turkiye), Herat (Afghanistan), and Beyond (see page 1318).**	**Detecting, Characterizing and Monitoring Mass Movements (see page 1262).**	**Seismic Monitoring, Modelling and Management Needed for Geothermal Energy and Geologic Carbon Storage (see page 1393).**
10:30 AM	SPECFEM++: A Modular and Portable Spectral-element Framework for Seismic Wave Propagation. **Kakodkar, R. R.**, Tromp, J.	High-Resolution Fault Imaging From Fault Zone Guided Waves Recorded by Dense Arrays in the Aftershock Zone of the 2023 Kahramanmaras Earthquake Sequence in Southern Türkiye. **Peng, Z.**, Mach, P. V., Ding, C., Yalvac, O., Sevim, F., *et al.*	STUDENT: Towards Building a Machine Learning Based Automatic Detection System for Surface Events in the Pacific Northwest. **Kharita, A.**	STUDENT: Factors Controlling Rate and Magnitudes of Induced Seismicity. **Kim, T.**, Avouac, J.

Time	*Tikahtnu Ballroom C*	*Tikahtnu Ballroom E/F*	*Tubughnenq' 3*	*Tubughnenq' 4*	*Tubughnenq' 5*
	Characteristics and Mechanics of Fault Zone (continued)	**Advancements in Forensic Seismology (continued)**	**Seismology in the Oceans: (continued)**	**From Earthquake Recordings (continued)**	**Network Seismology: (continued)**
8:45 AM	INVITED: Fault Zone Material Heterogeneities May Trigger Repeating Earthquakes in Kanto, Japan. **Huang, Y.**, Ide, S., Kato, A., Yoshida, K., Jiang, C.	Source Characterization and Uncertainty Quantification of the North Korean Nuclear Tests 2006-2017. **Alfaro-Diaz, R. A.**, Kintner, J. A., Phillips, S., Delbridge, B., Carmichael, J. D.	Estimating the Extent of Low-temperature Ductile Deformation in the Lithosphere Using Seismic Anisotropy Measurements Around the Alpine Fault. **Mark, H. F.**	STUDENT: Perturbations of Free-Field Seismic Recordings Caused by Soil-Structure Interaction, From the Effects of Buildings to the Impact of Coupling Slabs: Preliminary Results From Empirical Studies Carried Out in Greece. **Rischette, P.**, Hollender, F., Theodoulidis, N., Roumelioti, Z., Perron, V., *et al.*	STUDENT: A Comprehensive Earthquake Focal Mechanism Catalog for Nevada Obtained Through Deep Learning Algorithms. **Chatterjee, A.**, Srikar, G., Pennington, C. N., Walter, W. R., Trugman, D. T.
9:00 AM	The Alto Tiberina Near Fault Observatory: A State of Art Monitoring Infrastructure for Studying Earthquakes Faults and Preparatory Phases. **Chiaraluce, L.**	Regional Characterization of Natural and Anthropogenic Seismic Events for Monitoring Efforts With Machine Learning. **Barama, L.**, Kong, Q.	Crustal and Uppermost Mantle Structure North of the Gloria Fault Inferred From OBS-Recorded Surface Waves. Pinzon, J., **Custódio, S.**, Silveira, G., Krüger, F., João, M., *et al.*	INVITED: Seismic Station Installations and Their Impact on Recorded Signals and Derived Quantities. **Castellaro, S.**, Musinu, G., Alessandrini, G.	STUDENT: Deep Learning Enhanced Earthquake Catalog for Northern California. **McBrearty, I. W.**, Beroza, G. C.
9:15–10:30 AM	Poster Break				
	Characteristics and Mechanics of Fault Zone Rupture Processes, from Micro to Macro Scales (see page 1244).	**Advancements in Forensic Seismology and Explosion Monitoring (see page 1208).**	**Seismology in the Oceans: Pacific Hemisphere and Beyond (see page 1410).**	**From Earthquake Recordings to Empirical Ground-Motion Modelling (see page 1292).**	**Network Seismology: Recent Developments, Challenges and Lessons Learned (see page 1353).**
10:30 AM	Dynamic Rupture Simulations on the Alpine Fault, New Zealand: Investigating the Role of Fault Geometry on Rupture Size and Behavior Over Multiple Earthquake Cycles. **Lozos, J.**, Warren-Smith, E., Townend, J.	Source-Type Discrimination Using Phase and Amplitude Metrics Derived From Nonlinear Alignment Methods. **Ramos, M. D.**, Tibi, R., Emry, E. L., Young, C. J.	Overthickened Lithosphere Beneath the Blanco Transform Faults. **Bao, X.**, Dai, A., Yang, Y., Hu, J., Zhang, W.	Three Relational Databases in Support of Model Development for Earthquake Hazard Products. **Hearne, M. G.**, Cunningham, A. E., Knodel, E. J., Ambruz, N. B., Aagaard, B. T., *et al.*	An Agent Based Model to Quantify Gains in Network Processing. **Carmichael, J. D.**

Thursday, 2 May (*continued*)

Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom A/B*
	3D Wavefield Simulations (continued)	**Illuminating Complex, Multiplet Earthquake (continued)**	**Detecting, Characterizing and Monitoring Mass Movements (continued)**	**Seismic Monitoring, Modelling and Management (continued)**
10:45 AM	STUDENT: Forward Simulation of Air and Ground Vibration Induced by Series of Wind Turbines Using the Spectral-Element Method. **Fitzgerald, J.**, Wiboonwipa, N., Gharti, H., Braun, A.	Strong Ground Motion Characterization for the 6 February 2023 Mw 7.8 Pazarcık Earthquake in Kahramanmaraş, Türkiye. **Tang, Y.**, Şeşetyan, K., Mai, M.	Source Characterization of Surface Events in the Pacific Northwest. **Denolle, M. A.**, Skene, F., Smoczyk, N., Ni, Y., Kharita, A., *et al.*	How to Tame an Earthquake (Analogue). **Schultz, R.**
11:00 AM	Multiscale Rupture Modeling: Bridging Laboratory Acoustic Emissions and Earthquake Ground Motions. **Gu, C.**, Meng, C.	Conjugate Strike-Slip Faulting in the Truckee Basin of California, Northern Walker Lane. **Pierce, I. K. D.**, Koehler, R., Owen, L., Wesnousky, S., Figueiredo, P. M., *et al.*	Dissecting Seismic Signals to Estimate Landslide Volume. **Collins, E.**, Allstadt, K. E., Toney, L. D.	Picoseismic Response of Hectometer-Scale Fracture Systems to Stimulation With Cm-Scale Resolution Under the Swiss Alps, in the Bedretto Underground Laboratory. **Obermann, A.**, Rosskopf, M., Durand, V., Plenkers, K., Bröker, K., *et al.*
11:15 AM	Local Geological Changes and Simplicial Remeshing for Wave Propagation. **Cupillard, P.**, Caumon, G., Anquez, P., Legentil, C., Glinsky, N., *et al.*	How Often Do Subduction Interfaces and Overriding Upper-Plate Faults Rupture in the Same Earthquake (Or Close Enough in Time to Be the Same Situation)?. **Rollins, C.**, Penney, C. E., Howell, A., Fry, B., Nicol, A.	Radial Backprojection Imaging of Recent Mass Movements in Alaska. **Haney, M. M.**, Toney, L., Karasozen, E.	STUDENT: Characterization of Fracture Activation During EGS Stimulation Using Waveform Cross-Correlation: An Example Application at Utah Forge. **Asirifi, R.**
11:30 AM	3D Multiresolution Velocity Model Fusion With Probability Graphical Models. **Zhou, Z.**, Gerstoft, P., Olsen, K. B.	2021 and 2022 North Coast California Earthquake Sequences Light Up Gorda Plate Faults Beneath the North American Plate. **Hellweg, M.**, Dreger, D. S., Lomax, A., McPherson, R. C., Dengler, L. A.	Enhancing Real-Time Landslide Detection for Improved Tsunamigenic Landslides in Alaska. **Karasozen, E.**, West, M. E.	Circulation Experiments at Utah Forge: Post-Shut-in Fracture Growth Revealed by Limited Near-Surface Monitoring. **Niemz, P.**, McLennan, J., Pankow, K. L., Rutledge, J., England, K.
NOON–2:00 PM	Annual Business and Awards Luncheon			

Time	*Tikahtnu Ballroom C*	*Tikahtnu Ballroom E/F*	*Tubughnenq' 3*	*Tubughnenq' 4*	*Tubughnenq' 5*
	Characteristics and Mechanics of Fault Zone (continued)	**Advancements in Forensic Seismology (continued)**	**Seismology in the Oceans (continued)**	**From Earthquake Recordings (continued)**	**Network Seismology (continued)**
10:45 AM	Deformation Partitioning, Directivity Effects, and Stress-Drop of Seismicity Along the Main Marmara Fault Offshore Istanbul/Türkiye in the Light of an Overdue M7+ Earthquake. **Bohnhoff, M.**, Cheng, X., Martinez-Garzon, P., Becker, D., Kwiatek, G., *et al.*	Seismic Observations and Aftershock Analysis from a Fully Coupled Chemical Explosion in Layered Tuff. **Sprinkle, D.**, St. Clair, J., Chojnicki, K., Knox, H., Strickland, C., *et al.*	The Anelastic Fingerprint of Small-Scale Convection: Grain-Size Reduction in Pacific Asthenosphere Revealed by Regional Shear Attenuation. **Russell, J. B.**, Dalton, C., Havlin, C., Holtzman, B., Eilon, Z., *et al.*	A Magnitude Invariant Workflow for Automated End-to-End Ground Motion Processing. **Lavrentiadis, G.**, Shi, Y., Aday, K., Asimaki, D.	Seismology as a Service: Portable Product Generation at the Southern California Seismic Network Using Service-Oriented Architecture and Cloud Computing. **Yu, E. C.**, Tepp, G., Tam, R., Bhaskaran, A., Chen, S., *et al.*
11:00 AM	INVITED: Insight Into Depth Variations in Effective Stress and Fault Strength From Geodynamic-Seismic Cycle and Earthquake Dynamic Rupture Modeling. **Madden, E. H.**, Gabriel, A. A., Ulrich, T., van Dinther, Y., van Zelst, I.	Seismic Source Parameters and Scaling Relations for Microseismic Lower-Yield Military Explosive Events. **Milburn, T. W.**	An Ocean-Bottom View of Mantle Convection Beneath the Pacific Basin. **Gaherty, J.**, Eilon, Z., Russell, J., Phillips, J., Hariharan, A., *et al.*	STUDENT: Epistemic Uncertainty Associated to Parametric and Non-Parametric Git Results Related to Initial Parametrization and Target Region Dataset: Application on the Epos-France Database. **Buscetti, M.**, Traversa, P., Hollender, F., Perron, V.	NEIC Developments: Updates on the U.S. Geological Survey National Earthquake Information Center's Earthquake Monitoring Systems. **Patton, J.**, Guy, M., Earle, P., Yeck, W., Cole, H.
11:15 AM	Deep Slip Occurs Prior to Surface Creep Events on the San Andreas Fault. **Gittins, D. B.**, Hawthorne, J. C.	Discriminating S-Wave Polarization Angles of Explosive and Earthquake Sources. **Nelson, P.**, Creasy, N.	Deep Learning for Deep Earthquakes in Oceans: Insights From Obs Observations of the Tonga Subduction Zone. **Wei, S. S.**, Xi, Z., Zhu, W., Beroza, G. C., Jie, Y., *et al.*	Ground Motion Models Uncertainties and Variability: The Impact of Seismic Station Installation Conditions and Earthquake Catalog Quality. **Traversa, P.**, Buscetti, M., Arroucau, P., Kotha, S. R., Hollender, F., *et al.*	gCent: Geodetic Centroid Products for Earthquake Monitoring. **Barnhart, W.**
11:30 AM	Simulating the Formation and Evolution of Complex Fracture Patterns Arising From Shallow Strike-Slip Faulting With Finite and Discrete Element Analyses. **Baden, C. W.**, Nevitt, J. M., Garcia, F. E.	Simulations of Local Wave Propagation Effects on the Performance of P/s Source Discriminant. **Pitarka, A.**, Walter, W. R., Pyle, M.	Earthquakes and Slab Morphology in Southern Mariana and Yap Subduction Zones. **Yang, H.**, Zhu, G.	Earthquake Ground Motion Insights From the USGS Lake Almanor, California, Aftershock Nodal Array Deployment. **Parker, G. A.**, Baltay, A. S., Hirakawa, E. T., Catchings, R. D., Goldman, M. R., *et al.*	Overcoming Challenges in Near-Field Seismic Velocity Estimation: Insights from continuos GPS and Strong Motion Data. **Riquelme, S.**, Crempien, J., Koch, P.
NOON–2:00 PM	Annual Business and Awards Luncheon				

Thursday, 2 May (*continued*)

Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom A/B*
	3D Wavefield Simulations: From Seismic Imaging to Ground Motion Modelling (see page 1201).	**Six Decades of Tsunami Science: From the Source of the 1964 Tsunami to Modern Community Preparedness (see page 1415).**	**Detecting, Characterizing and Monitoring Mass Movements (see page 1262).**	**Seismic Monitoring, Modelling and Management Needed for Geothermal Energy and Geologic Carbon Storage (see page 1393).**
2:00 PM	Multi-Scale Seismic Imaging of Fault-Zone Structures in Southern California With Full-Waveform Inversions of Regional and Dense Array Data. **Li, G.**, Ben-Zion, Y.	INVITED: The 2021 Antarctic (South Sandwich) Tsunami as Recorded in the North Pacific. **Rabinovich, A. B.**, Tsukanova, E., Thomson, R. E.	Seismic Collapse Mechanisms of Large (M~4) Rock and Ice Avalanches in Southeast Alaska. **Alvizuri, C.**, Rupper, N., Karasozen, E.	Geophysical Monitoring for Feeding Decision Support Tools: The Crucial Role of Uncertainty for a Sound Management of Induced Seismicity. **Garcia, A.**, Zaheer, A., Faenza, L., Danesi, S., Braun, T., *et al.*
2:15 PM	INVITED: STUDENT: Global Source-Encoded Waveform Inversion: Preliminary Results. **Cui, C.**, Bachmann, E., Tromp, J.	INVITED: Re-evaluating Global Threat of Tsunamis Generated by Air-pressure Waves from Volcano Explosions. **Titov, V.**	The Seismic Puzzles of the 2022 Chaos Canyon Landslide in Rocky Mountain National Park. **Allstadt, K.**, Coe, J., Collins, E., Rengers, F., Mangeney, A., *et al.*	B-Positive for Induced Seismicity Catalogs With Time-Varying Incompleteness? Proceed With Caution. **Muntendam-Bos, A. G.**
2:30 PM	STUDENT: LLNLGlobeFWI Analysing Alpine Fault Earthquakes: First Iterations Using a Semi-Automatic FWI Framework Applied to the Globe With Spiral as the Starting Model. **Vazquez, L.**, Morency, C., Simmons, N. A.	Multi-Scale Geophysical Characterization and Tsunami Modeling of Active Listric Normal Faults Offshore Grays Harbor, Wa. **Watt, J.**, Geist, E., La Selle, S., Hill, J.	New Insights on the Åknes Rockslide (Norway) Using Borehole Microseismic Data. **Langet, N.**, Oye, V., Grøvan Aspaas, A., Lacroix, P., Renard, F.	Heimdall: A Graph-Based Seismic Detector and Locator for Microseismicity. **Bagagli, M.**, Grigoli, F., Bacciu, D.
2:45 PM	Homogenized Full Waveform Inversion : Application to Earth Model for Long Period Seismic Waves. **Colvez, M.**, Burgos, G., Capdeville, Y., Guillot, L.	Real-Time Prediction of Tsunami Amplitude Using Gaussian Process Regression. **Nichols, T.**	How Do Slow-moving Landslides Maintain Steady Motion?. **Xu, Y.**, Bürgmann, R., Bilham, R.	STUDENT: Characterizing Subsurface Structures for Geologic Carbon Storage at Iron Mountain in Utah. **Li, D.**, Huang, L., Gao, K., Chen, B., Zheng, Y., *et al.*

Time	*Tikahtnu Ballroom C*	*Tikahtnu Ballroom E/F*	*Tubughnenq' 3*	*Tubughnenq' 4*	*Tubughnenq' 5*
	Regional-Scale Hazard, Risk and Loss Assessments (see page 1382).	**Advancements in Forensic Seismology and Explosion Monitoring (see page 1208).**	**Multidisciplinary Approaches for Volcanic Eruption Forecasting (see page 1348).**	**From Earthquake Recordings to Empirical Ground-Motion Modelling (see page 1292).**	**Network Seismology: Recent Developments, Challenges and Lessons Learned (see page 1353).**
2:00 PM	Development of a Physics-Guided Non-Ergodic Ground Motion Model for the Groningen, Netherlands Region. **Lavrentiadis, G.**, Oral, E., Aday, K., Asimaki, D.	Moment Tensor Inversion and Its Uncertainty from Green's Functions with Different Algorithms. **Zhou, R.**, Saikia, C. K., Roman-Nieves, J., VanDeMark, T. F.	INVITED: STUDENT: Fracture Insights and Predicting Failures: Acoustic Emission Study in Peteroa Volcano's Basalt Rock. **Vesga-Ramírez, A.**, Zitto, M. E., Filipussi, D., Camilión, E., Piotrkowski, R., *et al.*	Ground Motion and Entropy. **Clements, T.**, Cochran, E., Baltay, A. S., Minson, S., Yoon, C.	STUDENT: Precision and Accuracy of Earthquake Locators: Insights From a Synthetic 2019 Ridgecrest Sequence Experiment. **Yu, Y.**, Ellsworth, W. L., Beroza, G. C.
2:15 PM	Developing a Data-centric Workflow for Seismic Source Model Construction and Testing. **Styron, R. H.**, Pagani, M., Johnson, K. E., Bayliss, K.	Physics Experiment 1: Chemical Explosive, Gas Tracer, Electromagnetic, and Atmospheric Experiments for Improved Monitoring of Nuclear-Explosive Testing. **Myers, S.**, Foxe, M., Dzenitis, B., Knox, H., Cari Seifert, C., *et al.*	Small Earthquakes Matter for Triggering Volcanic Unrest. **Gomberg, J.**, Prejean, S., Taveras, O., Bodin, P., Pacheco, J., *et al.*	Comparisons of Recent Prediction Models of Ground-Motion and Seismic Duration for Mexican Interplate and Intraslab Earthquakes Including the Vertical Component and V/H Ratios. **García-Soto, A.**, Jaimes, M.	Improving Shear-Arrival Time Estimates for Real-Time Association and Location Algorithms. **Baker, B.**, Armstrong, A. D., Pankow, K. L.
2:30 PM	INVITED: Developing Software to Assess the Seismic Risk of Natural Gas Infrastructure: OpenSRA. Zheng, B., **Largent, M.**, Watson-Lamprey, J., Bray, J., Abrahamson, N. A., *et al.*	Seismo-Acoustic Signals From an Accidental Chemical Explosion in South Korea. **Park, J.**, Arrowsmith, S., Che, I., Hayward, C., Stump, B.	Toward Unbiased Volcano-Seismic Monitoring: Leveraging Weakly Supervised Learning for Comprehensive Insights. **Titos, M.**, Benítez, M., Carthy, J., Ibáñez, J.	Using Proxies Obtained From Horizontal-to-Vertical Spectral Ratio to Reduce the Epistemic Uncertainty in Ground Motion Models. **Yazdi, M.**, Anderson, J. G., Motamed, R.	Comparing Three-Dimensional Seismic Velocity Models for Location Accuracy. **Begnaud, M.**, Conley, A., Davenport, K., Porritt, R., Ballard, S., *et al.*
2:45 PM	INVITED: Addressing Challenges in Regional Seismic Risk Assessments in British Columbia: M9 Cascadia Subduction Zone Earthquakes, Deep Sedimentary Basin Amplification and Non-Ductile Reinforced Concrete Shear Wall Buildings. **Molina Hutt, C.**, Kakoty, P.	Estimating Crustal Velocity Structure in Alaska From Acoustic-to-Seismic Coupling From the 2022 Hunga Eruption, Tonga. **Macpherson, K. A.**, Fee, D., Coffey, J. R., Awender, S., Chow, B., *et al.*	Volcanic Eruption Forecasts Through Seismic Data Assimilation: The 2023 Paroxysms of Shishaldin Volcano, Alaska. **Girona, T.**, Haney, M. M., Fee, D., Power, J.	Are Ground Motions Different for Aftershocks or Earthquakes Doublets?. **Baltay, A. S.**, Parker, G. A., Abrahamson, N. A., Hanks, T. C.	Regionalization of ML and Its Relation to Mw. **Herrmann, R. B.**, Benz, H. M.

Thursday, 2 May (*continued*)

Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom A/B*
	3D Wavefield Simulations (continued)	**Six Decades of Tsunami Science (continued)**	**Detecting, Characterizing and Monitoring (continued)**	**Seismic Monitoring, Modelling and Management (continued)**
3:00 PM	Adjoint-State Traveltime Tomography (tomoatt.com). **Tong, P.**, Chen, J., Nagaso, M., Hao, S., Xu, M.	A Behavioral Theory Framework for Tsunami Preparedness. **Grant Ludwig, L.**	Big Tsunamis in Little Lakes. **Higman, B.**, Karasozen, E., Geertsema, M., Schwartz, S.	3D Fault Detection on a Seismic Migration Image at the Lightning Dock Geothermal Area. **Huang, L.**, Wu, B., Gao, K., Li, D., Zheng, Y., *et al.*
3:15– 4:30 PM	Poster Break			
Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom C*
	Applications and Discoveries in Cryoseismology Across Spatial and Temporal Scales (see page 1235).	**Special Applications in Seismology (see page 1420).**	**New Insights into the Development, Testing and Communication of Seismicity Forecasts (see page 1367).**	**Regional-Scale Hazard, Risk and Loss Assessments (see page 1382).**
4:30 PM	STUDENT: Integrated Geophysical and Temperature Sensing Techniques Towards Scalable Monitoring of Permafrost Variability in Utqiaġvik, AK. **Tourei, A.**, Ji, X., Martin, E. R., Xiao, M., Rocha dos Santos, G. F., *et al.*	STUDENT: Receiver Functions in the Los Angeles Basin. **Villa, V.**, Clayton, R., Gkogkas, K., Lin, F.	INVITED: Testing Rate-and-State Predictions of Aftershock Decay. **Page, M.**, van der Elst, N., Felzer, K.	Probabilistic Approach for Site Response Analysis and Seismic Microzonation. **Ansal, A.**
4:45 PM	STUDENT: Observations From an Active Seismic Distributed Acoustic Sensing Survey, Combatant Col, British Columbia. **Manos, J. M.**, Lipovsky, B., Gräff, D.	Resolving the Structure of the Los Angeles Basin Through High-Resolution Seismic Tomography. **Biondi, E.**, Li, J., Clayton, R., Zhan, Z.	Time-Dependent Earthquake Forecasts With Pre-Existing Populations of Faults: Application to the Groningen Gas Field, the Netherland. **Dahm, T.**, Hainzl, S.	STUDENT: Analysis of Shakemap Residuals for Spatially Variable Site Terms. **Cunningham, A. E.**, Knodel, E. J., Hearne, M. G., Thompson, E. M., Worden, C. B., *et al.*
5:00 PM	Plucking Base Notes: Seismic Character of a Potential Glacial Quarrying Event at Saskatchewan Glacier, Canadian Rocky Mountains. **Stevens, N. T.**, Hansen, D. D., Zoet, L. K., Alley, R. B.	STUDENT: Upper-Plate Seismicity and Focal Mechanism for Studying the Stress State in the Mendocino Triple Junction. **Islam, M.**, Gong, J.	What Drives the Variability in Earthquake Sequence Productivity in California and Nevada?. **Trugman, D. T.**, Ben-Zion, Y.	Regionalized Earthquake Source Models of Subduction Interface Earthquakes. **Skarlatoudis, A.**, Thio, H. K., Somerville, P., Ahdi, S. K., Condon, S.

Time	Tikahtnu Ballroom C	Tikahtnu Ballroom E/F	Tubughnenq' 3	Tubughnenq' 4	Tubughnenq' 5
	Regional-Scale Hazard, Risk and Loss (continued)	**Advancements in Forensic Seismology (continued)**	**Multidisciplinary Approaches for (continued)**	**From Earthquake Recordings to (continued)**	**Network Seismology: Recent (continued)**
3:00 PM	Using Comparative Subductology to Constrain Future Subduction Zone Earthquake Losses. **Wald, D. J.**, Hayes, G., Haynie, K. L., Jaiswal, K. S., Marano, K.	Detection of Seismic and Acoustic Signals With Serial Network Data Fusion: Demonstration Against Atmospheric Explosions. **Carmichael, J. D.**, Alfaro Diaz, R., Light, T., Blom, P., Gammans, C., *et al.*	Source Mechanism and Catalog Statistics for the Last Decade of Seismicity at the Campi Flegrei Volcanic Complex, Italy. **Saccorotti, G.**, Bianco, F., Chiarabba, C., Piccinin i, D.	Why Did the Pulse-Like Ground-Motion Differ Three Times in Pgv and Tp Within a 3 Km Wide Near-Fault Region of the 2023 Mw 7.8 Turkiye Earthquake?. **Huang, J.**, Sung, C., Kuo, C., Lin, C.	Noisy Stations Make Earthquake Magnitudes Larger. **Ringler, A.**, Ambruz, N. B., Earle, P., Kragness, D., Shelly, D., *et al.*
3:15– 4:30 PM	Poster Break				

Time	Tikahtnu Ballroom E/F	Tubughnenq' 3	Tubughnenq' 4	Tubughnenq' 5
	Advancements in Forensic Seismology and Explosion Monitoring (see page 1208).	**Multidisciplinary Approaches for Volcanic Eruption Forecasting (see page 1348).**	**Leveraging Cutting-Edge Cyberinfrastructure for Large Scale Data Analysis and Education (see page 1339).**	**Cordilleran Strike-Slip Faults as Seismogenic and Seismological Features (see page 1249).**
4:30 PM	Surface-to-Space Acoustic Propagation Model Validation Using Chemical Explosion Sources: The DARPA AtmoSense AIRWaveS Project. Nayak, M., Snively, J. B., Sabatini, R., **Bowman, D. C.**, Egan, S.	Resonance in the Earth's Crust as a Generation Mechanism of Very-Long-Period Volcanic Tremor. **Xia, Y.**, Feng, X., Chen, X.	INVITED: Advancing USGS Scientific Modeling Through Cloud Computing. **Haynie, K. L.**, Hunsinger, H., Martinez, E., Brito Silveria, L., Cassidy, K., *et al.*	STUDENT: Is the Rocky Mountain—Tintina Trench Tectonically Active?. **Finley, T.**, Nissen, E., Cassidy, J., Leonard, L., Sethanant, I., *et al.*
4:45 PM	Solid/atmosphere Moment Partitioning in Hypervelocity Impacts on Mars From Seis Recorded Seismic and Acoustic Signals and High Resolution Crater Imaging. **Lognonné, P. H.**, Bill, C., Collins, G. S., Daubar, I. J., Kim, D., *et al.*	Volcanic Eruption Forecasting Using Shannon Entropy: 2021 Tajogaite Eruption (Spain). Rey-Devesa, P., Carthy, J., Titos, M., Benítez, C., D'Auria, L., **Prudencio, J.** *et al.*	STUDENT: Parallel Processing of Large Seismic Data Sets With Mspass. **Wang, C.**, Wang, Y., Pavlis, G. L., Mohapatra, S., Ma, J.	Evolution of Subsidiary Faults Associated With the Migration of the Mount Mckinley Restraining Bend, Denali Fault, Alaska. **Bemis, S. P.**, Benowitz, J. A., Goehring, B. M., Priddy, M. S., Terhune, P. J.
5:00 PM	End-to-End Numerical Simulation of Explosion Cavity Creation, Cavity Circulation Processes, Subsurface Gas Transport, and Prompt Atmospheric Releases. **Ezzedine, S. M.**, Velsko, C., Vorobiev, O.	Automated Identification and Characterization of Very Long-Period Seismic Events for Applications in Monitoring Volcanic Activities. **Gammaldi, S.**, Delle Donne, D., Cantiello, P., Bobbio, A., De Cesare, W., *et al.*	Enabling Large Data Analysis on the Earthscope Data Repositories. Trabant, C., **Dittmann, T.**, Bravo, T. K., Weekly, R. T., Johnson, S., *et al.*	Residual Yakutat Microplate Velocity Drives Rapid Thrust Faulting North of the Central Denali Fault. **Bender, A. M.**, Lease, R. O., Rittenour, T.

Thursday, 2 May (*continued*)

Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom C*
	Applications and Discoveries (continued)	**Special Applications in Seismology (continued)**	**New Insights into the Development, Testing (continued)**	**Advancements in Forensic Seismology (continued)**
5:15 PM	Ross Ice Shelf Lamb Wave Propagation and Permanent Displacement Induced by Whillans Ice Stream Slip Events. **Wiens, D. A.**, Aster, R. C., Nyblade, A. A., Bromirski, P. D., Gerstoft, P., *et al.*	STUDENT: Complex Deformation of the Northern Deep Tonga Slab. **Williams, A.**, Wiens, D. A., Bergman, E. A.	INVITED: STUDENT: Modernizing Earthquake Forecasts Testing and Experimentation: CSEP Open-Software Contributions. **Iturrieta, P.**, Maechling, P. J., Savran, W. H., Bayona, J., Silva, F., *et al.*	STUDENT: Region-Specific Geospatial Liquefaction Model for Alaska by Bayesian Model Updating of the Global Liquefaction Model. **Shirzadi, H.**, Asadi, A., Baise, L. G., Moaveni, B.
5:30 PM	Seismology at South Pole, Antarctica: History and Future Opportunities. **Anthony, R. E.**, DuVernois, M., Aster, R. C., Bainbridge, G., Braun, J., *et al.*	Using Machine Learning Algorithms to Explore the Seismoacoustic Wavefield at an Industrial Facility. **Chai, C.**, Marcillo, O., Maceira, M., Park, J., Arrowsmith, S., *et al.*	Operational Earthquake Forecasting in Japan: A Study of Municipal Government Planning for an Earthquake Advisory or Warning in the Nankai Region. **Goltz, J. D.**, Yamori, K., Nakayachi, K., Shiroshita, H., Sugiyama, T., *et al.*	A Regional Earthquake-Triggered Landslide Susceptibility Map of the Cook Inlet Region, Southcentral Alaska. **Ellison, S. M.**, Allstadt, K. E., Thompson, E. M., Martinez, S. N.
6:00–8:00 PM	Joyner Lecture and Reception			

Poster Sessions

Earth's Structure from the Crust to the Core [Poster Session] **(see page 1271).**

1. Cenozoic Uplift and Volcanism of Hangai Dome, Central Mongolia Triggered by Lower Mantle Upwellings. **Bao, X.**, Wu, Y.
2. Single-Station Teleseismic Data Analysis and Structure Imaging on Both Earth and Mars. **Chen, L.**, Wang, X., Wang, X., Yang, R.
3. STUDENT: Full-Waveform Inversion of the Upper Mantle Beneath the Arabia-Eurasia Collision Zone. **Clennett, E. J.**, Liu, C., Grand, S. P., Becker, T. W.
4. STUDENT: Finite Difference Approach to Seismic Wavefield Modeling Across the Hawaii-Emperor Ridge. **Fujimoto, M.**, Dunn, R.
5. STUDENT: Global Shear-Wave Amplitude Observations using Full Waveform Modeling. **Ghosh, A.**, Bozdag, E., Ritsema, J.
6. Building a Community Velocity Model for the Cascadia Region and Beyond. **Hooft, E.**, Delph, J. R., Grant, A., Sahakian, V. J., Share, P., *et al.*
7. STUDENT: Complex Upper Mantle Flow Beneath the Southern Korean Peninsula Constrained by Shear Wave Splitting and Numerical Mantle Convection Simulation. **Jo, K.**, Song, J., Kim, S.
8. Advancing the Resolution of Mid-Mantle Structures: Full-Waveform Box Tomography of the Yellowstone Mantle Plume. **Kumar, U.**, Lyu, C., Munch, F., Romanowicz, B.
9. STUDENT: Imaging the Deformation Belt of Western Hispaniola Using Multi-Component Ambient Noise Cross-Correlations. **Lee, H.**, Rabade, S., Lin, F., Douilly, R.
10. STUDENT: The Crust was Strengthened or Weakened After Mantle Plume: Evidence from Tarim Basin. **Li, W.**, Wang, X., Liang, X., Zuo, S., Shilin, L., *et al.*
11. Using Multiple Voronoi Partitions to Conduct Array-Based Ambient Noise Surface Wave Imaging. **Li, Z.**, Dong, S., Shi, C., Chen, X.
12. Challenges and Triumphs Seismic Surveying in a Historic Underground Metals Mine. **McBride, J.**, Lambeck, L., Rey, K. A., Nelson, S. T., Keach, II, R.
13. Searching for Blind Faults Beneath Metropolitan Los Angeles: Preliminary Results From the 2023 San Fernando Valley Array. **Persaud, P.**, Juarez-Zuniga, A., Clayton, R.

Time	Tikahtnu Ballroom E/F	Tubughnenq' 3	Tubughnenq' 4	Tubughnenq' 5
	Advancements in Forensic Seismology (continued)	**Multidisciplinary Approaches for Volcanic (continued)**	**Leveraging Cutting-Edge (continued).**	**Cordilleran Strike-Slip Faults as (continued)**
5:15 PM	Joint Inversion of Body and Surface Waves at the Rock Valley Direct Comparison (Nevada) Study Site. **Syracuse, E. M.**, Rowe, C., Li, D., Ranasinghe, N.	Volcanic Eruption Forecasts Through Seismic Pattern Recognition: The 2023 Paroxysms of Shishaldin Volcano, Alaska. **Girona, T.**, Burgos, V.	STUDENT: Exploring the Impact of Lossy Compression on Passive Seismic Event Detection and Arrival Time Precision. **Issah, A. S.**, Martin, E. R.	Seismic Imaging of the Eastern Alaska Range Crustal Structure. **Miller, M. S.**, Zhang, P., Pickle, R., Waldien, T. S., Roeske, S.
5:30 PM	Joint Inversion Using Waveform, First-motion Polarities and InSAR Deformation for the 2007 Crandall Canyon Mine Collapse, Utah. **Chi-Durán, R.**, Dreger, D. S., Rodgers, A., Lindsay, D.	Enhancing Eruption Forecasting at Axial Seamount With Real-Time, Machine Learning-Based Seismic Monitoring. **Wang, K.**, Waldhauser, F., Schaff, D., Tolstoy, M., Wilcock, W., *et al.*	INVITED: Towards End-to-End Earthquake Monitoring Using a Multitask Deep Learning Model. **Zhu, W.**	INVITED: STUDENT: The Crustal Magmatic Structure Beneath the Denali Volcanic Gap in Central Alaska Across the Denali Fault. **Rabade, S.**, Lin, F., Tape, C., Ward, K. M., Allam, A.
6:00–8:00 PM	Joyner Lecture and Reception			

14. STUDENT: Receiver Function Inversion at Erebus Volcano, Antarctica, With Multi-Station Weighting. **Reisinger, R.**, Chaput, J., Aster, R. C., Grapenthin, R.
15. Shallow Imaging of the Valles of Caldera, Northern New Mexico: Preliminary Results From Ambient Noise Tomography. **Rodriguez, E. E.**, Donahue, C., Roberts, P. M., Maier, N.
16. STUDENT: Lithospheric Modification in Northeastern Alaska Interpreted From Full-Wave Ambient Noise Tomography. **Sassard, V.**, Yang, X., Ridgway, K. D., Flesch, L. M.
17. High-Resolution Moho Depth Mapping Beneath the Italian Peninsula and Carpatho-Pannonian Region Using P-Wave Coda Autocorrelation. **Thapa, H. R.**, Vlahovic, G.
18. Shallow Seismic Structure of the Canary Islands Using Local Earthquakes Recorded on an Amphibious Seismic Network. **Villasenor, A.**, Díaz-Suárez, E. A., del Fresno, C., Domínguez-Cerdeña, I., Dannowski, A., *et al.*
19. STUDENT: Slab Morphology and Mantle Wedge Processes in the Tonga Subduction Zone Revealed by Body-wave Double-difference Tomography. **Wang, F.**, Wei, S., Wiens, D. A., Adams, A.
20. Direct Inversion of Ambient Noise Multi-Modal Surface Wave Dispersions for 3D Velocity Structures. **Zhang, G.**, Yu, C., Chen, X.
21. S-Wave Seismic Data Interpretation for Channel Sand Reservoir at Sanhu Area, West China. **Zhang, R.**
22. Multi-Scale, Finite-Frequency Body Wave Tomography With Relative Kernels. **Ben Mansour, W.**, Wiens, D., Maupin, V.

Seismology in the Oceans: Pacific Hemisphere and Beyond [Poster Session] **(see page 1413).**

23. Upper Mantle Velocity Structure Beneath the Galapagos Archipelagos From the Analysis of Pn Wave Recorded by Broadband Seismic Instruments and Mermaids. **Ben Mansour, W.**, Nolet, G.
24. Seismic Structure of the Young Oceanic Cocos Plate From the Ridge to the Trench Axis Offshore the Mexico Subduction Zone. **Bécel, A.**, Hagemeier, D., Acquisto, T., Cruz-Atienza, V. M., Boston, B., *et al.*
25. STUDENT: Adjoint Waveform Tomography of the Cascadia Subduction Zone Using CASIE21 Controlled-Source Data. **Brunsvik, B. R.**, Miller, N., Eilon, Z., Jian, H., Canales, J.

26. Student: Seismicity of the Atlantis Massif Oceanic Core Complex: 2005-2006 OBS Data Revisit. **Dewaelsche, P.**, Gong, J.
27. Student: P-Wave Anisotropic Velocity Model of the Galápagos Plume. **Hufstetler, R. S.**, Hooft, E. E. E., Toomey, D. R., VanderBeek, B. P.
28. Shear Wave Velocity Structure of the Upper Mantle Beneath the Oldest Pacific Seafloor Revealed by Finite-Frequency Traveltime Tomography. **Kim, Y.**, Kang, H., Hung, S., Lin, P., Isse, T., *et al.*
29. A New 3D Reference Velocity Model for Offshore Cascadia Based on CASIE21 Data. **Miller, N.**, Canales, J., Carbotte, S., Han, S., Boston, B.
30. Student: Seismicity Observation in the Oldest Pacific Plate Using Pacific Array (Oldest-1) Data. **Park, J.**, Kim, Y., Isse, T., Kim, K., Shiobara, H., *et al.*
31. The Upflow Experiment: Data Report for 49 Ocean Bottom Seismometer Deployment in the Azores-Madeira-Canaries Region, Atlantic Ocean. Tsekhmistrenko, M., Ferreira, A., Miranda, M., **Tilmann, F.**, Harris, K., *et al.*
32. Using Deep Learning Algorithms to Study Seismicity Changes Preceding and Following the 2021 Central Hikurangi Slow Slip Event, New Zealand. Kwong, S., Savage, M. K., **Warren-Smith, E.**, Jacobs, K., Wallace, L., *et al.*

Leveraging Cutting-Edge Cyberinfrastructure for Large Scale Data Analysis and Education [Poster Session] **(see page 1340).**

33. SCOPED Update: A Cloud and HPC Software Platform for Computational Seismology. **Denolle, M. A.**, Tape, C., Wang, Y., Bozdag, E., Waldhauser, F., *et al.*
34. Updates to the U.S. Geological Survey's Product Distribution Layer and Impacts on Comcat and Realtime Systems. **Hunsinger, H.**, Martinez, E., Brown, J., Cloutet, Z., Haynie, K., *et al.*
35. Alaska Earthquake Center's Workforce Development Program Takes Shape. **Nadin, E. S.**, Low, G., West, M. E., Mohler, M., Parcheta, C.
36. Cloud-Based Gnss Processing Pipeline for the Shakealert Earthquake Early Warning System. **Ronan, T.**, Hamilton, A., Sievers, C., Dittmann, T., Berglund, H., *et al.*
37. Student: Deep Implicit Time Series Modeling for Earthquake Phase Picking on Edge Devices. **Tsai, A.**, Chuang, L., Peng, Z., El Ghaoui, L.
38. Using Learning Analytics to Evaluate the Instructional Design and Student Performance in a Large-Enrollment Scientific Computing Workshop. Haberli, G., **Brudzinski, M. R.**, Hubenthal, M.

New Insights into the Development, Testing and Communication of Seismicity Forecasts [Poster Session] **(see page 1368).**

39. The Pattern of Earthquake Magnitude Clustering Based on Interevent Distance and Time. Gossett, D., **Brudzinski, M. R.**, Xiong, Q., Hampton, J.
40. ETAS-positive: An Epidemic-Type Aftershock Model That Is Insensitive to Catalog Incompleteness. **van der Elst, N.**
41. Correlations of Deep Low-Frequency and Crustal Earthquake Activity in Parkfield, Ca, and Implications for Their Joint Use in Forecasting Frameworks. **Farge, G.**, Dascher-Cousineau, K., Brodsky, E.
42. Stress Shadows: Insights into Physical Models of Aftershock Triggering. **Hardebeck, J.**, Harris, R. A.
43. The Generalized Long-Term Fault Memory Model and Applications to Paleoseismic Records. **Neely, J. S.**, Salditch, L., Spencer, B. D., Stein, S.
44. Prototyping Aftershock Forecast Maps and Products Based on User Needs. **Schneider, M.**, Artigas, B.
45. Observations of the Aftershock Sequences of Intermediate-Depth Earthquakes Beneath Japan. **Warren, L. M.**, Igarashi, T., Kato, A.

Multidisciplinary Approaches for Volcanic Eruption Forecasting [Poster Session] **(see page 1350).**

46. Information Theory in the Context of Volcano Seismic Singals for Forecasting Purposes. **Benítez, M.**, Rey-Devesa, P., Prudencio, J., Marcelino, M., Ibáñez, J.
47. Student: Unraveling Dynamical Influences on Volcanic Structures Through Seismic Signatures. **Brenot, L.**, Caudron, C., Girona, T., Lecocq, T., Yates, A., *et al.*
48. Simulating Ground Deformation From Magma Migration Utilizing a Dipole Source. **Cannavo', F.**
49. Surface-Wave Relocation and Characterization of the October 2023 Izu Islands, Japan Earthquake Swarm. **Deane, C. A.**, Earle, P., Pesicek, J. D., Prejean, S. G., Shelly, D. R., *et al.*
50. The Relationship Between a 2022-2023 Magmatic Intrusion at Aniakchak Caldera and the 2021 m8.2 Chignik Earthquake, Alaska. **Grapenthin, R.**, Parameswaran, R., Angarita, M., Shreve, T., Cheng, Y., *et al.*
51. Student: Characterization of the Onset of the 2021 Great Sitkin Dome-Building Eruption Through the Trans-Dimensional Bayesian Inversion of LP Seismicity. **Kim, K.**, Girona, T., Anderson, K.
52. How Is Differential Shannon Entropy Related to Volcanic Processes?. Rey-Devesa, P., Girona, T., **Prudencio, J.**, Ibáñez, J., Benitez, C.

53. Student: Systematic Investigation and Comparison of the 2018 and 2020 Kīlauea Volcano Eruptions Based on Ambient Seismic Noise Analysis. **Vinarski, E.**, Lin, G.
54. Real-Time Seismic Estimation of Vei: Improving Reduced Displacement & Introducing the Mvo Energy Magnitude Scale. **Thompson, G.**, McNutt, S. R., Rodriguez Cardozo, F. R.

Detecting, Characterizing and Monitoring Mass Movements [Poster Session] **(see page 1265).**

55. The MVO Rockfall Location System 24 Years On: Reimplementation, and Re-Analysis of Pyroclastic Flow Trajectories. **Thompson, G.**
56. Using Infrasound to Detect Snow Avalanches and Inform Forecasts in Alaska. **Albert, S. A.**, Fleigle, M. J., Schaible, L. P.
57. Deep Transfer Learning Framework for Regional Landslide Mapping Using Post-Event Imagery. **Asadi, A.**, Baise, L. G., Chatterjee, S., Koch, M., Moaveni, B.
58. Student: Quantifying Seismic Properties of a River Channel at Mount Rainier for Use in Debris-Flow Monitoring and Analysis. **Conner, A. E.**, Thomas, A. M., Allstadt, K. E., Collins, E., Thelen, W. A.
59. Student: Investigating Seismic Signals From the Barry Arm Landslide. **Davy, G. K.**, Karasozen, E., West, M. E., Lyons, J.
60. Seismology Versus Infrasound: Which Monitoring Technique Is Better for Detecting Advancing Lahars?. Roca, A., Pineda, A., **Johnson, J.**, Mock, J., Bejar, G., *et al.*
61. Student: Repeated Seismicity Conditions Paraglacial Valleys for Slope Failure in Prince William Sound, Alaska. **McCreary, M. E.**, Moore, J., Jensen, E., Gischig, V.
62. Student: Optimizing Landslide Detection and Validation Through Sentinel-1 Radar Imagery: Case Studies of Hokkaido and Hiroshima in Japan. **Thapa, M.**, Jiang, J., Regmi, N.
63. Student: Landslide Susceptibility Assessment Using Earthquake Ground Motion for Different Return Periods in Rasuwa District, Central Nepal. **Thapa, M.**, Pradhan, A. M. S., Chamlagain, D., Jiang, J., Regmi, N.
64. [Un]supervised Clustering of [Non-]Earthquake Signals Commonly Recorded on Regional Seismic Networks. **Toney, L.**, Allstadt, K., Collins, E., Yeck, W.
65. Seismically-Derived Ground Tilt From Rainfall-Triggered Lahars at Volcán De Fuego, Guatemala. **Waite, G. P.**, Bejar, G., Johnson, J. B., Escobar-Wolf, R., Roca, A., *et al.*
66. The September 16, 2023 Greenland Event: Mysterious Days-Long Monochromatic Very Long-Period Signal Triggered by a Landslide. Carrillo-Ponce, A., Petersen, G., Cesca, S., Heimann, S., Walter, T., **Dahm, T.,** *et al.*

Illuminating Complex, Multiplet Earthquake Sequences at Kahramanmaras (Turkiye), Herat (Afghanistan), and Beyond [Poster Session] **(see page 1320).**

67. Coulomb Stress Variation and Frictional Properties Control Postseismic Fault Slip and Late Aftershocks of the 2022 Zagros Earthquake Sequences: Deductions From Bayesian Inference and Insar Observations. Zhao, X., **Dahm, T.**, Vasyara-Bathke, H., Xu, C.
68. Rupture History and Elastic Interaction of the 2022 Multiple Earthquakes in the Zagros Mountains, Iran. Metz, M., Asayesh, B., Aref, M., Jamalreyhani, M., **Büyükakpınar, P.**, *et al.*
69. Nodal Seismometer Array Recordings of Aftershocks of the 6 February 2023 Mw 7.8 and Mw 7.6 Kahramanmaraş, Turkiye Earthquake Sequence. **Catchings, R. D.**, Celebi, M. K., Goldman, M. R., Chan, J. H., Sickler, R. R., *et al.*
70. Student: High-Resolution Three-Month Aftershock Catalog using Nodal Stations of the 2023 Kahramanmaraş Earthquake Sequence in Southeastern Türkiye. **Mach, P. V.**, Peng, Z., Sandvol, E., Ergin, M., Zor, E., *et al.*
71. Investigating the Türkiye-Syria and Afghanistan 2023 Seismic Sequences. **Svigkas, N.**, Atzori, S., Striano, P., Bonano, M., Vavlas, N., *et al.*
72. Measuring Afterslip From the February 2023 Mw 7.8 Pazarcık Earthquake Using Optical Images and Radar Data. **Tan, M.**, Reitman, N., Burgi, P. M., Briggs, R.
73. Student: Decoding the Rupture Kinematics of the 2023 Mw 7.8 and Mw 7.5 Kahramanmaraş Earthquake Doublet: Insights From Comprehensive Seismic and Geodetic Analysis. **Xu, L.**, Mohanna, S., Meng, L., Ji, C., Ampuero, J., *et al.*

Characteristics and Mechanics of Fault Zone Rupture Processes, from Micro to Macro Scales [Poster Session] **(see page 1246).**

74. Constraining 3D Fault Geometry With a Data-Driven Approach at the San Andreas—Calaveras Fault Junction. **Alongi, T.**, Elliott, A., Skoumal, R., Hatem, A. E., Harris, R. A., *et al.*
75. Unveiling Shallow Earthquake Ruptures in the Ryukyu Area: A Comprehensive Study Through Bp Imaging and Regional Cmt Catalog. **Jian, P.**, Tseng, T., Hsu, Y., Yang, H., Tang, C.
76. Probing Transient Rheology and Spatial Heterogeneity of Faults Using Repeating Earthquakes and Deformation Data. **Jiang, J.**, Taira, T.
77. Illuminating the Jericho Fault from A New Local Seismic Network. **Klinger, A. G.**, Kurzon, I.
78. Student: Fault Network Geometry's Control on Earthquake Rupture Behavior. **Lee, J.**, Tsai, V. C., Hirth, G., Trugman, D. T., Chatterjee, A.

79. STUDENT: Posterior Exploration of Bayesian Kinematic Finite-Fault Earthquake Source Models. **Viteri Lopez, J.**, Jiang, J.
80. STUDENT: Comparing Fault Zones that Host Induced and Tectonic Earthquakes in Oklahoma and California. **Neo, J.**, Huang, Y., Gable, S.
81. STUDENT: Systematic Measurements of Rupture Directivity for Small-to-Moderate Earthquakes in California. **Patton, A.**, Trugman, D. T.
82. STUDENT: Lithospheric Structure of the Hispaniola and Puerto Rico/Virgin Islands Microplates Using Teleseismic and Local Data. **Rosero Rueda, S.**, Pulliam, J., Huerfano, V., Polanco Rivera, E., Leonel, J.
83. STUDENT: Investigation of Earthquake Nucleation Processes: A Case Study of the 2019 Ridgecrest Earthquake Sequence. **Wang, Y.**, Lin, G., Fan, W.
84. New Zealand's South Westland Alpine Fault: What's Down There and How Does It Make Earthquakes Stop?. **Warren-Smith, E.**, Townend, J., Lozos, J., Chamberlain, C. J., Eberhart-Phillips, D.
85. Spatio-Temporal Slip Distributions of Deep Short-Term Slow Slip Events in the Nankai Subduction Zone Using Gnss, Tilt, and Strain Data. **Yabe, S.**, Ochi, T., Matsumoto, N., Matsuzawa, T.

Cordilleran Strike-Slip Faults as Seismogenic and Seismological Features [Poster Session] **(see page 1250).**

86. STUDENT: Refining the Nature of Distributed and Localized Slip-Partitioning of the Totschunda-Fairweather to Denali Corridor Using Earthquake Relocations and Focal Mechanisms. **Biegel, K.**, Gosselin, J. M., Dettmer, J., Colpron, M., Enkelmann, E., *et al.*
87. Revisiting the Enigmatic Magnitude-7 Denali Fault Earthquake of July 7, 1912. **Tape, C.**, Lomax, A.

Seismic Monitoring, Modelling and Management Needed for Geothermal Energy and Geologic Carbon Storage [Poster Session] **(see page 1397).**

88. STUDENT: Applying Dynamic Fracture Propagation and Activation Models to Microseismicity Generation in a Geothermal Development Project at Blue Mountain, Nevada. **Awe, E.**
89. End-to-End High-Quality Geophysics Workflow to Analyze Das-Acquired Induced Seismicity. Calvez, J. L., Mizuno, T., **Ay, E.**
90. Application of State of Stress Analysis Tool (SoSAT) to Estimate Risk of Induced Seismicity From CO2 Injections. **Saxena, S.**, Haagenson, R. J., Wang, W., Appriou, D., Burghardt, J. A.
91. Toward Improving the Assessment of Induced Earthquakes in the Rome Trough of West Virginia. **Carpenter, S.**, Schmidt, J. P., Hickman, J. B., Sparks, T. N., Greb, S., *et al.*
92. OhioNET: Reducing Risk from Induced Seismicity Using Real-Time Seismic Monitoring for Regulation and Mitigation in Ohio. **Dade, S. L.**
93. Automated Earthquake Detection and Location Applied to Local-Scale Seismic Monitoring. **Dzubay, A.**, Leifer, J., Stachnik, J., Friberg, P.
94. STUDENT: Using Deep Learning for High-Resolution Fault Analysis and Stress Characterization at the Forge Site, Utah. **Mohammadi Ghanatghestani, A.**, Chen, X., Asirifi, R.
95. STUDENT: A Comparison of Machine Learning and Array-Beamforming Methods in Detecting Microearthquakes Near Cushing, Oklahoma, Using a Dense Nodal Array. Chen, X., Cheng, Y., **Hoefer, B. A.**
96. Innovative Use of Broadband Sensors for Carbon Capture Utilization and Storage ("CCUS") Monitoring Applications. **Lindsey, J. C.**, Watkiss, N., Hill, P., O'Neill, J.
97. The Utah Frontier Observatory for Research in Geothermal Energy: A Field Laboratory for Enhanced Geothermal System (EGS) Development. **Moore, J. N.**, McLennan, J., Pankow, K. L., Podgorney, R., Rutledge, J., *et al.*
98. Microseismicity Observation and Structure Characterization at Cape Modern, Utah. **Nakata, N.**, Wu, S., Hopp, C., Robertson, M., Jung, Y., *et al.*
99. Weak Soils, Active Faults, and the Inheritance of Groningen Induced Seismicity: How to Proceed With Safe Use of the Subsurface for the Energy Transition in the Netherlands?. **van der Wal, J. L. N.**, Muntendam-Bos, A. G., Schouten, M. W.
100. Application of Static Stress Drops and Similarity of Seismic Events Induced by Underground Fluid Injection in Characterization of Seismogenic Zones on the Example of The Geysers Geothermal Field. **Staszek, M.**, Rudziński, Ł., Wiszniowski, J.
101. Mapping of the Seismic B-Value Before and After Mine Collapse Main Shocks, Rudna Mine, SW Poland. Sobiesiak, M. M., **Staszek, M.**, Leptokaropoulos, K., Rudzinski, L.
102. Focal Mechanisms of Microseismicity at the Decatur, Illinois, CCS Site Inverted From Multiple Borehole Seismic Arrays. **Woo, J.**, Ting, C.
103. Microseismicity Moment Tensor Estimation Using Surface and Downhole Geophone Arrays at Utah FORGE. **Wu, S.**, Nakata, N.
104. Shear-wave Splitting Observed in the Geysers Geothermal Field to Monitor the Spatiotemporal Crustal Conditions. **Yoshimitsu, N.**
105. A Cost-Effective GCS Monitoring Approach Using Localized Seismic Waves. **Zheng, Y.**, Sun, M., Huang, L.

106. A Risk-Based Adaptive Monitoring Planning Tool Based on Elastic-Wave Sensitivities for Cost-Effective Seismic Monitoring for Geologic Carbon Storage. **Tian, Y.**, Yang, X., Huang, L., Gao, K., Vasylkivska, V., *et al.*

3D Wavefield Simulations: From Seismic Imaging to Ground Motion Modelling [Poster Session] (see page 1204).

107. A Detailed Analysis of Seismic Waves Amplification for Basins Using 3D Seismic Simulations. **Tian, Y.**, Tape, C.
108. Student: Estimating Ground Motion Intensities Using Simulation-Based Estimates of Local Crustal Seismic Response. **Agrawal, H.**, McCloskey, J.
109. Student: Effects of the Distribution of Ambient Noise Sources in Subsurface Models Inverted From Noise Correlations. **Valero Cano, E.**, Fichtner, A., Peter, D., Mai, P. M.
110. Southern Italy: An Intricate Litosphere. **Casarotti, E.**, Magnoni, F., Ciaccio, M., Di Stefano, R.
111. Student: Synthetic Inversions for Anisotropic Structures using Wavefield Simulations and Adjoint Methods. **Gupta, A.**, Chow, B., Tape, C.
112. Student: Analysing Alpine Fault Earthquakes Through Ambient Seismic Noise. **Juarez Garfias, I.**, Townend, J., Chamberlain, C., Holden, C.
113. Selection of a Starting Model for Adjoint Tomography of the Pacific Northwest. **Kehoe, H. L.**, Bozdag, E., Boyd, O. S., Wirth, E., Stephenson, W. J., *et al.*
114. Rupture Dynamics and Ground Motions Characteristics of the 2023 Türkiye Mw 7.8 and Mw 7.6 Earthquake Doublet. **Li, B.**, Palgunadi, K., Wu, B., Suhendi, C., Zhou, Y., *et al.*
115. Student: Lithospheric Structures of the Central Cascadia Subduction Zone Resolved by Full-waveform Inversion of Ambient Noise and Receiver Functions. Du, N., **Liu, Q.**
116. Ambient Noise Attenuation and Differential Adjoint Tomography Applied to the Hongkou Linear Array Across the Longmenshan Fault Behind the 2008 M 7.9 Sichuan Earthquake. **Liu, X.**, Li, H., Beroza, G. C., Yang, L., Zhao, G.
117. Student: Validating Tomographic Models of Alaska Using 3D Wavefield Simulations. **McPherson, A.**, Tape, C., Onyango, E., Chow, B., Peter, D.
118. High-Resolution Surface Wave Tomography of the Hayward Fault in the Berkeley Region Using Ambient Noise Recorded by a Dense Nodal Array. **Miao, W.**, Qiu, H., Qin, L.
119. Computational Challenges of Large-Scale Numerical Simulations and Full-Waveform Inversion Workflows. Orsvuran, R., **Nagaso, M.**, Wang, I., Peter, D., Bozdag, E.
120. Student: Homogenization of Sedimentary Basins for the Simulation of Lithological Site Effects. **Rapenne, M.**, Cupillard, P., Gouache, C.
121. Student: Rapid 3D Green's Functions Using Reduced-Order Models of Physics-Based Seismic Wave Propagation Simulations. **Rekoske, J. M.**, May, D. A., Gabriel, A. A.
122. Comparison of Fundamental Fault Green's Functions (GFs) Computed Using Frequency-Wavenumber and Finite-Difference (SW4) Techniques for 1D Velocity Models. **Saikia, C. K.**, Zhou, R., Modrak, R. T.
123. A Sparse Fault Parametrization for Large-scale Ruptures Based on Moment Tensor Interpolation. **Thurin, J.**

Advancements in Forensic Seismology and Explosion Monitoring [Poster Session] (see page 1213).

124. Moment Tensor Estimation and Uncertainty Quantification (MTUQ). **Thurin, J.**, Modrak, R., McPherson, A., Rodríguez-Cardozo, F., Braunmiller, J., *et al.*
125. Observations on Explosion-Triggered Seismic Events via Fiber Optic Sensing at Small Scales. **Beskardes, G. D.**, Young, B., Stanciu, C., Baker, M. G.
126. Leveraging Infrasound Signals for Integration of Ground- and Space-Based Nuclear Explosion Monitoring Capabilities. **Blom, P. S.**, Bishop, J., Gammans, C., Carmichael, J. D., Delbridge, B., *et al.*
127. Influence of Local 3-D Structure at Degelen Test Site on Short-Period Teleseismic P-Wave via Reciprocal Hybrid Modeling. **Burgos, G.**, Guillot, L.
128. Far-Field DAS Recordings of a Chemical Explosion. **St Clair, J. T.**, Chojnicki, K., Sprinkle, P., Ely, J.
129. Capturing the Spatial Variation of Seismic Observations in SW4 Simulations of the Dry Alluvium Geology Experiment Series at the Nevada National Security Site. **Saxena, S.**, St Clair, J., Sprinkle, P., Chojnicki, K., Knox, H., *et al.*
130. Time-Variable Moment Tensor Inversion of Seismic and Seismoacoustic Data at the Source Physics Experiment Phase II: Dry Alluvium Geology. **Darrh, A.**, Berg, E. M., Preston, L. A., Poppeliers, C.
131. Exploring Paired Neural Networks to Rapidly Characterize Aftershock Events. **Emry, E. L.**, Donohoe, B., Tibi, R., Young, C. J., Ramos, M., *et al.*
132. A New Tool to Integrate Instrument Responses From Seismological Databases Into Python Workflows. **Gammans, C.**, MacCarthy, J. K.
133. Ambient Seismic Noise Tomography of Heterogeneous Geological Formations. **Gochenour, J. A.**, Zeiler, C. P., Bilek, S., Luhmann, A. J.

134. Using Deep Learning Models to Characterize Subsurface Physical Parameters at Modeled Underground Chemical Explosion Sources. **Harding, J. L.**, Preston, L. A., Eliassi, M., Gauvain, S. J.
135. Comparing Observed and Modelled Station Terms from the Source Physics Experiments Phase 2 (Dry Alluvium Geology) Explosions. **Heyburn, R.**, Green, D.
136. Comparisons Between Geophone Array and DAS Array Detections. **Ichinose, G. A.**
137. Explosion Source Analysis and Discrimination From Regional Distance Seismic Observations. **Kintner, J. A.**, Pippin, J., Alfaro-Diaz, R., Delbridge, B., Ammon, C. J.
138. Inferring the Focal Depths of Small Earthquakes in Southern California Using Physics-Based Waveform Features. **Koper, K. D.**, Burlacu, R., Murray, R., Baker, B., Tibi, R., *et al.*
139. Providing Data for Nuclear Explosion Monitoring—WFNE Repository. **Oancea, V.**, Kung, Y., Murphy, J. R., Piraino, P. E.
140. Investigating Shallow Subsurface Structure Near Legacy Nuclear Test Sites Using Single Station HVSR. **Miller, D. J.**, Berg, E. M., Preston, L. A., Abbott, R. E.
141. Detecting Subsurface Mining Activity using Cross-Correlation and Local Surface Arrays. **Miller, D. J.**, Berg, E. M., Marcillo, O., Chai, C., Cunningham, E., *et al.*
142. Investigation of Full Moment Tensor Solutions for Earthquakes and Announced Nuclear Tests at the Punggye-Ri Test Site, DPRK. **Ogden, C. S.**, Selby, N., Heyburn, R., Nippress, S.
143. Relative Source Time Function Estimation, Applications to the Source Physics Experiments. **Pippin, J. E.**, Kintner, J. A., Ammon, C. J.
144. Transportability of a Convolutional Neural Network Seismic Denoising Model. **Quinones, L. A.**, Tibi, R.
145. Gravity Mapping to Validate the Rock Valley Geological Framework Model. **Ranasinghe, N. R.**, Rowe, C., Stanbury, C.
146. Observations of Epicentral Infrasound From Shallow Low-Magnitude Earthquakes in the Permian Basin, West Texas. **Schaible, L.**, Dannemann Dugick, F., Bowman, D. C., Savvaidis, A., McCabe, C.
147. Student: Seismic Soundscape of the Parks Highway Corridor, Central Alaska. **Seppi, I.**, Tape, C., West, M.
148. Seismic Data Denoising Using Multi-Scale Mathematical Morphological Filtering. **Tibi, R.**
149. Evaluation of Multiple-Event Location Methods Using Ground-Truth and Synthetic Data. **Tibuleac, I. M.**, Antolik, M. S., VanDeMark, T. F., Brumbaugh, D.
150. Moment Tensor Inversions for Rapid Seismic Source Detection and Characterization of the North Korean Nuclear Tests. **Guilhem Trilla, A.**
151. Modeling the Ground Motions From Chemical Explosions in Proximity of a Fault. **Vorobiev, O. Y.**, Ezzedine, S. M.
152. Signal Arrival Databases for Ground Truth Infrasound Events. Dannemann Dugick, F., **Wynn, N. R.**

From Earthquake Recordings to Empirical Ground-Motion Modelling [Poster Session] **(see page 1292).**

154. Frequency-Dependent Transfer Functions for Hydroseisms in Devils Hole. **Bonner, J. L.**, Symons, N., Russell, C.
155. High Frequency Seismic Waves of Normal and Leaky Modes Excited by Heavy Trains. **Feng, X.**, Li, Z., Chen, X.
156. Progress on the Characterization of Epos-France Accelerometric (Rap) and Broad-Band (Rlpb) Network Station: Focus on Implemented Methodologies. **Hollender, F.**, Burlot, R., Rischette, P., Douste-Bacqué, I., Wathelet, M., *et al.*
157. Student: Separation of Intrinsic and Scattering Seismic Wave Attenuation in the Crust of Central and South-Central Alaska. **Mahanama, A.**, Cramer, C. H., Gabrielli, S., Akinci, A.
158. Student: How Can Shaking Observations From the MyShake Smartphone Platform Inform Free-Field Ground Motion Residual Estimates?. **Marcou, S.**, Allen, R. M.
159. Student: Estimating Hazard From Crustal Sources: An Empirical Observation Approach. **Martínez-Jaramillo, D.**, Zúñiga Dávila-Madrid, F., Kotha, S.
160. Student: Multi-Resolution Basin Terms for Ground Motion Models in Central and Eastern North America. **Meyer, E. H.**, Dioslaki, A., Nie, S., Zhan, W., Kaklamanos, J., *et al.*
161. Student: The Effect of Short Wavelength Topography on Seismic Recordings: Results of Experiments Conducted on Kefalonia Island in Greece. **Rischette, P.**, Hollender, F., Theodoulidis, N., Roumelioti, Z., Perron, V., *et al.*
162. Student: Geospatial Variable Based Site Terms for Nonergodic Ground Motion Models. **Roberts, M. E.**, Gaskins Baise, L., Kaklamanos, J., Zhan, W., Nie, S.
163. NGA-Subduction Region-Specific Ground Motion Models Using Machine Learning Algorithms. **Sedaghati, F.**, Pezeshk, S.
164. Ground Motion Models Using Machine Learning Techniques Based on the NGA-West2 Data. **Sedaghati, F.**, Pezeshk, S.
165. Student: Developing a Hybrid Ground-Motion Modeling Framework for the Himalayan Region of India. **Sharma, S.**
166. Domain Confusion in Dispersions Picking Based on Neural Network and the Learning Features From Dispersion Spectrograms. **Song, W.**, Chen, X.

167. Monitoring Temporal Velocity Variations of Shallow Subsurface and Engineering Structures Using 6c Single-Station Measurement. **Yuan, S.**, Martin, E., Bernauer, F.

Six Decades of Tsunami Science: From the Source of the 1964 Tsunami to Modern Community Preparedness [Poster Session] (see page 1416).

168. Depth Variation in Megathrust Rupture Leads to Mature Tsunami Gap in Metropolitan Chile. **Carvajal, M.**, Cisternas, M., Wang, K., Moreno, M., Wesson, R. L., *et al.*
169. Student: Constraining Offshore Coupling in the 1946 Tsunami Earthquake Rupture Area. **Chavarria Esquivel, N.**, Newman, A.
170. Efficient Forward Modelling of Tsunamis Using the Spectral-Element Method. **Gharti, H.**, Fitzgerald, J.
171. Adding Tsunami Observations and Modeling to the USGS Finite Fault Modeling Procedure. **Goldberg, D. E.**, Koch, P., Melgar, D., Hunsinger, H., Haynie, K.
172. The What, When and Whys of Alert Progression During Tsunamigenic Events: A Simple Generative Approach to Forecasting Decision Points and Developing Heuristics. **Heath, B.**, Ohlendorf, S., Kim, Y., Gridley, J.
173. Estimating Tsunami Vulnerability along Western Coast of India. **Jha, K.**
174. Precise Point Positioning of Ships to Detect Tsunamis. **Manaster, A. E.**, Sheehan, A. F., Goldberg, D. E., Roth, E. H., Barnhart, K. R.
175. Testing Crustal Fault Tsunami Sources in the Salish Sea: Comparing Modeled Inundation With the Geologic Record at Discovery Bay, WA. Wei, Y., Garrison-Laney, C., **Moore, C.**, Pells, C.
176. KOERI Activities in Tsunami Early Warning and Risk Mitigation System in the Eastern Mediterranean and Its Connected Seas. **Ozener, H.**, Cambaz, M., Turhan, F., Güneş, Y., Deniz Hisarlı, P., *et al.*
177. Estimation of the Tsunami Hazard for the Bering and Chukchi Seas Based on Numerical Modeling of Trans-Oceanic and Local Tsunamis. Medvedeva, A. E., Fine, I. E., Medvedev, I., Kulikov, E., **Rabinovich, A. B.**, *et al.*
178. Real Time Tsunami Run-Up Estimation From Real Time Finite Fault Models. **Riquelme, S.**, Fuentes, M.
179. Student: Measuring and Forecasting the Background Open Ocean Tsunami Spectrum. **Santellanes, S. R.**, Melgar, D.
180. The Role of Climate-Change Sea Level Rise Exacerbating California's Tsunami Hazards. **Sepulveda, I.**, Mosqueda, A.
181. In Search of the Missing Tsunami: Is There a Tsunami Threat to Anchorage?. **Suleimani, E.**, Salisbury, J. B., Nicolsky, D., Picasso, A.

Applications and Discoveries in Cryoseismology Across Spatial and Temporal Scales [Poster Session] (see page 1237).

182. Student: Machine Learning for Icequake Detection and Location Across the Eastern Shear Margin of Thwaites Glacier, West Antarctica. **Gonzalez, L. F.**
183. Probabilistic Multiphysics Inference for Permafrost Characterization and Earthquake Site Hazards Assessment. **Gosselin, J. M.**, Dettmer, J., Shahsavari, P.
184. Student: Bayesian Surface Wave Dispersion Data Inversion of Glaciated Environments. **Lanteri, A.**, Gebraad, L., Zunino, A., Keating, S., Klaasen, S., *et al.*
185. Unsupervised Detection and Characterization of Glaciogenic Noise Sources in Greenland During Winter. **Maier, N.**
186. Student: Microseismicity Catalog of Icequakes Induced by Ocean Swell at the Ross Ice Shelf Ice-Front. **McGhee, E.**, Aster, R. C.
187. Distributed Acoustic Sensing Reveals What's in Store (Glacier). **Olinger, S.**, Lipovsky, B., Denolle, M., Booth, A.
188. Array-based Characterization of Seismicity from a Glacial Lake Outburst Flood. **Sawi, T.**, Holtzman, B. K., Beaucé, E., Walter, F., Seydoux, L.
189. Student: Controlled-Source Seismic Imaging of Mcmurdo Ice Shelf Near Williams Airfield. **Seldon, Y.**, Karplus, M. S.
190. Student: Unsupervised Clustering of Cryoseismic Events Recorded by Distributed Acoustic Sensing at Rhonegletscher, Switzerland. **Willis, R.**, Grimm, J., Stanek, F., Edme, P., Fichtner, A., *et al.*

Friday, 3 May 2024—Oral Sessions

Presenting author is indicated in bold.

Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom A/B*
	Advancing Seismology with Distributed Fiber Optic Sensing (see page 1224).	**Physics-Based Ground Motion Modeling (see page 1377).**	**Seismoacoustic, Geodetic and Other Geophysical Investigations of Active Volcanoes (see page 1402).**	**Structure and Behavior of the Alaska-Aleutian Subduction Zone (see page 1424).**
8:00 AM	High-Resolution Analysis of Earthquake Sources and Subsurface Structures Using Downhole Optical Fiber Crossing Active Fault. **Ma, K.**, Liao, J., Hsiao, L.	Evaluation of Seismic Community Velocity Models With Simulations of Small Earthquakes. **Pinilla Ramos, C.**, Ben-Zion, Y., Abrahamson, N. A., Maechling, P. J., Callaghan, S., *et al.*	STUDENT: Using Deep Long-Period Earthquakes to Constrain Magmatic Volatile Transport at Mauna Kea. **Scholz, K. J.**, Thomas, A. M., Townsend, M. R.	INVITED: Forty-Five Years of the Shumagin Gap: What Recent Earthquakes Tell Us About This Seismic Gap. **Herman, M. W.**, Furlong, K. P., Benz, H. M.
8:15 AM	STUDENT: Dascore: A Python Library for Distributed Acoustic Sensing. **Chambers, D. J. A.**, Martin, E. R., Jin, G., Tourei, A., Girard, A., *et al.*	Waveguide or Not? Expected Ground Motions in the Greater Los Angeles Area From the ShakeOut scenario. Yeh, T., **Olsen, K. B.**	Probing Magma Storage and Transport Beneath Pāhala, Hawaiʻi. **Janiszewski, H. A.**, Bennington, N., Wight, J., Glasgow, M.	STUDENT: Putting the Pieces Together: A Kinematic Coseismic Model of the Mw 7.2 Alaska Earthquake. **DeGrande, J.**, Crowell, B.
8:30 AM	STUDENT: Characterizing South Pole Firn Structure With Fiber Optic Sensing. **Yang, Y.**, Zhan, Z., Reid-McLaughlin, A., Biondi, E., Karrenbach, M., *et al.*	Effect of Soil Nonlinearity on Physics-Based Ground Motion Simulations. **Zhang, W.**	Seismic Velocity Changes at Mauna Loa Derived From Seismicity Prior to and During Its 2022 Eruption. **Hotovec-Ellis, A. J.**	STUDENT: A Joint Coseismic and Early Postseismic Study of the 29 July 2021, Mw 8.2 Chignik Earthquake. **Zhuo, Z.**, Freymueller, J. T., Xiao, Z., Elliott, J., Grapenthin, R.

Time	*Tikahtnu Ballroom C*	*Tikahtnu Ballroom E/F*	*Tubughnenq' 3*	*Tubughnenq' 4*	*Tubughnenq' 5*
	The 2024 Magnitude 7.5 Earthquake and the Associated Earthquake Swarm Beneath the Noto Peninsula, Central Japan (See Supplemental Material)	**End-to-End Advancements in Earthquake Early Warning Systems (see page 1276).**	**Understanding and Quantifying the Variability in Earthquake Source Parameter Measurements (see page 1448).**	**Anisotropy Across Scales (see page 1232).**	**Tectonics and Seismicity of Stable Continental Interiors (see page 1436).**
8:00 AM		Exploring Five Years of Social Science and Education Research for Shakealert, the Earthquake Early Warning System for the West Coast of the United States. **McBride, S. K.**, de Groot, R. M., Sumy, D. F.	Estimating Seismic Attenuation, Site Corrections and Geometrical Spreading From Large Seismic Catalogues Using Linearized Spectral Ratios and Regression Regularization Paths. **Lapins, S.**	A Seismic View of the Stress Field. **Delorey, A. A.**	Seismicity and Seismotectonics of the Basque-Cantabrian Zone and Adjacent Areas of the Pyrenean-Cantabrian Mountain Belt: New Data From the Siscan and Misterios Seismic Networks (2014-2020). **Olivar-Castaño, A.**, Díaz-González, A., Pulgar, J. A., Pedreira, D., González-Cortina, J., *et al.*
8:15 AM		STUDENT: The Development of a Real-Time Urban Earthquake Early Warning System for Asset-Level Protection for Increased Community Restoration. **Martí, A. T. J.**, Daiss, I., Martí, J. R., Ventura, C. E., Andjelic, D., *et al.*	Extraction of Source Parameters for French Seismicity Based on a Radiative Transfer Approach: Importance for Attenuation and Site Corrections. **Heller, G.**, Sèbe, O., Margerin, L., Traversa, P., Mayor, J., *et al.*	STUDENT: Seismic Anisotropy and Stress-Field Variations Along the Dead Sea Fault Zone in Northern Israel. **Ben-Dor, G.**	The Earthquake Swarms of Eastern Maine and Nearby New Brunswick Since 2006. **Ebel, J. E.**
8:30 AM		What It Takes to Implement Earthquake Early Warning in the Real World. **Steele, W. P.**, Lotto, G.	A Joint Inversion Method for Computing Earthquake Stress Drop With Spectra and Spectral Ratios. **Guo, H.**, Thurber, C. H.	STUDENT: Imaging Los Angeles Basin via Directional Dependent Rayleigh Wave Ellipticity Using Data From the Lab2022 Nodal Array. **Gkogkas, K.**, Lin, F., Clayton, R., Villa, V., Ford, H., *et al.*	STUDENT: Seismotectonic Studies of the Nubia Fault System, Southwest Aswan Area, Egypt. **Elsayed Mohamed, M. M.**, Abdallah Hamimi, Z., Mohamed Moussa, H.

Friday, 3 May (*continued*)

Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom A/B*
	Advancing Seismology with Distributed Fiber Optic (continued)	**Physics-Based Ground Motion Modeling (continued).**	**Seismoacoustic, Geodetic and Other Geophysical (continued)**	**Structure and Behavior of the Alaska-Aleutian Subduction (continued)**
8:45 AM	Assessing Distributed Acoustic Sensing (DAS) for Moonquake Detection. **Husker, A.**, Zhai, Q., Zhan, Z., Biondi, E., Yin, J., *et al.*	STUDENT: 3D 0-10 Hz Physics-based Simulations of the 2020 Magna, Utah Earthquake Sequence. **Xu, K.**, Olsen, K. B.	STUDENT: A Catalog of Automated Focal Mechanisms for Microearthquakes at Axial Seamount Based on Waveform Cross-Correlation. **Zhang, M.**, Wilcock, W., Waldhauser, F., Wang, K., Schaff, D., *et al.*	Estimating Slip Models and Ground Motion for the 1964 Mw 9.2 Alaska Earthquake. **Thurin, J.**, Thio, H. K., Tape, C.
9:00 AM	INVITED: Rupture Imaging of Firn Quakes with Distributed Acoustic Sensing. **Li, J.**, Yang, Y., Biondi, E., Reid-McLaughlin, A., Aster, R. C., *et al.*	Spe Rock-Valley-Direct-Comparison Chemical Explosions Near-Field 3-D Ground Motion Simulations and Predictions. **Ezzedine, S. M.**, Vorobiev, O.	STUDENT: The Influence of Multiple Scattered Waves on the Spectral Stability of Volcanic Tremors. **Bracale, M.**, Campillo, M., Shapiro, N., Brossier, R., Melnik, O.	Earthquake Location Improvements for the Aleutian-Alaska Subduction Zone by Using Waveform Cross-Correlation Data. **Lin, G.**
9:15–10:30 AM	Poster Break			
	Advancing Seismology with Distributed Fiber Optic Sensing (see page 1224).	**Physics-Based Ground Motion Modeling (see page 1377).**	**Seismoacoustic, Geodetic and Other Geophysical Investigations of Active Volcanoes (see page 1402).**	**Structure and Behavior of the Alaska-Aleutian Subduction Zone (see page 1424).**
10:30 AM	SUBMERSE Project Paves the Way for Continuous Fiber-optic Monitoring in the Oceans with Submarine Telecommunications Cables. **Tilmann, F.**, Atherton, C., Kvatadze, R., Asero, C., Evangelidis, C., *et al.*	STUDENT: Modeling Topography and Fault Geometry Effects on Earthquake Ruptures and Ground Motions Along Double Compressional Bends. **Madera, N.**, Lozos, J.	Local Infrasound Monitoring of Lava Eruptions at Nyiragongo Volcano (d.r. Congo) Using Urban and Near-Source Stations. Barrière, J., **Oth, A.**, d'Oreye, N., Subira, J., Smittarello, D., *et al.*	Upper Plate Stress in the Alaskan Continental Crust: Spooky Interactions at a Variety of Distances. **Levandowski, W.**, Coulter, C.

Time	Tikahtnu Ballroom C	Tikahtnu Ballroom E/F	Tubughnenq' 3	Tubughnenq' 4	Tubughnenq' 5
	The 2024 Magnitude 7.5 (continued)	**End-to-End Advancements in (continued)**	**Understanding and Quantifying the (continued)**	**Anisotropy Across Scales (continued)**	**Tectonics and Seismicity of Stable (continued)**
8:45 AM		From Shakealert to Post-Earthquake Assessment—Improving Situation Awareness of Building Managers and Occupants. Parrott, B., **Franke, M.**, Skolnik, D.	STUDENT: Earthquake Source Parameter Analysis Using Peak Narrow Band Displacement Amplitudes. **Knudson, T.**, Ellsworth, W. L., Beroza, G. C., Shaw, B. E.	INVITED: Anisotropy in Flowing Firn and Ice: Insights from Ambient Noise and Active Source Studies in Antarctica. **Chaput, J.**, Aster, R. C., Karplus, M. S., Nakata, N.	STUDENT: Focal Mechanism Analysis of the 2019 Mw 4.9 Wang Nuea Earthquake and Its Implication for Seismotectonics. **Chansom, C.**, Jitmahantakul, S., Shengji, W.
9:00 AM		The Ojai California Earthquake of August 20, 2023: Earthquake Early Warning Performance and Alert Recipient Response in the m5.1 Event. **Goltz, J. D.**, Wald, D. J., McBride, S. K., Reddy, E., Quitoriano, V., *et al.*	Three Years of the International SCEC/USGS Community Stress Drop Validation Study: What Have We Achieved and Where Next. **Abercrombie, R. E.**, Baltay, A. S., Chu, S., Taira, T.	Broadband Rayleigh and Love Wave Phase Velocity Maps Based on Double-Beamforming of Ambient Noise Cross-Correlations. **Yang, Y.**, Zhao, K., Luo, Y.	Middle Crustal Earthquakes and Neotectonics in the Western East Sea (Sea of Japan). **Hong, T.**, Park, S., Lee, J., Lee, J., Kim, B.
9:15–10:30 AM		Poster Break			
	The 2024 Magnitude 7.5 Earthquake and the Associated Earthquake Swarm Beneath the Noto Peninsula, Central Japan (See Supplemental Material)	**End-to-End Advancements in Earthquake Early Warning Systems -IV (see page 1276).**	**Understanding and Quantifying the Variability in Earthquake Source Parameter Measurements (see page 1448).**	**Anisotropy Across Scales (see page 1232).**	**Tectonics and Seismicity of Stable Continental Interiors (see page 1436).**
10:30 AM		High-Rate Real-Time Gnss Installation and Data Acquisition at the Alaska Earthquake Center. **Paris, G.**, Holtkamp, S., Khan, S., Underwood, L., Farrell, A., *et al.*	INVITED: STUDENT: Understanding the Contribution of Site Effects to Variability in Microearthquake Source Parameter Measurements Using a Large, Dense Array in Oklahoma. **Chang, H.**, Abercrombie, R. E., Nakata, N., Qiu, H., Zhang, Z., *et al.*	STUDENT: Flow in the Mantle Beneath Eritrea and Yemen: Evidence From Seismic Anisotropy. **Gauntlett, M. Z.**, Kendall, J., Hudson, T., Hammond, J. O. S., Goitom, B., *et al.*	Seismicity and Structure of SW Australia via the SWAN and Western Australia Seismic Networks. **Pickle, R.**, Zhang, P., Mousavi, S., Yuan, H., Murdie, R., *et al.*

Friday, 3 May (*continued*)

Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom A/B*
	Advancing Seismology with Distributed Fiber Optic (continued)	**Physics-Based Ground Motion Modeling (continued).**	**Seismoacoustic, Geodetic and Other Geophysical (continued)**	**Structure and Behavior of the Alaska-Aleutian Subduction (continued)**
10:45 AM	Monitoring Soil Moisture With Distributed Acoustic Sensing in the Agricultural Setting. **Shi, Q.**, Collins, J., Denolle, M., Feng, K., Jeffery, S., *et al.*	STUDENT: The Effects of Surface Topography and Basin Layering on the Earthquake Ground Motion Intensities in Intermontane-Basin Settings. **Agrawal, H.**, Naylor, M.	Here Comes the Boom! Tracking Audible Acoustics Across Aotearoa New Zealand From the 2022 Eruption of Hunga Volcano. **Lamb, O.**, Clive, M., Lawson, R., Potter, S., Kilgour, G., *et al.*	STUDENT: A Chicken and Egg Dilemma: Forearc Strain Field and Seismic Behavior in the Andreanof Segment. **Cortés Rivas, V.**, Shillington, D. J., Lizarralde, D., Mark, H., Boston, B.
11:00 AM	Spatio-Temporal Fidelity of DAS Arrays to Compression Seismic Signals: Impacts on Real-Time Source Estimates. **Salaree, A.**, Miao, Y., Spica, Z., Nishida, K., Yamada, T., *et al.*	Analysis of Anomalously Large High-Frequency Amplification in Chugiak, Ak, From the 2018 Anchorage Earthquake and Aftershocks. Yeh, T., **Olsen, K. B.**, Steidl, J. H., Haeussler, P. J.	Internal Gravity Waves During the 2023 Eruption of Shishaldin Volcano, Alaska. **Haney, M. M.**, Fee, D., Lyons, J. J.	STUDENT: Structural and Compositional Controls on Megathrust Slip Behavior Inferred From a 3D, Crustal-Scale, P-Wave Velocity Model of the Alaska Subduction Zone Spanning the Incoming and Overriding Plates. **Acquisto, T. M.**, Bécel, A., Canales, J., Beauce, E.
11:15 AM	STUDENT: Understanding the Rupture Process of the Mw 7.6 2022 Michoacán Earthquake With Distributed Acoustic Sensing. **Miao, Y.**, Huang, Y., Neo, J., Spica, Z.	Findings from a Decade of Ground Motion Simulation Validation Research and a Path Forward. **Rezaeian, S.**, Stewart, J. P., Luco, N., Goulet, C.	Seismic and Infrasound Signals from the 2023 Shishaldin Volcano, Alaska Eruption. **Fee, D.**, Haney, M. M., Tan, D.	A Late Miocene to Pliocene Increase in Soft-Sediment Deformation in Cook Inlet Nonmarine Forearc Basin Strata—potential Evidence for Larger Magnitude Earthquakes Associated With Increased Sedimentation in the Alaska Trench. **Wartes, M. A.**, LePain, D. L., Stanley, R. G., Helmold, K. P., Gillis, R. J.
11:30 AM	INVITED: Distributed Environmental Sensing Using Trans-Oceanic Subsea Cables. **Mazur, M.**, Fontaine, N. K., Keheller, M., Kamalov, V., Ryf, R., *et al.*	Correlated Noise in Source Time Functions: A Method to Generate Realistic High Frequency Earthquake Sources. **Castro-Cruz, D.**, Aquib, T. T., Vyas, J. J., Mai, P. P. M.	A Seismic Sequence Capturing Magmatic Fluid Ascent and Phreatomagmatic Eruptions at Semisopochnoi Volcano, Alaska. **Lyons, J. J.**, Tan, D., Hotovec-Ellis, A., Lopez, T., Grapenthin, R., *et al.*	STUDENT: Variations in the Alaska-Aleutian Subduction Megathrust Properties Along Strike Using Several Seismic Imaging Techniques. **Daly, K. A.**, Abers, G. A., Mann, M. E., Pang, G., Kim, D.
11:45 AM–2:00 PM	Lunch Break			

Time	*Tikahtnu Ballroom C*	*Tikahtnu Ballroom E/F*	*Tubughnenq' 3*	*Tubughnenq' 4*	*Tubughnenq' 5*
	The 2024 Magnitude 7.5 (continued)	**End-to-End Advancements in (continued)**	**Understanding and Quantifying the (continued)**	**Anisotropy Across Scales (continued)**	**Tectonics and Seismicity of Stable (continued)**
10:45 AM		The Potential Contribution of Real-Time Distributed Slip Models to Subduction Zone Earthquake Early Warning in the Context of Ground Motion Thresholds and Alerting Strategy. **Murray, J. R.**	Demystifying Earthquake Stress Drop Discrepancies Using Synthetic Source Time Functions. **Neely, J. S.**, Park, S., Baltay, A. S.	INVITED: Modeling Layered Anisotropy in the Alaska-Aleutians Subduction Zone. **Birkey, A.**, Lynner, C.	Recurrent Large Intraplate Earthquakes on the Jindabyne Thrust, Southeast Highlands, Australia. **Griffin, J. D.**, Clark, D. J., Kemp, J., Stirling, M. W., King, T., *et al.*
11:00 AM		STUDENT: Toward Earthquake Early Warning in Alaska. **Fozkos, A.**, West, M., Ruppert, N., Grapenthin, R., Parcheta, C., *et al.*	Variable High Frequency Radiation From Complex Laboratory Ruptures Due to a Normal Stress Bump. **Cebry, S. B. L.**, McLaskey, G. C.	Depth-Dependent Seismic Azimuthal Anisotropy Beneath the Aleutian Subduction Zone and the Juan De Fuca-Gorda Plates. **Liu, C.**, Becker, T., Wu, M., Sheehan, A., Ritzwoller, M.	Seismic Evidence of Crustal Modifications Below the North American Midcontinent. **Yang, X.**, Stevens Goddard, A., Liu, L., Ridgway, K. D., Schmitt, D. R., *et al.*
11:15 AM		Application of the Support Vector Machine Classifier in Earthquake Magnitude Estimation. **Zaicenco, A. G.**, Weir-Jones, I.	INVITED: Source Parameter Scaling Relations for Shallow Crustal Earthquake with a Simple Heterogeneous Source Model. **Shimmoto, S.**	Exploring Mantle Dynamics of the Cascadia Subduction System Through Anisotropic Tomography With Transdimensional Inference Methods. **VanderBeek, B. P.**, Del Piccolo, G., Faccenda, M.	STUDENT: Crustal Thickness and Radial Anisotropy Below the North American Midcontinent. **Li, H.**, Yang, X., Herr, B., Liu, L., Stevens Goddard, A., *et al.*
11:30 AM		STUDENT: Enhancing Offshore Earthquake Early Warning with a Submarine DAS Array in Monterey Bay, California. **Gou, Y.**, Allen, R. M., Zhu, W., Chen, L., Taira, T., *et al.*	Reducing the Uncertainty of Stress-Drops. **Kurzon, I.**, Lyakhovsky, V., Sagy, A.	Segregated Melts Below the 660 in the Central Pacific: Implications on Water Transport in Mantle Upwellings. Deng, K., **Song, T.**	Lithospheric Layering and Seismic Activity of the British Isles. **Levin, V.**, Lebedev, S.
11:45 AM–2:00 PM		Lunch Break			

Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom A/B*
	Advancing Seismology with Distributed Fiber Optic Sensing (see page 1224).	**Assessing Seismic Hazard for Critical Facilities and Infrastructure—Insights and Challenges (see page 1239).**	**Seismoacoustic, Geodetic and Other Geophysical Investigations of Active Volcanoes (see page 1402).**	**Structure and Behavior of the Alaska-Aleutian Subduction Zone (see page 1424).**
2:00 PM	Enhancing Seismic Monitoring in Cook Inlet, Alaska: Integration of Distributed Acoustic Sensing with the Existing Seismic Network for Advanced Earthquake Denoising, Detection and Location. **Shi, Q.**, Ni, Y., Denolle, M., Williams, E. F.	INVITED: Challenges in Site-Specific Seismic Hazard Analyses for Mine Tailings Storage Facilities in South America. **Wong, I.**, Gray, B., Givler, R., Wu, Q., Darragh, R. B., *et al.*	INVITED: STUDENT: Investigation of Tremor and Explosion Sequences from the 2021-2022 Eruption of Pavlof Volcano, Alaska using Deep Learning. **Tan, D.**, Fee, D., Girona, T., Haney, M. M., Witsil, A., *et al.*	Implications of Yakutat Oceanic Plateau Buoyancy Versus Variable Interface Coupling on Deformation in South-Central Alaska. **Haynie, K. L.**, Jadamec, M. A.
2:15 PM	On DAS Recorded Strain Amplitude. Forbriger, T., Karamzadeh, N., Azzola, J., Widmer-Schnidrig, R., Gaucher, E., **Rietbrock, A.** *et al.*	Landfill Design Ground Motion at the Paducah Gaseous Diffusion Plant (Central United States). **Wang, Z.**, Carpenter, N.	Unique Seismic and Eruption Precursors to the 1996 Magmatic Eruptions of Popocatépetl: Coupled and Fluidized Bed Events. **McCausland, W.**, Caballero Jimenez, G. V., Guevara Ortiz, E., Trujillo Castrillón, N., Valdés González, C. M., *et al.*	Controls on Bending-Related Faulting Offshore of the Alaska Peninsula. **Clarke, J.**, Shillington, D. J., Regalla, C., Gaherty, J., Estep, J., *et al.*
2:30 PM	Evaluation of Passive Source DAS Methods on the Source Physics Experiment (SPE) Phase II. **Porritt, R.**, Stanciu, A. C., Abbott, R. E., Luckie, T. W.	Characterizing Uncertainty in the Canadian National Seismic Hazard Model. **Kolaj, M.**, Adams, J.	Constraining Links Between Seismicity and Eruptive Processes for the December 2018 Flank Eruption at Mt Etna. **Eyles, J.**, Frank, W. B., Poli, P.	STUDENT: Outer-Rise Earthquakes and Their Contribution to Tsunami Hazards Across the Alaska Subduction Zone. **Matulka, P.**, Wiens, D., Li, Z., Abers, G., Ruppert, N., *et al.*
2:45 PM	STUDENT: Lossy Compression and Reconstruction of Distributed Acoustic Sensing Data Using Deep Learning. **Ni, Y.**, Denolle, M. A., Lipovsky, B., Shi, Q., Pan, S., *et al.*	Importance of Site-Specific Ground Motion Data for Critical Facilities. **Hassani, B.**, Yan, L.	Tracking Seismicity in an Underfunded Institution: The Case of La Soufrière St Vincent Volcanic Eruption 2020–2021. **Contreras-Arratia, R.**	High-Resolution Rayleigh-Wave Tomography Constraints on Hydration in the Incoming Plate Along the Alaska Subduction Zone. Yakubu, T., **Gaherty, J.**, Shillington, D.

Time	Tikahtnu Ballroom C	Tikahtnu Ballroom E/F	Tubughnenq' 3	Tubughnenq' 4	Tubughnenq' 5
	ESC-SSA Joint Session: Climate Change and Environmental Seismology (see page 1284).	**End-to-End Advancements in Earthquake Early Warning Systems (see page 1276).**	**Understanding and Quantifying the Variability in Earthquake Source Parameter Measurements (see page 1448).**	**Advances in Operational and Research Analysis of Earthquake Swarms (see page 1220).**	**Tectonics and Seismicity of Stable Continental Interiors (see page 1436).**
2:00 PM	Multi-Decadal Analysis of the Global Microseism in Climate Context. **Aster, R. C.**	STUDENT: Improvement in Magnitude Estimation Performance with a Combined PGD-PGV Scaling Law for the G-Fast Earthquake Early Warning Module. **DeGrande, J.**, Crowell, B.	Constraining Source Parameters of Seismic Events Generated by Circular Gouge Patches on 4-meter-long Laboratory Fault. **Okubo, K.**, Yamashita, F., Fukuyama, E.	STUDENT: Seismic Clusters as Markers of Crustal Stability. **Zaccagnino, D.**, Telesca, L., Doglioni, C.	Complex and Contrasting Temporal Patterns of Large Intraplate and Interplate Earthquakes. **Liu, M.**, Chen, Y., Jin, X., Luo, G.
2:15 PM	STUDENT: Seismic Imprints of a Hurricane Landfall: Deciphering the Atmosphere-Generated Signals From Large-Eddy Simulation of Turbulence. **Ji, Q.**, Dunham, E. M., Dey, I.	Finite-Fault Rupture Detector (FinDer) for Earthquake Early Warning and Rapid Impact Estimates: Recent Developments using Large International Earthquakes. Böse, M., Andrews, J., **Saunders, J.**, Massin, F., Ceylan, S., *et al.*	Constraining the Rupture Extent of Mw 6--7 Intraslab Earthquakes Using Geodetic Data: The 110 Km Deep 2020 Calama Earthquake, Northern Chile. **Craig, T. J.**, Liu, F., Ebmeier, S., Elliott, J.	Investigating Slow Slip Transients and Earthquake Swarms on the Blanco Transform Fault With Obs Data Mining. **Journeau, C.**, Thomas, A. M., Hirao, B., Toomey, D. R., Hooft, E. E. E., *et al.*	Use of Seismometers in Studies of Precariously Balanced Rocks (PBRs) in the Eastern U.S. **Pratt, T. L.**, McPhillips, D., Stirling, M., Figueiredo, P., Lindberg, N. S.
2:30 PM	How Fast, How Deep, and How Much? — Rapid Assessment of Groundwater Recharge From 2023 California Storms With Seismic Sensing. **Mao, S.**, Beroza, G. C., Ellsworth, W. L.	Generalized Neural Networks for Universal Real-Time Earthquake Early Warning. **Zhang, X.**, Zhang, M.	Uncertainty Estimates for Moment Tensors and Quantities Derived From Them From Comparison of Global Catalogs. **Rösler, B.**, Stein, S., Spencer, B. D., Ringler, A., Vackář, J.	Distant Seismic Monitoring of a Volcanic Earthquake Swarm Near the Manu'a Islands, American Samoa, with Deep-learning and Template-matching Event Detection. **Yoon, C.**, Skoumal, R. J., Michael, A. J., Downs, D. T., Deligne, N. I., *et al.*	Identifying Probable Fault Planes in Stable Continental Regions of Canada for Use in Hazard Assessment. **Bent, A. L.**
2:45 PM	Monitoring Groundwater Dynamics at Lyon Water Catchment Using Seismic Attenuation Variations From Train Signals. **Pinzon Rincon, L.**, Nziengui Bâ, D., Mordret, A., Brenguier, F., Coutant, O.	STUDENT: Investigating Seismic Site Amplification for Improved Earthquake Early Warning in Canada. **Pietroniro, E.**, Perry, H., Crane, S., Audet, P.	Regional Moment Tensor Estimation With 3D Velocity Models—Application and Assessment to the 2017 Hojedk, Iran Sequence. **Rodriguez Cardozo, F. R.**, Braunmiller, J., Ghods, A., Sawade, L., Orsvuran, R., *et al.*	Improving Template Matching Detections Using a Convolutional Neural Network. **Jozinović, D.**, Toledo, T., Simon, V., Kraft, T.	INVITED: A Machine Learning Re-Analysis of Seismic Archives in the Northeastern U.S.: Implications for the Nature of Active Faults and Faulting. Beauce, E., **Wang, K.**, Waldhauser, F., Schaff, D., Kim, W.

Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom A/B*
	Advancing Seismology with Distributed Fiber Optic (continued)	**Assessing Seismic Hazard for Critical Facilities (continued)**	**Seismoacoustic, Geodetic and Other Geophysical (continued)**	**Structure and Behavior of the Alaska-Aleutian Subduction (continued)**
3:00 PM	Exploring Urban Distributed Acoustic Sensing Datasets With Scattering Networks. **Viens, L.**, Seydoux, L., Delbridge, B. G.	STUDENT: Site-Response Assessment Using Empirical Techniques for Nuclear Sites in South-Eastern France: Comparisons With Ssr and Numerical Simulation Estimates. **Buscetti, M.**, Traversa, P., Hollender, F., Perron, V., Moczo, P., *et al.*	INVITED: Understanding Volcanic Tremors Based on Seismic Network Analysis. **Shapiro, N. M.**, Journeau, C., Soubestre, J., Barajas, A., Seydoux, L., *et al.*	STUDENT: Slab Dehydration Linked to Great Earthquake Rupture Barriers Along the Alaska Peninsula. **Moser, L.**, Canales, J., Bécel, A.
3:15– 4:30 PM	Poster Break			

Time	*K'enakatnu 6/Boardroom*	*Kahtnu 1*	*Kahtnu 2*	*Tikahtnu Ballroom A/B*
	From Geodynamics to Earthquake Rupture, Models That Cross Time- and Length-Scales (see page 1308).	**Assessing Seismic Hazard for Critical Facilities and Infrastructure—Insights and Challenges (see page 1239).**	**Machine Learning for Full Waveform Inversion: From Hybrid to End-to-End Approaches (see page 1342).**	**Structure and Behavior of the Alaska-Aleutian Subduction Zone (see page 1424).**
4:30 PM	INVITED: Linking Geodynamic-Seismic Cycling Models With Earthquake Dynamic Rupture Models: 5 Choices to Consider. **Madden, E. H.**, van Dinther, Y., Gabriel, A. A., Ulrich, T., van Zelst, I.	INVITED: Issues in the Selection of Design Values for Surface Fault Rupture for Critical Facilities Using Probabilistic Fault Displacement Hazard Analysis. **Abrahamson, N. A.**	INVITED: Advancing Seismic Full Waveform Inversion: A Hybrid Approach of Machine Learning and Physical Models for Improved Generalizability and Efficiency. **Lin, Y.**	Seismic Structure of Arc Crust in the Andreanof Segment of the Aleutian Arc from Wide-angle Refraction Data. **Mark, H. F.**, Lizarralde, D., Shillington, D., Cortés Rivas, V.
4:45 PM	Using a Multi-Cycle, Physics-Based Earthquake Simulator to Explore Rupture Connectivity for Seismic Hazard: The Aotearoa New Zealand Example. **Howell, A.**, Penney, C., McLennan, T., Seebeck, H., Williams, C. A., *et al.*	Exposure of Australia's Infrastructure to Ground Surface Rupture Hazard. **Quigley, M.**, Werner, T., Yang, H.	STUDENT: Ambient Noise Full Waveform Inversion With Neural Operators. **Zou, C.**, Azizzadenesheli, K., Ross, Z. E., Clayton, R.	STUDENT: Along-strike Variations in Sub-arc Melting Beneath the Alaska Peninsula Revealed by Body Wave Attenuation. **Zhang, Z.**, Wei, S. S.
5:00 PM	INVITED: Bridging the Gap Between Millions of Years and Milliseconds in Visco-Elasto-Plastic Subduction Earthquake Sequence Models. **Koelzer, A. J.**, de Vos, M., Gerya, T., van Dinther, Y.	Studies of Fragile Geologic Features in Central New England, USA, and Northeastern New Zealand. **Stirling, M. W.**, Pratt, T. L.	Application of TCN, UMAP, and XGBoost to Pg and Lg Wave Amplitude to Identify Mining vs. Non Mining and Deep vs. Shallow Events. **Goddard, K.**, Saikia, C. K., Stanley, J., Patrick, T., Zhou, R., *et al.*	STUDENT: A Possible Slab Window Along the Alaska Subduction Zone Imaged by Full Wave Ambient Noise Tomography. **Sassard, V.**, Yang, X., Liu, L., Elliott, J.

Time	Tikahtnu Ballroom C	Tikahtnu Ballroom E/F	Tubughnenq' 3	Tubughnenq' 4	Tubughnenq' 5
	ESC-SSA Joint Session: Climate Change (continued)	**End-to-End Advancements (continued)**	**Understanding and Quantifying (continued)**	**Advances in Operational (continued)**	**Tectonics and Seismicity (continued)**
3:00 PM	Merits of Installing Environmental Sensors at Seismic Stations. **Tanimoto, T.**	Predicting Ground Motion Waveforms for Earthquake Early Warning Using Convolutional Long Expressive Memory Models. Lyu, D., **Nakata, R.**, Erichson, B. N., Nakata, N., Ren, P., *et al.*	Quantifying the Effect of 3D Wavespeed Models on Moment Tensors Using Synthetic Data in the Middle East. **Doody, C.**, Chiang, A., Simmons, N., Rodgers, A.	INVITED: STUDENT: Automated Detection and Characterization of Swarms and Mainshock-Aftershock Sequences in Southern Mexico. **Ventura-Valentin, W. A.**, Brudzinski, M. R., Bennett, A., Khalkhali, M., Coker, S.	Active Seismicity Around a Cretaceous Magmatic Intrusion in Monchique, SW Iberia. Neres, M., Cunha, G., **Custódio, S.**, Soares, A., Vales, D., *et al.*
3:15– 4:30 PM	Poster Break				

Time	Tikahtnu Ballroom C	Tikahtnu Ballroom E/F	Tubughnenq' 4	Tubughnenq' 5
	ESC-SSA Joint Session: Climate Change and Environmental Seismology (see page 1284).	**End-to-End Advancements in Earthquake Early Warning Systems (see page 1276).**	**Advances in Operational and Research Analysis of Earthquake Swarms -II (see page 1220).**	**Tectonics and Seismicity of Stable Continental Interiors (see page 1436).**
4:30 PM	INVITED: Leveraging Distributed Fiber Optic Sensing for Year-Round Observation of Sea Ice and Submarine Permafrost: Successes and Lessons Learned From the Beaufort Sea, Alaska. **Baker, M. G.**, Stanciu, C., Abbott, R. E., Frederick, J. M.	Engineering Earthquake Early Warning. **Galasso, C.**	Seismological Study of the West Bohemia/Vogtland Swarm Region With Waveform and Catalog Data. **Olivar-Castaño, A.**, Büyükakpinar, P., Ohrnberger, M., Dahm, T., Doubravová, J., *et al.*	INVITED: Amplification and Attenuation: Putting the Puzzle Together for Ground Motions in the Atlantic and Gulf Coastal Plains. **Cabas, A.**, Gann-Phillips, C., Ji, C.
4:45 PM	STUDENT: Storms, Sea Ice, and Microseismic Noise in Alaska. **John, S.**, West, M.	STUDENT: Toward Earthquake Early Warning in Nevada. **Kinkel, D.**, Trugman, D.	Systematic Measurements of Parameters During Earthquake Swarms. **McNutt, S. R.**, Thompson, G., Braunmiller, J., Rodriguez Cardozo, F., Holtkamp, S.	The 1886 Charleston, South Carolina, Earthquake: Source Properties and Ground Motions. **Hough, S. E.**, Bilham, R.
5:00 PM	Correlation of Environmental Factors With Seismic Records on the Alaska Geophysical Network. **Heslop, J.**, Murphy, N., West, M., Parcheta, C., Ruppert, N., *et al.*	Evaluation of the Ocean Networks Canada Earthquake Early Warning System: Magnitude Estimation and Site Condition. **Babaie Mahani, A.**	INVITED: Earthquake Swarms as a Window to Characterize Transient Processes. **Chen, X.**, Jiang, J., Sagae, K., Uchide, T.	Reactivated Paleozoic and Mesozoic Basement Faults in the Charleston, South Carolina, Seismic Zone. **Shah, A. K.**, Pratt, T. L.

Friday, 3 May (*continued*)

Time	K'enakatnu 6/Boardroom	Kahtnu 1	Kahtnu 2	Tikahtnu Ballroom A/B
	From Geodynamics to Earthquake Rupture, Models (continued)	**Assessing Seismic Hazard for Critical Facilities (continued)**	**Machine Learning for Full Waveform Inversion: From Hybrid (continued)**	**Structure and Behavior of the Alaska-Aleutian Subduction (continued)**
5:15 PM	STUDENT: Fully Dynamic Earthquake Cycle Modeling to Explore Interactions Between Large Earthquakes and Slow Slip Events on Heterogeneous Faults. **Tang, Z.**, Duan, B., Meng, Q.	Fault-Displacement Models for Aggregate, Principal, and Distributed Displacements. **Lavrentiadis, G.**, Abrahamson, N. A.	Scaling Up Large Fourier Neural Operator Training in 3D Seismic Waveform Modeling. **Kong, Q.**, Matzel, E., Zou, C., Choi, Y., Ross, Z., *et al.*	The Structure of the Alaskan Mantle: A Full Waveform Inversion Approach. **Frost, D. A.**, Romanowicz, B., Adourian, S.
5:30 PM	STUDENT: Insights Into Fault Interactions in Central New Zealand Using Paleoearthquake Records and Earthquake Simulators. **Humphrey, J. A.**, Howell, A., Penney, C., Nicol, A., Litchfield, N., *et al.*	Looking for kappa in the US and the UK Using Noise Modeling. **Ktenidou, O. J.**, Pikoulis, E. V., Darragh, R. B., Silva, W. J., Aldama-Bustos, G.	INVITED: Physics-Informed Deep Generative Models to Quantify Uncertainties in the Geophysical Full-Waveform Inversion. **Elmeliegy, A. M.**, Dhara, A., Sen, M. K., Harding, J. L., Yoon, H.	Upper Mantle Velocity Structure and Anisotropy of the Alaskan Subduction Zone from Surface Wave Tomography. Adams, A., **Ramirez, C.**, Wen, J., Leclerc, P.

Poster Sessions

The 2024 Magnitude 7.5 Earthquake and the Associated Earthquake Swarm Beneath the Noto Peninsula, Central Japan (See Supplemental Material)

Advancing Seismology with Distributed Fiber Optic Sensing (see page 1228).

1. Matched-Filter Earthquake Detection Applied to City-Scale DAS Fibre-Optic Systems in Aotearoa New Zealand: What More Can We Detect?. **Chamberlain, C. J.**, McNab, A., Lindsey, N., Townend, J., can Wijk, K.
2. STUDENT: Using AIS Data to Determine the Location of Ocean Bottom Fiber Optic Cables. **Collares, M. P.**, Spica, Z., Viens, L.
3. Near-Source T-Wave Observations in the North Atlantic Using Distributed Acoustic Sensing. Schlaphorst, D., Loureiro, A., Matias, L., **Custódio, S.**, Corela, C., *et al.*
4. STUDENT: Geolocalization and Preliminary Surface Signals of Cascadia DAS Array, Port Angeles, Washington. **Dingo, H.**, Sheehan, A. F., Mendoza, M. M., Martin, E. R.
5. Fiber Optic Wellbore Installation for Distributed Acoustic Sensing at Los Alamos National Laboratory. **Donahue, C.**, Maier, N., Roberts, P.
6. STUDENT: Use of Distributed Acoustic Sensing as a Tool for Monitoring Geohazards at Mt. Rainier. **Gaete Elgueta, V. A.**, Lipovsky, B., Denolle, M., Thelen, W., Kharita, A.
7. STUDENT: Signal Detection With Neural Networks in Dark Fiber Seismic Data. **Hoyle, A. M.**, Smolinski, K., Bozdag, E., Wu Fung, S., Fichtner, A., *et al.*
8. STUDENT: Modelling Wavefield Complexity for Submarine DAS Data From Santorini (Greece). **Igel, J.**, Klaasen, S., Noe, S., Nomikou, P., Karantzalos, K., *et al.*
9. Earthquake Detection of the MiDAS Seismic Monitoring System Containing Downhole Optic-Fiber Distributed Acoustic Sensing and Borehole Seismometers. **Lin, Y.**, Chan, J.
10. STUDENT: HD-TMA: A New Fast Template Matching Algorithm Implementation for Linear DAS Array Data. **Lv, H.**, Zeng, X., Song, Z.
11. 2-D Shear-Wave Velocity Profile of Shallow Sediments Using Ocean Bottom Distributed Acoustic Sensing and Ambient Noise Probabilistic Inversion. **Ben Mansour, W.**, Spica, Z., Viens, L., Liu, M.
12. Towards a Metadata Standard for Distributed Acoustic Sensing (DAS) Data Collection. **Mellors, R. J.**, Hui Lai, V., Hodgkinson, K. M., Porritt, R.
13. Exploring the Potential for Joint Monitoring of Tectonic Tremor Using Dark Fiber and Seismometers. **Mendoza, M. M.**, Martin, E. R., Issah, A. S., Jin, G., Gaete Elgueta, V. A., *et al.*
14. A Metadata and Time-Series DAS Workflow Using Cloud Computing. **Ramos, M. D.**, Hodgkinson, K. M., Tibi, R.

Time	Tikahtnu Ballroom C	Tikahtnu Ballroom E/F	Tubughnenq' 4	Tubughnenq' 5
	ESC-SSA Joint Session: Climate Change (continued)	**End-to-End Advancements in Earthquake (continued)**	**Advances in Operational and Research Analysis of Earthquake (continued)**	**Tectonics and Seismicity of Stable Continental Interiors (continued)**
5:15 PM	INVITED: An Extraordinary Tsunamigenic Rockslide Into a Greenland Fjord Rang the Earth for 9 Days. Svennevig, K., Hicks, S. P., Forbriger, T., Lecocq, T., Widmer-Schnidrig, R., **Mordret A.** *et al.*	STUDENT: Impact Assessment of Eew Systems in Central America. **Orihuela, B.**, Clinton, J., Papadopoulos, A., Danciu, L., Böse, M., *et al.*	Deep Learning Analysis of Transient Signals Preceding the 2023 Mw 7.8 Kahramanmaraş Earthquake in Türkiye. **Zali, Z.**, Martinez Garzon, P., Kwiatek, G., Bohnhoff, M., Beroza, G.	Evidence of Quaternary Deformation in the Ste. Genevieve Fault Zone, Southeastern Missouri: Preliminary Results. **Counts, R. C.**, Vaughn, J., Nelson, W., Devera, J. A., Curry, B.
5:30 PM	Insights for Adjacent Sciences—Connecting Science, Art and Deep Knowledge for Climate Adaptation and Mitigation. **Strickert, G. E. H.**, Bradford, L. E. A., Helgason, W.	Performance of Operational Earthquake Early Warning Across Central America. **Massin, F.**, Clinton, J., Bose, M., Burgoa, B., Marroquin, G., *et al.*	Enhanced Seismicity at a Geothermal Spot in Southern Tibet Following 2004 Mw 9.1 Sumatra and 2005 Mw 8.6 Nias Earthquakes and Its Implication for Rifting Process. **Liang, X.**	Microgal-Precision Gravity Imaging Within an Active Intraplate Fault: The 2020 m5.1 Sparta, Nc Epicentral Zone. **Levandowski, W.**

15. Exploring Source and Structure Sensitivity Kernels of DAS Ambient Noise Correlations. **Pinzon Rincon, L.**, Mordret, A., Brenguier, F., Gradon, C., Lavoué, A., *et al.*
16. Distributed Fiber-Optic Magnetic Sensing for Subsurface Imaging and Monitoring. **Yuan, S.**, Snyder, T., Martin, E., Homa, D., Dejneka, Z., *et al.*

End-to-End Advancements in Earthquake Early Warning Systems (see page 1281).

17. Improving Seismic Networks for the Earthquake Early Warning Mission. **Biasi, G.**, Stubailo, I., Alvarez, M.
18. Picket Fence: An Earthquake Alert System for the Ligo Detectors. **Bonilla, E. L.**, Aguilar, I., Lantz, B.
19. Examination of Usage Rates for the Multi-Hazards San Diego County Emergency App to Improve Earthquake Early Warning. **Brudzinski, M. R.**, Sumy, D., Gomez, K., Jordan, P., Robles, M., *et al.*
20. Implementation of a Machine Learning Classifier in the Real-Time EPIC Earthquake Early Warning Algorithm. **Lux, A. I.**, Henson, I., Meier, M., Allen, R. M.
21. Engage With Your Regional Museums, Parks, and Libraries for Community Resilience. Preciado Mendez, R. G., Benne, M., de Groot, R., **Herrán, C.**, Crayne, J.
22. Recent Earthquake Early Warning Research and Developments at the Southern California Seismic Network. **Saunders, J. K.**, Biondi, E., Boese, M., Bunn, J., Cochran, E., *et al.*
23. Preliminary Multilingual Survey Results on San Diego County's Sd Emergency Multi-Hazards App to Improve Equity in Disaster Risk Reduction. **Sumy, D.**, Brudzinski, M. R., Gomez, K., Briceno, Y., Jordan, P., *et al.*
24. Magnitude Station Corrections to Improve Initial Magnitude Estimates for ShakeAlert. **Terra, F.**, Lombard, P. N., Williamson, A., Uhrhammer, R., Taira, T., *et al.*
25. Low-Latency Digitization, Communication and Alerting for Earthquake Early Warning Systems: Güralp Minimus. **Lindsey, J. C.**, Watkiss, N. R., Hill, P., O'Neill, J.

ESC-SSA Joint Session: Climate Change and Environmental Seismology (see page 1286).

26. Successful Deployment of an 21km SMART Cable With Force-Feedback Seismometer and Accelerometers in the Mediterranean Sea. **Lindsey, J. C.**, O'Neill, J., Nicholson, B., Watkiss, N., Marinaro, G., *et al.*
27. Using Deep Learning to Detect Vehicle Related Signals From Seismic Records. **Chai, C.**, Marcillo, O., Maceira, M., Kerekes, R.
28. Monitoring Groundwater Using Ambient Seismic Noise. **D'Amico, S.**, Galone, L., Panzera, F., Colica, E., Fucks, E., *et al.*
29. Influence of the Hurricane Otis on the Mexican Seismic Network. **Dominguez, L. A.**, Quintanar, A., Cruz-Atieza, V. M., Gómez-Ramos, O., Plata-Martinez, R., *et al.*
30. Glacier Seismology Application. **Germenis, N. G.**

31. Student: Estimation of the Source Region of Secondary Microseism Generated by Pacific Typhoons Using CTBTO Seismic Arrays. **Kim, Y.**, Sheen, D.
32. Global Observation of an Up to 9 Day Long, Recurring, Monochromatic Seismic Source Near 10.9 mHz Associated With Tsunamigenic Landslides in a Northeast Greenland Fjord. Widmer-Schnidrig, R., **Mordret, A.**, Svennevig, K., Hicks, S. P., Forbriger, T., *et al.*
33. Exploration of Decadal Crustal Velocity Changes Associated With Tidal-Induced Strain Using Seismic Noise. **Wu, S.**, Nakata, N.
34. Student: Resolving Temporal Variations in Subsurface Velocity and Attenuation Structure Across the Taklimakan Desert Using Road Traffic Seismic Signals. **Zhao, L.**, Meng, H., Liang, X.

Tectonics and Seismicity of Stable Continental Interiors (see page 1440).

35. Student: Inferring Crustal Stress Distribution Within the Middleton Place/summerville Seismic Zone, South Carolina. **Adeboboye, O. E.**, Peng, Z., Jaume, S.
36. Student: Developing Ground Motion Model Using Nonparametric Machine Learning Techniques for Induced Earthquakes in Central and Eastern North America (Cena). **Alidadi, N.**, Pezeshk, S.
37. Seismic Networks Important in Lower Seismic Hazard Environments like Australia. **Borleis, E.**
38. Neotectonic Mapping of the Charleston Seismic Zone, South Carolina. **Thompson Jobe, J. A.**, Briggs, R., Collett, C., Shah, A. K., Pratt, T.
39. Student: Determination of Focal Depth of Offshore Earthquakes Around the Korean Peninsula Using Depth Phase. **Lee, H.**, Sheen, D.
40. Student: Africa's Lithospheric Architecture With Multi-Mode Body Wave Imaging. **Legre, J. B.**, Olugboji, T. M.
41. Crustal Structure and Mantle Deformation Across the Central African Plateau, Zambia: Evidence from Receiver Functions and Shear-Wave Splitting Analysis. Kounoudis, R., **Ogden, C. S.**, Chifwepa, C., Fishwick, S., Kendall, M., *et al.*
42. Student: Stochastic Inversions of Source, Path, and Site Parameters for West Texas Earthquakes. **Pandel, B.**, Rathje, E. M., Savvaidis, A., Kottke, A. R.
43. The 2020 Sparta, North Carolina, Earthquake: Insights From Double-Difference Earthquake Relocations, Regional Moment Tensor Inversion and Coulomb Static Stress Transfer. **Parija, M.**, Chapman, M. C., Pollyea, R.
44. Neotectonic Controls on the Meadow Bank Scarp, Wabash Valley Seismic Zone USA. **Woolery, E. W.**, Stephenson, W. J., Woller, K. L., Leeds, A. L., Lindberg, N. S., *et al.*
45. Source Characterization of the 2020 Mw 5.1 Sparta, North Carolina, Earthquake Sequence. **Wu, Q.**, Chapman, M.

Anisotropy Across Scales (see page 1234).

46. Student: Analysis of Anisotropic Characteristics in the Valley of Mexico. **Chacón, F.**, Quintanar-Robles, L., Rodríguez-Rasilla, I.
47. S Wave Velocity and Azimuthal Anisotropy From Ambient Noise Data in the Sanjiang Lateral Collision Zone of SE Tibetan Plateau. Tian, J., **Gao, Y.**, Li, Y.
48. Student: Exploration of Anisotropy from Crystal to Whole-Earth Scales. **Gupta, A.**, Tape, C.
49. 3D Shear Wave Velocity and Azimuthal Anisotropy Model for the Crust and Upper Mantle in Alaska Extracted by the Joint Inversion of Wave Gradiometry Method and Ambient Noise Tomography Method. **Liang, C.**, Liu, Z., Cao, F.
50. Imaging Lower Crustal Flow Using Harmonic Decomposition of Receiver Functions Beneath a Dense Seismic Profile in Eastern Massachusetts. **Link, F.**, Luo, Y., Long, M. D., Kuiper, Y. D.
51. Shear Wave Splitting Characteristics of Aligned Partial Melt Configurations in a Subduction Zone Back-Arc Setting. **Loeberich, E.**, Wolf, J., Long, M. D.
52. A Reformulation of the Browaeys and Chevrot Decomposition of Elastic Maps. **Tape, W.**, Tape, C.
53. Student: Refining Splitting Intensity Measurements of Shear Wave Splitting for Multi-Layer Anisotropy. **Valencia, N.**, Kumar, U., Soergel, D., Romanowicz, B.

Understanding and Quantifying the Variability in Earthquake Source Parameter Measurements (see page 1452).

54. Student: Using a 1-D Radially Symmetric Coda Envelope Model for Robust Source Scaling in Iraq's Tectonically Diverse Zones. **Al-Kaabi, M.**, Mayeda, K., Roman-Nieves, J., Chiang, A., Mahdi, H., *et al.*
55. A Comparison of the Stress Drop Estimates Derived From Different Techniques in Pollino, Italy. **Calderoni, G.**, Abercrombie, R. E.
56. Student: Sensitivity Analysis of Seismic Hazard Parameters for the Understanding of Its Uncertainties: A Study Case for Central America. **Gamboa-Canté, C.**, Arroyo-Solórzano, M., Rivas-Medina, A., Benito, B.
57. Adjoint Earthquake Source Inversion Method Using P-Wave Spectra and Focal Mechanism Solutions. **Cheng, Y.**, Dreger, D. S., Allen, R. M.
58. Bayesian Inference for the Seismic Moment Tensor Using Regional Waveforms and a Data-Derived Distribution of Velocity Models. **Chiang, A.**, Ford, S. R., Pasyanos, M.
59. Characterizing Directivity in Small (M3-5) Aftershocks of the Ridgecrest Sequence. **Chu, S.**, Baltay, A. S., Abercrombie, R.

60. DAS Derived Source Characterization of Ridgecrest Aftershocks Using Coda Spectral Ratios. **Delbridge, B. G.**, Viens, L., Zhan, Z., Chen, X.
61. STUDENT: Understanding Sources of Variability and Uncertainty in the Relative Magnitude Method. **Gable, S.**, Huang, Y.
62. STUDENT: Development of Empirical Scaling Relationships Between Spectral Displacement Amplitudes Measured in the Time Domain and Earthquake Magnitudes in South Korea. **Hong, Y.**, Kim, B., Sheen, D.
63. Moment-Rate Spectra, Source Scaling and Spectral Fall-Off in the Korean Peninsula Using the Coda Calibration Tool (2.0<Mw<5.5): Application to Natural and Man-Made Sources. **Mayeda, K.**, Roman-Nieves, J., Son, M.
64. STUDENT: Evaluating Scaling Relationships From Insar-Derived Earthquake Source Parameters. **Rivera, K. M.**, Funning, G. J.
65. STUDENT: Rupture Directivity of Small Earthquakes in Southern Korean Peninsula. **Seo, M.**, Han, S., Kim, W., Kim, Y.
66. On the Variability Discrepancy Between PGA and Spectral Stress Drop: Insight From Double-Corner-Frequency Spectra. **Shimmoto, S.**, Miyake, H.
67. New Version of the Earthquake Mechanism of Mediterranean Area (EMMA) Database With a Web-Gis Interface. **Vannucci, G.**, Tarabusi, G., Taccone, R., Biondini, E., Lolli, B., *et al.*

Seismoacoustic, Geodetic and Other Geophysical Investigations of Active Volcanoes **(see page 1405).**

68. STUDENT: Surface Deformation at the Socorro Magma Body: A Natural Laboratory for Probing Mush and Magma in the Mid-Crust. **Block, G. A.**, Roy, M., Graves, E., Grapenthin, R.
69. Automated Detection of Volcanic Seismicity Using Network Covariance and Image Processing. Maher, S., **Dawson, P.**, Hotovec-Ellis, A., Thelen, W., Matoza, R.
70. Long-Period Earthquakes in the Yellowstone Volcanic System: When, Where, Why?. **Farrell, J.**, Hale, M., Baker, B.
71. STUDENT: Mining for Hidden Seismicity at Mount St. Helens. **Hirao, B. W.**, Thomas, A. M., Shelly, D. R., Thelen, W.
72. Ground-Tilt Caused by Atmospheric Lamb Waves From the 2022 Tonga Eruption Recorded at Fiji and Pinon Flat Observatory. **Ichinose, G. A.**, Mellors, R. J.
73. Soundquakes: Seismo-Infrasonic and Seismo-Infra-Seismic Phases During a Swarm of Earthquakes at Kilauea Volcano on September 30th, 2021. **Johnson, J.**, Jolly, A., Anderson, J. F.
74. STUDENT: Laboratory Experiments on Gas-Driven Volcanic Tremor and Long Period Seismicity. **Kim, K.**, Spina, L., Taddeucci, J., Pennacchia, F., Cornelio, C., *et al.*
75. Monitoring Unrest at a Supervolcano: Insights From the 2022-23 Unrest Episode at Taupō Volcano, Aotearoa New Zealand. **Lamb, O.**, Hreinsdóttir, S., Power, W., Bannister, S., Ristau, J., *et al.*
76. STUDENT: Imaging the Magma Plumbing System Below Okmok Volcano Using Full-Wave Ambient Noise Tomography. **Lizik, Y.**, Maurer, J., Yang, X., Kupres, C. A.
77. STUDENT: Crustal Structure of the Laguna Del Maule Volcanic Field Using Receiver Functions. **Nolt-Caraway, S.**, Portner, D.
78. Seismological Models and Seismicity Patterns in the Kivu Rift and Virunga Volcanic Province (D.R. Congo). Subira, J., Barrière, J., Caudron, C., **Oth, A.**, d'Oreye, N., *et al.*
79. STUDENT: Seismicity Classification From Eruptions: Analysis of Hawaiian and Aleutian Island Volcanoes. **Rinty, S.**, Goebel, T. H.
80. Analysis of the Seismicity Recorded Before the May 22, 2021 Eruption of Nyiragongo Volcano, Democratic Republic of the Congo. **Sadiki, A.**, Kyambikwa, A., Namogo, D., Diomi, L., Munguiko, O., *et al.*
81. Seismic Source Scaling of Volcano-Seismic Events: Tracking Magma Plumbing System Overpressure and Volume Through Macroscopic Seismic Source Parameters. Niu, J., **Song, T.**
82. Eruption Dynamics of the 2022 Mauna Loa Eruption Revealed Through Tremor. **Thelen, W.**, Iezzi, A. M., Chang, J. C., Dotray, P.
83. Using Remote Hydroacoustic Recordings to Track Volcanic Unrest Near the Taʻū Islands, American Samoa. **Wech, A.**, Haney, M. M., Chang, J. C., Jolly, A., Yoon, C.
84. STUDENT: Inversion of Multiple Concurrent Resonant Oscillations at Kīlauea Volcano During Very-Long-Period Seismic Events Informs Magma System Properties. **Wilde, K. L.**, Karlstrom, L., Crozier, J. A., Lynn, K. J.
85. Seismic Velocity Changes Across Multiple Eruption Cycles at Shishaldin Volcano in the Eastern Aleutian Arc. **Yang, X.**, Freymueller, J. T., Kupres, C. A., Denolle, M. A., Haney, M. M.
86. Seismicity, Ambient Noise Tomography, and Anthropogenic Noise via the Auckland-Hauraki Node Array in New Zealand. **Zhang, P.**, Pickle, R., Miller, M. S.

Physics-Based Ground Motion Modeling **(see page 1380).**

87. A Parametric Analysis on the Behaviors of Seismic Waves Interacting With Geologic Metamaterials. **Beskardes, G. D.**, Preston, L.
88. STUDENT: Updated Regional Seismic Velocity Model for the US Atlantic and Gulf Coastal Plains Based on Measured Shear Wave Velocity, Sediment Thickness,

Varying Geologic Structure With Depth, and Lateral Variations. **Gann-Phillips, C.**, Cabas, A.

89. Physics-based Numerical Modeling of Site-specific Amplification in Ground Motions: A Case Study of Wellington Basin. **Li, D.**, Thingbaijam, K., Hill, M., Howell, A., Bora, S., *et al.*
90. Constraining Large Magnitude Event Source and Path Effects Using Ground Motion Simulations. **Meng, X.**, Graves, R., Goulet, C.
91. Student: The Case of the Missing Frequencies: Reduction of Artificial Spectral Deficiency in Semistochastic Broadband Simulation. **Nye, T.**, Dybing, S., Melgar, D., Sahakian, V. J.
92. Student: 3D Ground Motion Simulations of the 1755 Lisbon Earthquake. **Patel, A.**, Olsen, K., Yeh, T., Custódio, S.
93. Student: Extended Finite-Fault Ground Motion Modeling Framework: Sensitivity Analysis of Number of Sub-Faults. **Singh, O.**

From Geodynamics to Earthquake Rupture, Models That Cross Time- and Length-Scales (see page 1309).

94. Bridging Spatial and Temporal Scales in Modeling Coseismic and Interseismic Crustal Deformation with PyLith. **Aagaard, B. T.**, Knepley, M. G., Williams, C. A.
95. Student: Spatiotemporal Evolution of Postseismic Stress and Aftershocks Following the 2010 Mw 8.8 Maule Earthquake. **Bodunde, S. S.**, Jiang, J.
96. Geodynamic Modeling of Flat Slab Subduction Driving Microplate Tectonics in Alaska. **Jadamec, M. A.**, Haynie, K. L., Knepley, M. G.
97. Fast and Slow Earthquakes in Alaska: Insights From Three-Dimensional Thermal Structure and Slab Dehydration. **Ji, Y.**, Qu, R., Zhu, W.
98. Student: Modeling the Proposed Deep Slab-Deformation Processes Behind Potential Precursory Signals Preceding Large Subduction Zone Earthquakes. **Lemus, I. C.**, Baden, C. W., Chanard, K., Wang, L., Bürgmann, R.
99. Geodynamic Models Connecting the Seismic Timescale to the Tectonic Timescale. **Moresi, L.**, Yang, H., Giordani, J., Knight, B.

Machine Learning for Full Waveform Inversion: From Hybrid to End-to-End Approaches (see page 1343).

100. Physics-Guided Neural Network for Full Waveform Inversion With Structural Enhancement. **Bi, Z.**, Nakata, N.
101. Student: Physics-Guided Unsupervised Deep Learning Approach for the Inversion of Receiver Functions in Dipping and Anisotropic Media. **Dalai, B.**, Kumar, P., Sen, M. K.
102. Towards a Practical Physics-Informed Neural Network Method for End-to-End Full Waveform Inversion. **Harding, J. L.**, Lizama, D., Yoon, H., Gauvain, S. J., Preston, L. A., *et al.*
103. Student: An Autoencoder-Based Prior for Bayesian Full Waveform Inversion. **Hu, S.**, Sen, M. K., Zhao, Z., Elmeliegy, A. M.

Structure and Behavior of the Alaska-Aleutian Subduction Zone (see page 1428).

104. Student: A Re-Evaulation of Slip During the 2021 M8.2 Chignik, Alaska Earthquake. **Bennett, A. J. M.**, Elliott, J., Grapenthin, R., Freymueller, J. T.
105. Take the Cook Inlet DAS Earthquake Challenge!. **Bodin, P.**, Williams, E. F., Shi, Q., Ni, Y., Lipovsky, B., *et al.*
106. Student: Searching for Microseismic Precursors to the July 2020 Mw 7.8 Simeonof, Alaska Earthquake in a Machine-Learning Enhanced Catalog. **Friedman-Alvarez, C.**, Barcheck, G., Nolan, S., Abers, G. A.
107. Introducing the Alaska Broadband Accessory Deployment for Geophysical Research (BADGER): A New Seismic Dataset for Investigating Slow Slip and Subduction Zone Structure. **Golos, E.**, Aleid, M. H., Lord, N., Sobol, P., Denolle, M., *et al.*
108. Mapping the Alaskan Lithosphere Based Upon Joint Full-Waveform Inversion of Ambient Noise and Local Earthquake Data. **Liu, T.**, Wang, K., Tape, C., He, B., Yang, Y., *et al.*
109. Insights Into Inherited Crustal Features and Southern Alaska Tectonic History From Sp Receiver Functions and Seismicity. **Mann, M.**, Fischer, K. M., Benowitz, J. A., Wech, A.
110. Student: Examining the Distribution of Earthquakes Within the Alaska-Aleutian Subduction Zone Using Events Detected by the Alaska Amphibious Community Seismic Experiment. **Nolan, S.**, Abers, G., Barcheck, G., Friedman-Alvarez, C., Roecker, S. W.
111. Student: Searching for Tectonic Tremor Along the Lower Cook Inlet Portion of the Alaska-Aleutian Subduction Zone. **Ochoa, E.**, Golos, E. M.
112. Student: Probabilistic Teleseismic Tomography of the Alaskan Mantle With Corrections for Distant Structure. **Okkonen, N.**, Burdick, S.
113. Building a 3D Seismic Velocity Model for the Gulf of Alaska. **Onyango, E. A.**, Tape, C., Mcpherson, A.
114. Student: Investigating Temporal Velocity Changes and Plate Interface Structure in the Southern Mw 9.2 1964 Great Alaska Earthquake Rupture Area: A Comparative Study of Ambient Noise and Earthquake Observations Using a Dense Node Array. **Osasona, J. O.**, Worthington, L. L., Schmandt, B., Barcheck, G., Abers, G., *et al.*
115. Upper Plate Structure in the Alaska Subduction Zone Across the 2020 and 2021 Ruptures From 2D Wide-Angle

Seismic Data. Burstein, J., **Shillington, D.**, Bécel, A., Nedimović, M. R.

116. Student: Comparison of Crustal Magmatic Storage at Aleutian Volcanoes, Gareloi and Kanaga, using Teleseismic Receiver Function Analysis. **Wandasan, C.**, Janiszewski, H., Wynn, I. V.., Power, J. A., Haney, M. M.
117. Cook Inlet DAS (CI-DAS): A Year-Long Experiment Studying Structure, Seismicity, Ocean Waves, and Acoustics Offshore Southern Alaska. **Williams, E. F.**, Abadi, S., Aderhold, K., Bodin, P., Denolle, M., *et al.*
118. Invited: Student: Investigation of Magmatic Systems Through Novel Seismic Receiver Function Analysis at Alaska-Aleutian Arc Volcanoes. **Wynn, I. V.**, Janiszewski, H. A., Power, J. A., Haney, M. M., Roman, D.
119. Student: Testing Machine Learning Phase Pickers to Develop a High-Resolution Earthquake Catalog With a 398-Instrument Nodal Array on Kodiak Island, Alaska. **Zhu, H.**, Ayling, S., Worthington, L. L., Barcheck, G.

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120. Student: Feature-based Magnitude Estimates for Small, Nearby Earthquakes in the Yellowstone Volcanic Region. **Armstrong, A. D.**, Baker, B., Koper, K.
121. Student: Analysis of Yellowstone Earthquake Swarms After Relocating Using Nonlinloc-Ssst and a 3D Velocity Model. **Czech, T. L.**, Farrell, J.
122. It's Swarmy Outside: Defining Swarms for the Purpose of Forecasting. **Llenos, A. L.**, Michael, A. J., McBride, S. K., Page, M. T., van der Elst, N., *et al.*
123. Event-Event Waveform Correlation and Multi-Event Multi-Channel Deconvolution Applied to Temporal-Spatial Patterns of Micro Earthquake Sequences (Swarms). **McLaughlin, K. L.**, Jaume, S. C.
124. Heterogeneous Seismic Swarm Activity in Central Utah: Triggering Mechanisms and Their Complex Interactions. Petersen, G., Whidden, K., **Pankow, K. L.**
125. What Has Unimak Island in Alaska Witnessed in the Last ~30 Years?—a Seismic Recap. **Parameswaran, R. M.**, Grapenthin, R.
126. Correlations and Change Points Identification in Crustal Anisotropy, b-Value and Vp/vs, Time Series During Seismic Swarm Occurrences in the Alto Tiberina Fault Zone (Italy). **Zaccarelli, L.**, Taroni, M., Baccheschi, P.

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127. Implementation of Interconnected Fault Systems in PSHA: Testing Existing Algorithms in Different Tectonic Context. El Kadri, S., **Beauval, C.**, Brax, M., Klinger, Y.
128. Magnitude Dependency of Spectral Decay Parameter (Kappa) at Rock Stations from Event Dataset that is Restricted Only from Events that are Originated around Eastern Anatolian Fault (EAF). **Biro, Y.**
129. Monitoring and No-Money-Toring of Oil and Gas Production in Southern Italy. **Braun, T.**, Danesi, S.
130. Student: Insights From Distinct Element Method Models on Fault Scarp Morphology in Thrust and Reverse Fault Earthquakes. **Chiama, K.**, Bednarz, W., Moss, R., Shaw, J. H.
131. Overcoming Factors That Limit the Predictive Power of Probabilistic Fault Displacement Hazard Models. **Elliott, A.**, Hammer, M., Vermeer, J., DeLong, S., Kottke, A., *et al.*
132. Time-Domain Seismic Response Retrieval from Ambient Noise Recorded by the Existing Seismometer of Dams Based on Interferometric Processing. **Kuroda, S.**
133. Comparison of Methods to Produce Virtual Ruptures for Background Seismicity. Yust, M., **Largent, M.**, Williams, T., Watson-Lamprey, J., Montaldo-Falero, V., *et al.*
134. Student: The Role of Epistemic Uncertainty Estimations in Seismic Safety Decision Making and Relation to Levels of Input Model Simplification. **Liou, I. Y.**, Abrahamson, N. A.
135. Using 3D Seismic Simulations to Determine Structural Designs That Best Preserve Structural Integrity of Buildings in an Earthquake. **Ronnett, M.**

Integrative Assessment of Soil-Structure Interaction and Local Site Effects in Seismic Hazard Analysis (see page 1330).

136. Student: Assessment and Results From New Bayesian SPAC Analysis for 1D Velocity Profiles Compared to Traditional MASW in Puerto Rico. **Toro Acosta, C.**, Vanacore, E., Pachhai, S., Stephenson, W. J.
137. Seismic Response in Pyramids of the Chichén Itzá Area, México. **Cardenas-Soto, M.**, Escobedo-Zenil, D., Cifuentes-Nava, G., Sánchez-González, J., Martínez-González, J., *et al.*
138. Site Response Analysis and Its Significance at Nonlinear Sites. **Lee, J.**, Bayudanto, A., Yazdi, M., Rong, W., Walker, M.
139. Student: Ambient Vibration Testing of Canada's Tallest Wood Frame Building. **Leishman, T.**, Ventura, C. E., Motamedi, M., Cassidy, J. F., Dosso, S. E.
140. Wind Turbines as a Metamaterial-Like Urban Layer: An Experimental Investigation Using a Dense Seismic Array and Complementary Sensing Technologies. **Pilz, M.**, Roux, P., Mohammed, S. A., Garcia, R. F., Steinmann, R., *et al.*

141. Site-City Interaction in the Valley of Mexico: 3D Simulations and Observations. **Ramirez-Guzman, L.**, Carrillo Lucia, M. A., Contreras, M. G., Bañuelos, D.
142. Seismic Response of Nenana Sedimentary Basin, Central Alaska. **Smith, K.**, Tape, C., Tsai, V. C.
143. State of the Art in Seismic Metamaterials. **Stephane, B.**

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144. Impact of November 2023 Earthquake in Western Nepal. **Dhakal, H.**
145. Student: Examining the 1953 Kefalonian Earthquakes, From a Social Perspective. **Galanos, N.**, Kouskouna, V., Sakellariou, N., Galanos, G. S.
146. Seismic Hazard and Risk in Lae City, Papua New Guinea (PNG). **Griffin, J. D.**, Cummins, P. R., Clark, D. J., Edwards, M., Espi, J., *et al.*
147. The "Earthquake Suitcase"—A Research-Inspired Educational Tool for Earthquake Vulnerable Communities. **Kouskouna, V.**, Sakkas, G., Sakellariou, N., Galanos, N., Ridge, H.
148. Student: High-Impact Earthquakes on Hidden, Secondary Faults Within the Sparsely Instrumented Golden Triangle Region of Laos, Thailand, and Myanmar. **Sethanant, I.**, Nissen, E., Bergman, E., Oliva, S., Pousse-Beltran, L., *et al.*
149. The Center for Collective Impact in Earthquake Science (C-CIES). **Velasco, A. A.**, Weidner, J., Karplus, M. S., Bilek, S., Bolton Valencius, C., *et al.*

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150. Validation of Probabilistic Coseismic Coastal Deformation Models using Geologic and Geomorphic Evidence. **Clark, K. J.**, Howell, A., Delano, J., Litchfield, N.
151. Student: How Will Earthquakes Change Sea Level? a Probabilistic Coast-Seismic Hazard Model. **Delano, J.**, Howell, A., Clark, K., Rollins, C., Stahl, T., *et al.*
152. Toward Resilient Coastal Communities: A Probabilistic Assessment of Co- and Inter-Seismic Vertical Land Motion. **Kim, J.**, Schmidt, D., Pearson, A.
153. Decade-to-Century Scale Vertical Earthquake-Cycle Deformation at Subduction Zones: Implications for Cascadia and Nankai. **Li, S.**, Chen, L.
154. Assimilation of Vertical Land Movement Observations and Models to Support Sea Level Rise Planning Along the Shorelines of the Cascadia Subduction Zone. **Miller, I. M.**, Schmidt, D., Pearson, A., Kim, J.
155. Complex Earthquake Deformation Drives Relative Sea-Level Change Where Oblique Contraction Focuses Rock Uplift West of the Fairweather Fault, Southeast Alaska. **Witter, R.**, Kelsey, H., Lease, R., Bender, A., Scharer, K., *et al.*

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156. Empirical Response of Subduction-Zone Ground Motions in the Cook Inlet Basin of Alaska. **Ahdi, S. K.**, Parker, G. A., Skarlatoudis, A.
157. Student: Physics-based Seismic Hazard Assessment Using Multi-cycle Earthquake Simulations: Influence of Segment Connectivity and Strength Distribution. **Aspiotis, T.**, Zielke, O., Mai, M. P.
158. Seismic Hazard Assessments for the Jackson Purchase Region (Upper Mississippi Embayment) Using Reelfoot Fault Scenarios and Site-Specific Vs Profiles. **Carpenter, S.**, Wang, Z.
159. A Remarkable Absence of Liquefaction: Data-Driven Lessons From the 2014 South Napa Earthquake. **Greenfield, M. W.**
160. Offshore Seismic Hazards in Southern Cascadia. McPherson, R. C., Patton, J. R., Dreger, D. S., Dengler, L. A., **Hellweg, M.**, *et al.*
161. Modelled Impacts of Rupture on the Newly Discovered XEOLXELEK-Elk Lake Fault, BC, Canada. **Hobbs, T. E.**, Patchett, M., Silva, V., Rao, A., Kim, J.
162. A Future Scenario Earthquake and Ground Motion Hazards for Kathmandu, Nepal. **Koketsu, K.**, Miyake, H., Okumura, K., Suzuki, H.
163. Unraveling Seismic Complexity: Repeating Rupture Patterns and Varied Seismogenic Environments in the Mexico Subduction Zone. **Liu, C.**, He, P., Lay, T., Xiong, X.
164. Student: Influence of Site Effects' Spatial Variability on Spatially Variable Ground Motion Intensity Measures. **Lorenzo-Velazquez, C.**, Cabas, A.
165. Towards Probabilistic Tsunami Risk Estimates Using Stochastic Earthquake Sources. **Melgar, D.**, Eguchi, R., Koshimura, S., Crowell, B., Lee, Y., *et al.*
166. Seismic Geohazards in Italy: Seismic Geohazards in Italy: An Integrated Geotechnical Earthquake Hazard Assessment Map. **Mitra, D.**, Nath, R. R., Sethi, S., Adarshi, N.
167. An Empirical Bayesian Kriging Approach for Site Period Mapping of Santiago Basin, Chile. **Mitra, D.**
168. Understanding Regional Site-Amplification Effects in the San Francisco Bay Region, California Through Ground-Motion Analysis and Modeling of Regional Seismic Velocity Structure. **Moschetti, M. P.**, Aagaard, B. T., Boyd, O. S.

169. Development of a Seismically Induced Landslide Susceptibility Scale for Greece for Addressing Data Imbalance. **Nath, R. R.**, Mitra, D.
170. National Seismic Hazard Assessment for Azerbaijan Using New Seismic Data and Ground Motion Simulations. **Onur, T.**, Gok, R., Yetirmishli, G., Herrera, C., Godoladze, T., *et al.*
171. Data-Driven Performance Evaluation of Ground Motion Models Applicable for Active Crustal Region in Italy. **Paramasivam, B.**, Kim, S., Seyhan, E.
172. Dependence of Seismic Hazard Assessment on the Observation Time Interval: Insights From Physics-Based Simulated Seismicity in Southeastern Spain. **Pascual-Sánchez, E.**, Álvarez-Gómez, J. A., García-Mayordomo, J., Herrero-Barbero, P.
174. Student: Improving Geospatial Liquefaction Prediction Models by Optimizing Non-Liquefaction Points Sampling: A Case Study of the 2023 Kahramanmaras, Turkey Earthquake Sequence. **Shirzadi, H.**, Baise, L. G., Moaveni, B.
175. Student: Correlating Resonance Frequency From Hvsr With Vs30 Along the Wasatch Fault, Northern Utah, USA. **Smith, K.**, McBride, J., Harris, R., Worthen, B.
176. Student: Epistemic Uncertainty and Aleatoric Variability within Probabilistic Liquefaction Analysis. **Thum, T.**, Rodriguez-Marek, A., Stafford, P. J., Green, R. A.

Abstracts of the Annual Meeting

The 2023 USGS National Seismic Hazard Model and Beyond

Oral Session • Wednesday 1 May • 8:00 AM Pacific

Conveners: Jason M. Altekruse, U.S. Geological Survey (jaltekruse@usgs.gov); Julie A. Herrick, U.S. Geological Survey (jherrick@usgs.gov); Mark D. Petersen, U.S. Geological Survey (mpetersen@usgs.gov); Peter M. Powers, U.S. Geological Survey (pmpowers@usgs.gov); Emel Seyhan, Moody's RMS (Emel.Seyhan@rms.com); Allison M. Shumway, U.S. Geological Survey (ashumway@usgs.gov)

Recommendations on Best Available Science for the United States National Seismic Hazard Model

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The 50 state update to the 2023 United States National Seismic Hazard Model (NSHM) is the latest in a sequence published by the U. S. Geological Survey (USGS). The 2023 NSHM is intended for use in building codes and similar applications at return periods of 475 years (corresponding to exceedance probabilities of 10% in 50 years) or longer. In reviewing the model, the NSHM Program Steering Committee, consisting of the authors of this paper, considered the characteristics of "best available science" that are applicable to the NSHM. Best available science must perform better than the previous NSHM, and there should be no available alternatives that could improve the models. The following are suggested characteristics of "best available science": A) Clear objectives B) Rigorous conceptual model C) Timely, relevant and inclusive D) Verified and reproducible E) Validated intermediate and final models F) Replicable within uncertainties G) Peer reviewed H) Permanent documentation

This presentation focuses on the justification for, and intent of, the above criteria for best available science. As of December, 2023, considering these and additional criteria, and subject to further steps to verify and document the model for Alaska, the NSHM Steering Committee concluded that the 2023 National Seismic Hazard Model is suitable for use in building codes and similar applications at return periods of 475 years (i.e corresponding to exceedance probabilities of 10% in 50 years) or longer.

The 2023 U.S. 50-State National Seismic Hazard Model: Overview and Implications

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The U.S. National Seismic Hazard Model (NSHM) was updated in 2023 for all 50 states using new science on seismicity, fault ruptures, ground motions, and probabilistic techniques to produce a standard of practice for public policy and other engineering applications (defined for return periods greater than ~475 or less than ~10,000 years). Changes in 2023 time-independent seismic hazard (both increases and decreases compared to previous NSHMs) are substantial because the new model considers more data and updated earthquake rupture forecasts and ground motion components. In developing the 2023 model, we tried to apply best available or applicable science based on advice of co-authors, more than 50 reviewers, and hundreds of hazard scientists and end users, who attended public workshops and provided technical inputs. The hazard assessment incorporates new catalogs, declustering algorithms, gridded seismicity models, magnitude-scaling equations, fault-based structural and deformation models, multi-fault earthquake rupture forecast models, semi-empirical and simulation-based ground motion models, and site amplification models conditioned on *VS30* soil and deeper sedimentary basin structures. Seismic hazard calculations yield hazard curves at hundreds of thousands of sites, ground motion maps, uniform hazard response spectra, and disaggregations developed for pseudo-spectral accelerations at 21 oscillator periods and two peak parameters, Modified Mercalli Intensity, and 8 site classes required by building codes and other public policy applications. Tests show the new model is consistent with past ShakeMap intensity observations. Sensitivity and uncertainty assessments ensure resulting ground motions are compatible with known hazard information and highlight the range and causes of variability in ground motions. We produce several impact products including building seismic design criteria, intensity maps, planning scenarios, and engineering risk assessments showing the potential physical and social impacts. These applications provide a basis for assessing, planning, and mitigating the effects of future earthquakes.

The 2023 Alaska National Seismic Hazard Model

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The U.S. Geological Survey (USGS) has developed a major revision to the Alaska portion of the 2023 National Seismic Hazard Model (NSHM). This update incorporates new data and models that have been gathered and published since the last update of the Alaska NSHM in 2007. The 2023 Alaska NSHM includes updates to both earthquake rupture forecast (ERF) and ground motion model (GMM) components. The ERF includes updates to the crustal fault inventory and considers both geologic and geodetic deformation models. The large-magnitude subduction interface model uses an updated segmentation and structural model (based on the Slab2 geometry of the Alaska-Aleutian arc) and includes geologic, geodetic, and earthquake catalog-derived earthquake rates. A new catalog that includes earthquakes from 2007 to 2020 was compiled to inform the rate model for the both the crustal and subduction gridded seismicity components. The gridded seismicity rate model considers multiple declustering and smoothing methods, and subduction interface (small magnitude) and intraslab sources are modeled at depths derived from Slab2. For the GMM component, the model uses the new NGA-Subduction GMMs. For interface ruptures, the global NGA-Subduction GMMs are used along with bias corrected versions of the models; the corrections are based on recent Alaska earthquakes to better represent ground motions in south-central Alaska. For intraslab ruptures, the Alaska regionalized versions of the NGA-Subduction GMMs are used, and the NGA-West2 GMMs are used with crustal sources. The updated model implies significant increases in hazard across south-central Alaska that are due to updated subduction interface rupture rates, the adoption of new GMMs, and improved representations of ruptures in the ERF that are consistent with recent NSHMs for the conterminous U.S. In particular, the newer GMMs considered include higher aleatory variability (sigma), which maps into increased probabilistic ground motions. Here we present implementation details of the 2023 Alaska NSHM and comparisons to the prior NSHM from 2007.

Another Look at Time-Dependent Hazard and its Implications to Seismic Design in Southeastern Alaska

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Seismic design in the U.S. is based on the USGS National Seismic Hazard Maps (NSHM) which assume time-independent (TI) hazard. For regions where the data are robust enough, time-dependent (TD) hazard estimates should be included because of the economic consequences of overly conservative seismic design ground motions (Wong and Thomas, 2020). Southeastern Alaska is a region which can benefit from TD hazard estimates because of the recent occurrence of the 1964 M 9.2 Great Alaska earthquake. Based on Shennan *et al.* (2014) who identified and dated six "1964"-like earthquakes, we computed an average recurrence interval of 594 ± 162 years. A mean COV value of 0.27 was also estimated, which is a relatively low value indicating rather periodic

behavior. Given the short time since 1964, the Brownian Passage Time model predicts very low equivalent Poisson rates for a 50-year period. Incorporating these rates into a PSHA, TD hazard in Anchorage at a building-code return period of 2,475 years is up to 48% lower than the TI hazard. In contrast to the 2023 NSHM, TD analysis indicates the 1964 rupture is not significant to the probabilistic seismic hazard in southeastern Alaska, with the Wadati-Benioff zone being the controlling seismic source. The current seismic design ground motions for Anchorage are based on the 2007 NSHM and are deterministically capped. The significantly increased hazard in the 2023 NSHM for southeastern Alaska will be challenging for the engineering community with regards to seismic design. Considering TD hazard is one approach to reduce the seismic hazard estimates in southeastern Alaska.

USGS 2025 Puerto Rico and the U.S. Virgin Islands National Seismic Hazard Model Update

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The U.S. Geological Survey is currently developing the next update of the National Seismic Hazard Model (NSHM) for Puerto Rico and the U.S. Virgin Islands (PRVI), with a planned release by the end of calendar year 2025. The last update to the PRVI NSHM was in 2003, so this update will include over 20 years of updated science and engineering data, models, and methods. Updates being considered include (1) an updated seismicity catalog based on improved Puerto Rico Seismic Network data, (2) new declustering (space-and-time and nearest-neighbor), smoothing (fixed and adaptive), and seismicity rate models, (3) new magnitude scaling relationships, (4) updated geologic and geodetic deformation models, (5) improved fault source models and a more complete representation of epistemic uncertainties, (6) improved modeling of subduction zone geometries, and (7) updated ground motion models (GMMs) for both crustal (NGA-West2 and other available Puerto Rico-specific models) and subduction (NGA-Subduction) sources, with particular attention paid to whether the site terms of the selected GMMs are appropriate for use in PRVI. These updates follow similar efforts performed in the recent 2023 50-state NSHM. Uncertainty and engineering impact studies will also be performed for this update. NSHMs are community- and consensus-based models, with the goal to incorporate the latest data, models, and methods currently available. Public workshops throughout the update process will allow the scientific community to evaluate the input models and draft model, providing valuable feedback as the model is developed and finalized.

Next Steps for USGS Earthquake Rupture Forecast Developments

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An earthquake rupture forecast (ERF), also known as a seismic source characterization, is one of the two main modeling components used in seismic hazard analysis (the other being a ground-motion model). This presentation provides an overview of recent, ongoing, and future ERF developments at the United States Geological Survey (USGS). Two overarching goals, both a manifestation of the paucity of data at large magnitudes, are a better representation of epistemic uncertainties and a greater utilization of physics-based approaches. Recent accomplishments include a broader representation of multi-fault ruptures, including a wider range of epistemic uncertainties associated with the degree of fault segmentation. Ongoing efforts include the addition of time-dependencies, both in terms of elastic-rebound effects and spatiotemporal clustering (e.g., aftershocks), with the eventual goal of deploying an operational earthquake forecasting capability. Fundamental remaining challenges include spanning a complete range of geodedic-constrained deformation models (fault slip rates and off-fault deformations) and representing sampling errors associated with off-fault gridded seismicity components (currently inferred from a single sample of historical earthquakes). Another challenge is adequate representation of epistemic uncertainty in the face of unknown correlation structures, which can be particularly impactful in portfolio risk analyses. We also aim to simplify models and operationalize implementations wherever we can, and to deploy a more continuously developed research model. Finally, we also plan to add model *valuation* to our *verification* and *validation* protocols because a less scientifically correct model might actually be more useful with respect to some hazard and risk metrics.

Earthquake Geology Contributions Across the U.S. Geological Survey 2023 50-State National Seismic Hazard Model

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The earthquake geology community made significant contributions to the U.S. Geological Survey 2023 50-State National Seismic Hazard Model (NSHM). Since 2019, we worked with this community through workshops and state geological surveys to provide the most inclusive and realistic depiction of earthquake geologic datasets used in an NSHM release. Fault section databases were reviewed, revised, and significantly augmented across the conterminous U.S. and Alaska, increasing the number of fault sections included nationwide from ~650 to ~1,100. Across the conterminous U.S., geologic slip rates were cataloged for >450 study locations; activity rates were included with fault section data in Alaska. Slip rate datasets in the western U.S. were used to constrain four unique geodetic deformation models, providing a broad range of possible fault deformation rates. A new geologic deformation model provided preferred slip rates and distribution for faults without field-based slip rates across the western U.S. Over 60 paleoseismic datasets were cataloged and reinterpreted in California, along the Wasatch fault in Utah, and in the central and eastern U.S. Paleoseismic recurrence information was used as a constraint on the inversion-derived rupture rates. Following the western U.S. fault system solution inversion, we reviewed preliminary results for tectonic and geologic consistency. The review identified priority areas of potential future research, including defining uncertainties of fault geometry in three dimensions; defining plausibility filters on dipping faults; placing bounds on maximum rupture length; better characterization of per-event displacements and slip distributions along rupture extents; defining paleoseismic rupture lengths as inversion constraints; reconsidering the repeating large magnitude earthquake assumption in the central and eastern U.S.; and parameterizing connectivity between subduction interface and upper plate faults near Cascadia and Alaska–Aleutian trenches. This submission seeks to encourage discussion of these and next avenues of earthquake geology research.

Continued Work on a Geodetic Strain Rate and Slip Deficit Rate Model for New Zealand

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Data-based fault slip rates are key inputs into national seismic hazard models: they are one of several "budgets" that help constrain the likelihoods of large earthquakes at each location. In regions featuring subduction zones, such as Aotearoa New Zealand, there are (in one sense) three kinds of faults to worry about: upper-plate faults, subduction interfaces, and intraslab/outer-rise faults. Slip rates in the first two regimes can be constrained by data. The 2022 revision of the New Zealand National Seismic Hazard Model (NZ NSHM 2022) included two alternate models for upper-plate fault slip rates, one based on geologic data and one based on geodetic data. The geodesy-based model itself included four alternative strain rate models and made use of a novel method to invert surface strain rates directly for slip deficit rates in a way that obviates the need to connect all of the faults as block boundaries. The NZ NSHM 2022 also included two geodesy-based models of coupling on the Hikurangi-Kermadec subduction zone (respectively featuring full locking and no locking at the offshore subduction trench). We are now working on improving this model by adding new data in slow-deforming regions (Auckland/Northland and Southland/Otago), vertical deformation rates, InSAR data (where possible), and improvements to methods (e.g. accounting for uncertainty in fault geometry, and the trade-offs between subduction and upper-plate coupling in terms of their effect on the velocity field).

Correlation of Epistemic Uncertainties in Seismic Hazard Models: An NSHM23 Case Study for Western U.S. Faults

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Uncertainties in probabilistic seismic hazard analysis are typically represented using epistemic logic trees where each branching level represents a modeling choice or alternative dataset used. Ideally, each branch of the logic tree represents a plausible realization of reality. In practice, certain branches may not be reasonable when applied uniformly and systemwide, even if they are reasonable for individual faults or in particular sub-regions of a model.

One such example is fault connectivity. In the 2023 U.S. National Seismic Hazard Model (NSHM23), connectivity of western U.S. faults was modeled with 5 segmentation branches ranging from fully segmented to fully unsegmented. Those end-member branches are unlikely to be correct at a regional scale, even if they are the most correct for some faults. Fault-specific *b*-values are another example; NSHM23 includes end-member models of b=0 and b=1 that are applied uniformly to all faults on their respective branches. We present an alternative model where we randomly sample from the *b*-value and segmentation branches for individual faults; that model decreases epistemic uncertainties in hazard calculations, indicating that NSHM23 might overstate uncertainties. Additionally, rates of large (M>8) ruptures are lower for the randomly sampled alternative model.

Deformation model slip rates are another important uncertainty. Ideally, deformation modelers would provide many samples of realistic deformation models that map out the solution space of viable models while maintaining kinematic consistency. Lacking that, NSHM23 chose to over-fit slip rates. We present an alternative model where deformation model realizations are randomly sampled from their uncertainties using a reasonable covariance structure. We find that using these randomly sampled deformation models increases epistemic uncertainties relative to NSHM23.

We will describe both of these alternative uncertainty models and their impact on standard hazard metrics (individually and together) relative to the published NSHM23 model.

Enhancing Decision-Making Stability in Model Updates Through Explicit Consideration of Epistemic Uncertainty in Seismic Hazard and Risk Assessments

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Significant efforts have been dedicated to characterizing the epistemic uncertainty within the National Seismic Hazard Model (NSHM). The "mean" hazard and risk, derived from the epistemic uncertainty distribution, serves as a pivotal basis for various design, hazard and risk mitigation, and risk financing applications. While the fundamental natural processes remain unchanged, the scientific models representing them continuously evolve, leading to fluctuations, akin to a "see-saw" effect, in estimated mean hazard and risk with each cycle of model updates. This effect, at times substantial, can wield significant influence over critical financial decisions and public policies, presenting practical and political challenges.

The current NSHM retains a considerable level of epistemic uncertainty. A growing consensus underscores the importance of transparently communicating epistemic uncertainty in the NSHM to inform user expectations. However, there is a notable absence of clarity and guidance on effectively incorporating this uncertainty into decision-making, particularly during model updates.

This study aims to bridge this gap by exploring two alternative methods that explicitly consider epistemic uncertainty within the NSHM for decision making. The goal is to alleviate the potential "see-saw" effect in mean hazard and risk estimates resulting from model updates and enhance decision-making stability amid the ongoing evolution of scientific models.

Subduction Ground Motion Models for Cascadia in the 2023 USGS National Seismic Hazard Model

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The U.S. Geological Survey National Seismic Hazard Models (NSHMs) are used to calculate earthquake ground-shaking intensities for design and retrofit of structures in the United States. The most recent 2014 and 2018 versions of the NSHM for the conterminous U.S. included major updates to ground motion models (GMMs) for active and stable crustal tectonic settings; however, the subduction zone GMMs were largely unchanged. With recent development of the Next Generation Attenuation Subduction (NGA-Sub) GMMs, as well as recent progress in utilization of "M9" Cascadia earthquake simulations, we now have access to improved models of ground shaking in U.S. subduction zones and the Seattle Basin. The new NGA-Sub GMMs support "multi-period response spectra" calculations by providing median and variability models that can be used for periods up to 10 s and for eight site classes. They provide global models as well as regional terms specific to Cascadia and terms that account for deep sedimentary basin effects. This study focuses on updates to subduction GMMs for the Cascadia portion of the 2023 NSHM and compares them to the GMMs of previous NSHMs. Individual subduction GMMs, their weighted combinations, and their impact on hazard relative to the 2018 NSHM are discussed. Logic trees are described that include three of the new NGA-Sub GMMs and retain two older models to represent epistemic uncertainty in both the median and standard deviation of ground-shaking intensities at all periods of interest. Epistemic uncertainty is further represented by a three-point logic tree for a given NGA-Sub median model. Finally, in the Seattle region, basin amplification factors are adjusted at long periods based on state-of-the-art M9 Cascadia earthquake simulations. Overall, the GMM changes increase the mean hazard values at shorter periods and short source-to-site distances, but decrease them otherwise, relative to the 2018 NSHM. On deep sedimentary basins, the new models cause hazard decreases for longer periods in the Puget Lowland but increases for shorter periods within the Seattle Basin relative to 2018 NSHM.

Ground-Motion Characterization of Puerto Rico and the U.S. Virgin Islands for the 2025 Update of the USGS National Seismic Hazard Model

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We assess ground-motion models (GMMs) developed for shallow crustal faulting or subduction zones for application in Puerto Rico and the U.S. Virgin Islands as part of the 2025 update of the U.S. Geological Survey (USGS) National Seismic Hazard Model. We present preliminary analysis of GMM performance, including for site response, using linear mixed-effects regression. For our analysis we used the USGS software gmprocess to compile a dataset with over 8000 ground-motion records since 2006 from 888 earthquakes with magnitudes ranging from 4.0 to 6.5 and depths reaching up to 200 km; more than half of the ground motions were recorded since January 2020. We use the USGS SeismoTectonic Regime Earthquake Calculator (STREC) and the USGS Slab-2 subduction zone geometry model to associate ground motions with either subduction zone or shallow crustal earthquakes. We compute within-event residuals using linear mixed-effects regressions relative to Next Generation Attenuation West2 (NGA-West2) and East (NGA-East) GMMs for shallow crustal earthquakes and NGA Subduction (NGA-Sub) GMMs for subduction zone earthquakes. We consider both measured and proxy values for the time-averaged shear wave speed in the top 30 m (Vs30) when computing site terms for the GMMs. For each GMM, we examine trends with predictive variables, such as earthquake magnitude and rupture distance, and the overall bias values. Future work will likely leverage Sammon mapping to provide a more quantitative basis for assigning weights to the epistemic uncertainty logic tree for GMMs.

Development of Ground Motion Models in Central and Eastern United States for Use in the Coastal Plain Using Sediment Thickness

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This study focuses on developing ground-motion models, specifically Pezeshk et al. (2018), initially derived for areas outside the Coastal Plain, to enhance their applicability within Coastal Plain regions. The adjustment factors developed are intricately linked to sedimental thickness and rupture distance within the Coastal Plain. Utilizing recently established sediment thickness contour maps by Boyd et al. (2023), our approach incorporates an integrated dataset that combines the NGA-East original dataset (Goulet et al., 2014), data from Chapman and Guo (2021) and a newly compiled and verified dataset by Thompson et al. (2023). Residuals are computed by contrasting the logarithms of observed data against those predicted by Pezeshk et al. (2018) ground-motion models while considering the site amplification model of Stewart et al. (2020) and employing three datasets. Through a mixed-effects regression, we conduct residual analyses to partition total residuals into components attributed to between-events and within-event residuals. We tailor an equation correlating within-event residuals and sediment depth and rupture distance. The outcomes reveal that, for stations within the Coastal Plain region, the proposed correction significantly eliminates residual trends (with respect to VS30, sediment depth, and rupture distance) across most periods. These findings have practical implications for seismic hazard and risk analyses at sites within the Coastal Plain, emphasizing the importance of incorporating sediment thickness considerations for more accurate predictions

New Ground-Motion Model With Long-Period Non-Ergodic Path Effects From the Cybershake Simulations in the Southern California Region

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Sung et al. (2023) developed a methodology to integrate the 3-D path effects in CyberShake simulations (Graves et al., 2011) into the Abrahamson et al. (2014) (ASK14) ground-motion model (GMM), creating a non-ergodic GMM that captured site-specific path effects caused by the 3-D crustal model using the varying coefficient model (VCM), but the example application only used a subset of 600 scenarios from the v15.4 CyberShake simulations and only modeled the 3-second response spectral values. In this study, we utilized a much larger dataset from the v15.4 CyberShake simulations, which includes 565,000 events and 117 million seismograms at 336 stations for spectral periods of 2, 3, 4, 5, 7.5, and 10 seconds. Additionally, we applied a new form of the spatial correlation (Lacour et al., 2024) that considers the azimuths differences between ray paths that better reflects the spatial correlation in the CyberShake data. For most ray paths, the larger data set shows a strong correlation between the path effects for moderate and large earthquakes with the same closest point to a site (correlation coefficient of 0.7 to 0.85), indicating that the path effects of large-magnitude earthquakes can be approximated by using the path effects of smaller earthquakes. The modified ASK14 GMM with CyberShake site and path effects at periods of 2-10 s, and it has reduced aleatory variability. Compared to an ergodic GMM representation of the CyberShake data, for the period range of 2-10 s, the total standard deviation is reduced from 0.565 to 0.636 for the ergodic GMM to 0.435 to 0. 544 for the non-ergodic GMM. An additional advantage of using the larger data set is that it reduces the potential for overfitting as compared to the previous subset. We present examples of hazards calculation for T = 3 s and T = 5 s for the ergodic and non-ergodic GMMs and for the hazard computed using the CyberShake data directly. The resulting modified ASK14 GMM can effectively capture the path effects observed in the CyberShake simulations, including both the median and the aleatory standard deviation.

An Updated Version of the New Empirical Source-Scaling Laws for Crustal Earthquakes Incorporating Fault Dip and Seismogenic-Thickness Effects

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New global source-scaling relations for the aspect ratio and rupture area for crustal earthquakes, including the width-limited effect and a possible free-surface effect, are derived using a global data set of finite-fault rupture models. In contrast to the commonly used scaling relations between moment magnitude (M), fault length (L), width (W), and area, we built self-consistent scaling relations by relating M to the aspect ratio (L/W) and to the fault area to model the change in the aspect ratio once the rupture width reaches the down-dip width limit of the fault. The width-limited effect for large-magnitude earthquakes depends on the fault dip and a regional term for the seismogenic thickness. The magnitude scaling of the aspect ratio includes a break in the magnitude scaling that is dip-angle-dependent. This dip-angle-dependent magnitude scaling in the magnitude-area relation is thereby modeled by a trilinear relation incorporating a dip-related transition range. The effect of the free surface was observed using a normalized depth term and parameterizing the source by the depth of the top of the fault rupture; it is more apparent in the area scaling relation. The scaling differences are related to the fault geometry, not the rake angle, as commonly assumed. Finally, the corresponding L and W scaling relations obtained by converting the area and aspect-ratio models to L and W models showed good agreement with the previous regional scaling laws on average but provided better fault-specific application due to the inclusion of fault-specific dip angles and seismogenic thicknesses.

The 2023 USGS National Seismic Hazard Model and Beyond [Poster Session]

Poster Session • Wednesday 1 May

Conveners: Jason M. Altekruse, U.S. Geological Survey (jaltekruse@usgs.gov); Julie A. Herrick, U.S. Geological Survey (jherrick@usgs.gov); Mark D. Petersen, U.S. Geological Survey (mpetersen@usgs.gov); Peter M. Powers, U.S. Geological Survey (pmpowers@usgs.gov); Emel Seyhan, Moody's RMS (Emel.Seyhan@rms.com); Allison M. Shumway, U.S. Geological Survey (ashumway@usgs.gov)

POSTER 133

The 2023 Alaska National Seismic Hazard Model: Hazard Implications

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The 2023 U.S. Geological Survey (USGS) National Seismic Hazard Model (NSHM) for the State of Alaska incorporates more than fifteen years of new data in updates to the earthquake rupture forecast (ERF) and ground motion model (GMM) components of the model. These changes result in large increases in predicted ground motions compared to the previous model published in 2007. The ERF incorporates an expanded crustal fault inventory, updated geologic and geodetic rate models, and several new source zones in key areas (e.g., Cook Inlet and the Coast Shear Zone). Crustal and subduction gridded seismicity models, based on an updated earthquake catalog that includes events through 2020, incorporate multiple catalog declustering and spatial smoothing methods. The Alaska-Aleutian arc geometry from Slab 2 is used to model depths for intraslab and small-magnitude (<M7) interface sources as well as the large-magnitude subduction interface geometry. The large-magnitude interface model also uses updated megathrust segmentation models and multiple earthquake rate models. The 2023 NSHM for Alaska uses the NGA-West 2 GMMs for crustal sources, NGA-Subduction global models for subduction interface sources, and NGA-Subduction Alaska regional models for subduction intraslab sources. Details of the updates to the ERF and GMM components have been presented elsewhere; here we focus on how key model updates lead to significant increases of more than a factor of two, in some areas, in earthquake hazard across south-central Alaska. For example, the updated interface rupture rates and the adoption of NGA-Subduction GMMs both lead to higher hazard across much of the Alaska-Aleutian arc. We show stepwise ratio and difference maps that illustrate the relative contributions to changes in hazard arising from each update to the ERF and GMM model components.

POSTER 134

Implementing Rupture Directivity Effects Into PSHA

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The effects of rupture directivity on near-fault ground motions are known to be significant and should be included to accurately estimate the hazard, especially for long-period ground motions (Abrahamson, 2000). However, these effects are not explicitly accounted for in typical ground motions models, and therefore not in typical probabilistic seismic hazard analyses (PSHAs) because substantial confusion exists in practice about which directivity models to use and how to apply them to the median and aleatory variability of GMMs, especially to complex multi-segment rupture models (Donahue et al., 2019). In the response spectral approach, which we adopt, rupture directivity effects are considered by including adjustment factors to the elastic acceleration response spectrum at 5% damping. This approach lends itself readily to inclusion into PSHA (Rodriguez-Marek and Cofer, 2009).

This work describes an update to our 2020 rupture directivity model (Bayless et al., 2020), including formalized instructions for adjustments to the median and aleatory variability of the ground motion model to which it is applied. Additionally, we provide guidance on implementation, including deterministic and probabilistic applications, and methods for modeling hypocenter locations and multi-segment ruptures. The result is a comprehensive model suitable for use in future PSHAs, including those performed as part of the USGS National Seismic Hazard Model. The model applies to strike-slip earthquakes only. A future update will address directivity effects for other styles of faulting.

POSTER 135

Conterminous U.S. Site Parameter Maps for Ground Motion Models

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The amplitude of earthquake ground motions depends on parameters related to the source (e.g., magnitude and stress drop), path (e.g., geometric spreading and path attenuation), and site. The site component has typically been characterized in terms of *VS*30, the time-averaged shear-wave velocity to 30-meters depth and in some cases, $Z_{1.0}$ or $Z_{2.5}$, the depths to a shear-wave velocity of 1.0 and 2.5 km/s, respectively. Other parameters have been proposed including 1) a site's fundamental period at which there is a peak in site amplification, 2) k_0, which represents the site's scattering and anelastic attenuation, and 3) sediment thickness, the last of which is being modeled in the Atlantic and Gulf Coastal Plains for the 2023 update of the U.S. National Seismic Hazard Model. Application of these parameters and the concomitant improvement in hazard assessments is limited to where these models are available. Whereas there are global and regional models for V_{S30}, models of $Z_{1.0}$, $Z_{2.5}$, and sediment thickness are spatially restricted. With the completion of the USGS National Crustal Model for Seismic Hazard Studies (NCM), conterminous U.S. models of V_{S30}, $Z_{1.0}$, $Z_{2.5}$, and sediment thickness are available, in addition to other potentially explanatory site parameters. In this study, we derive conterminous U.S. site-parameter maps from the NCM that can be used in ground motion model development and application. Site parameters considered include V_{S30}, $Z_{1.0}$, $Z_{2.5}$, Z_X derived from time-averaged velocity profiles, sediment thickness, sediment travel time, fundamental period, and k_0. In this preliminary study, we compare these maps to existing measurements and models and present correlations between site parameters and ground motion residuals in the western U.S.

POSTER 136

Recurrence Model for Puerto Rico Subduction Zone Interface and Muertos Thrust Belt Earthquakes

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In preparation for the 2025 update to the Puerto Rico and U.S. Virgin Islands portion of the USGS National Seismic Hazard Model, we compiled geologic, geodetic, geophysical, and seismologic observations to characterize earthquake recurrence along the Puerto Rico subduction zone (PRSZ) and the Muertos thrust belt. Limited historical seismicity suggests the PRSZ is active and capable of hosting Mw 8+ ruptures. Previously reported geologic observations document precolonial (pre-1492 C.E.) inundation of Anegada, consistent with either a subduction interface event or an outer rise event. Because geologic observations to constrain subduction interface rupture recurrence are scant, we estimate recurrence from geodetically determined coupling and convergence rates. Eight subduction interface fault sections are defined on the basis of structural and geometric discontinuities and coupling is generalized along uniform patches, ranging from 10 to 20%. Recurrence is inferred from moment accumulation rates with magnitudes derived from scaling relations. This approach yields preliminary recurrence intervals of 2900-5800 years for Mw 8.6-8.8 ruptures along the PRSZ for a set of prescribed interface events. A key question is whether highly oblique convergence along the PRSZ is partitioned into only trench-normal interface rupture, or if nearly trench-parallel rupture occurs on the dipping interface (e.g., Sagami Trough-style). Historical seismicity on the subduction interface is consistent with highly oblique rupture on the interface and we retain that possibility in the model. Based on seismicity, geodesy, and limited geophysical data, we model three sections along the Muertos thrust belt as 50% coupled with their down-dip extents near the southern coast of Puerto Rico. Using a methodology similar to the PRSZ yields earthquakes of Mw 7.8-8.5 with recurrence intervals of 770-9200 years on the Muertos thrust belt. Outstanding issues include constraining recurrence of outer rise events, testing the recurrence model against limited geologic and seismologic data, and incorporation of considerable epistemic uncertainty into the model.

POSTER 137

Seismic Hazard, Lithosphere Hydration, and Double-Verging Structure of the Puerto Rico Subduction Zone: A Seismic Reflection and Refraction Perspective

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The Puerto Rico Trench (PRT) is an oblique subduction zone where Atlantic lithosphere subducts under the Caribbean plate. The PRT poses major earthquake and tsunami hazards in the Caribbean and the US East Coast. In Fall 2023 we conducted the NSF-supported PRISTINA experiment (Puerto Rico Subduction Tectonics Seismic Investigation), a controlled-source seismic survey across the PRT, its outer rise, and across the island of Puerto Rico using the RV *Langseth*(cruises MGL2315 and MGL2316). PRISTINA consists of: (1) 2140 km of 2D ultra-long-offset (13.65 km) multichannel seismic reflection data along 8 primary profiles trending parallel to, and perpendicular to the main axis of the PRT; (2) an amphibious island-crossing 430-km-long N-S wide-angle profile sampling the incoming plate, PRT, Puerto Rico, Muertos thrust belt and Caribbean plate instrumented with 49 short-period, 3-component nodal land stations and with short-period, 3-component geophone+hydrophone ocean bottom seismometers (OBS) successfully deployed at 46 stations: 34 stations using OBS from the US OBS Instrument Center (OBSIC) and 12 stations with ultra-deep OBS (up to 8000 m) from GEOMAR; (3) a 220-km-long NE-SW wide-angle profile crossing the PRT north of the British Virgin Islands instrumented with 17 OBSIC and 7 ultra-deep OBS; (4) Four wide-angle fan profiles over the incoming plate; (5) Underway multibeam bathymetry, gravity and magnetics. In addition, a deployment of 6 temporary broadband in conjunction with permanent PRSN stations through central PR is currently collecting data. These datasets will be used to address the following scientific questions: the shallow geometry of the subducting slab and its lateral continuity along the PRT; the degree and spatial extent of hydration of the Atlantic lithosphere entering the PRT; the nature of an oceanic bivergent thrust system. In this presentation we will inform the interested community about PRISTINA objectives, datasets and expected derived models, which we anticipate will provide new critical constraints to inform the 2025 Puerto Rico and U.S. Virgin Islands USGS National Seismic Hazard Model.

POSTER 138

Deploying the USGS National Seismic Hazard Models

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We describe how the U.S. Geological Survey (USGS) develops and deploys the National Seismic Hazard Models (NSHMs) and related products to end users. The USGS NSHMS are developed using Java and use JSON, GeoJSON, and CSV files to describe model elements. The base codes and model files are used to perform time-consuming large scale (grid of multiple points) hazard calculations as well as on-demand calculations for end users via web service and web application wrappers. In the past, we deployed multiple models to a single on-premises server but quickly faced computing limitations as the number of models grew. To address this, we now deploy each NSHM to independent Amazon Web Services (AWS) servers that are matched to the compute requirements of each model. Each server provides identical web service access to the model it hosts, and the services for the NSHMs are brought together in a unified interface for end-users via the USGS Earthquake Hazard Toolbox (https://earthquake.usgs.gov/nshmp/). Behind the scenes, we use GitLab continuous integration and continuous delivery pipelines for automated deployments and use the AWS Cloud Development Kit (CDK) to write infrastructure as code using TypeScript to generate CloudFormation templates. The NSHM web service deployments use the Amazon Elastic Compute Cloud, and the USGS Earthquake Hazard Toolbox is deployed via the Amazon Elastic Container Service. This infrastructure allows us to automate deployments to development, staging, and production environments that include pulling version-controlled resources from multiple repositories and running quality assurance tests. This presentation describes NSHM infrastructure, the resources available to end users, and the process of moving a new NSHM from development through to publication and deployment. We also highlight the efficiencies gained through moving to the cloud and describe the benefits of using the CDK for NSHM deployments.

POSTER 139

USGS Earthquake Hazard Toolbox

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The U.S. Geological Survey (USGS) earthquake hazards website provides web services and applications that give users access to the National Seismic Hazard Models (NSHMs) for the United States and its territories. The USGS Earthquake Hazard Toolbox (https://earthquake.usgs.gov/nshmp) web application is the main entry point for end-users to calculate hazard and to query data for various USGS NSHMs. The tool currently supports the 2018 and 2023 conterminous U.S. NSHMs, the 2021 NSHM for the State of Hawaii, and the 2023 NSHM for the State of Alaska with additional older NSHMs to be added soon. One advantage of recent improvements to the USGS hazard modeling codebase is that models under development can be deployed to the tool for earlier end-user evaluation and adoption. In addition to providing web applications for hazard calculation and disaggregation, the NSHM hazard tool also provides model analysis applications. Applications for working with ground motion models include the response spectrum plotter and ground motion versus distance or magnitude plotters. Applications for working with source models, or earthquake rupture forecasts, include a magnitude-frequency distribution plotter and a source data mapping application. Each application is backed by web services that permit the underlying calculations and data to be easily accessed via third-party applications (e.g., MATLAB, Python, R). Moreover, each application provides export options to save any plot data in tabular form and plots as static images. Here we provide an overview of the various USGS Earthquake Hazard Toolbox applications, as well as examples of how to leverage the suite of underlying web services.

POSTER 140

The 2023 Alaska National Seismic Hazard Model: Inputs and Implications

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The National Seismic Hazard Model (NSHM) Project of the U.S. Geological Survey is tasked with modeling the seismic hazard from potentially damaging earthquakes for the 50 U.S. states and its territories. The last comprehensive assessment for Alaska was published in 2007, and a significant update was released in late 2023. The 2023 Alaska NSHM considers two main input components: an earthquake rupture forecast (ERF) and ground motion model. The 2023 ERF includes over 80 new faults and a refined treatment of the subduction zone, an updated earthquake catalog and new declustering and smoothing algorithms for background seismicity, new geodetic deformation models, and improved modeling of subduction zone interface and intraslab geometries using the SLAB2 model. Relative to the previous model of seismic hazard for Alaska, the new model results (ERF and ground motion) in an overall increase in hazard across the state. We present the ERF model components in a geospatial format and provide assessments of where damaging shaking is likely to occur. The extent of damaging shaking is represented in terms of Modified Mercalli Intensity (MMI), a measure of earthquake effects that describes the strength of earthquake shaking inferred from intensity observations. Test sites (Anchorage, Fairbanks, Juneau, Nome, Prudhoe Bay, and Seward) were reviewed to identify sources of change in hazard, and we describe and represent those locations with their contributing factors in this presentation. Relative change from the 2007 model is presented to highlight where the hazard (or damaging shaking) has increased or decreased.

POSTER 141

A New Seismic Reflection Study for Southwestern Puerto Rico Fault Characterization

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Southwestern Puerto Rico (SWPR) seismic activity received significant attention after the 2020 earthquake sequence. All previous research suggest that seismicity propagated in the onshore area where it was found the presence and interaction of left-lateral strike slip and normal faults. The sequence suggests a diffuse zone of active offshore faulting at the western side driven by coupling at the northern boundary of the Caribbean plate. Most of the previous work in the area was conducted through offshore seismic reflection surveys, leaving behind significant gaps to understand onshore faults. Strike, dip, and depth of fault planes are critical for comprehensively characterizing fault structures along Puerto Rico's tectonic boundaries for future hazard assessments. How can these enhanced descriptions of onshore faults help assess the overall tectonic extent of Puerto Rico-Virgin Islands block which may include a boundary in SWPR associated with observed seismic activity? We present a geophysical approach to produce a new onshore fault characterization qualitatively and quantitatively in Lajas Valley, SWPR, including the Punta Montalva Fault. An initial phase of data acquisition has been completed using a 2D-channel seismic system supplemented with nodal recorders. Seismic data processing and data analysis are being carried out using the Seismic Unix processing system. Preliminary results show excellent imaging of several faults beneath the Lajas Valley, indicating potential for understanding the tectonics of this important area.

POSTER 142

Gridded Seismicity Models for the 2025 USGS National Seismic Hazard Model for Puerto Rico and the U.S. Virgin Islands

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Gridded (or background) seismicity models are a critical component of probabilistic seismic hazard assessments, accounting for off-fault and smaller magnitude earthquakes. They are typically developed by declustering and spatially smoothing an earthquake catalog to estimate a long-term seismicity rate that can be used to forecast future earthquakes. Here, we present new gridded seismicity models for use in the 2025 National Seismic Hazard Model (NSHM) for Puerto Rico and the U.S. Virgin Islands (PRVI). The previous PRVI NSHM was released in 2003, and so our new models incorporate updates to both data and methodology. We utilize an updated earthquake catalog based on improved Puerto Rico Seismic Network data with newly characterized completeness epochs. The catalog is divided into crustal, subduction interface, and intraslab seismicity using new methods and an updated subduction zone geometry. We consider three declustering methods: Gardner and Knopoff (BSSA, 1974; also used in the 2003 model), Reasenberg (JGR, 1985) and the nearest-neighbor method of Zaliapin and Ben-Zion (JGR, 2020). To spatially smooth the catalogs, we employ two-dimensional Gaussian kernels of either fixed or adaptive (variable) bandwidth (Frankel, SRL, 1995; Helmstetter et al., SRL, 2007; Moschetti, BSSA, 2015). The spatial probability density functions that result from declustering and smoothing are later combined with a rate model developed using the new methodology applied to the 2023 U.S. NSHM 50-state update (Petersen et al., Earthquake Spectra, 2023), which improves representation of epistemic uncertainty relative to the 2003 model. We present preliminary PRVI gridded seismicity models and examine how they are impacted by the ongoing and extraordinarily active Southwest Puerto Rico sequence.

POSTER 143

A Seismological Method for Estimating the Long-Period Transition Period Tl in the Seismic Building Code

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The design response spectrum in the ASCE 7 Standard has undergone numerous changes in recent years. Despite these updates, one crucial parameter, the long-period transition period parameter (T_L), has remained unchanged since its inception in FEMA 450-1/2003. T_L represents the corner period signifying the shift from constant velocity to constant displacement segments within the design response spectrum. This parameter holds particular significance for structures with longer periods, like high-rise buildings and bridges. Presently, the estimation of T_L utilized in engineering design standards is primarily based on a correlation between modal magnitude (Mw) and T_L, overlooking factors such as stress drop (Δσ) or crustal velocity in the source region (β). This study seeks to integrate both Δσ and β into the TL estimation process. Modal magnitude data is derived from disaggregation data from the 2018 National Seismic Hazard Model (NSHM) for the contiguous United States (CONUS) and the 2021 NSHM for Hawaii (HI). β values are obtained from existing literature. To calculate Δσ for events in the Central and Eastern United States (CEUS), ground motion models are inverted. For events in the Western United States (WUS) and HI, published information is utilized to determine Δσ. The T_L is then determined using the definition of the corner period. The outcomes of this study indicate a generally more conservative or longer estimation of TL compared to the current approach employed in engineering design standards.

POSTER 144

Why Seismic Hazard Models Appear to Overpredict Historical Shaking Observations: An Intensely Simple Answer

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To understand how well seismic hazard maps predict actual shaking, we use performance metrics to compare them via hindcasting. Our hindcasting approach uses seismic intensities derived from documented shaking effects, which provide the only source of information for shaking caused by historical earthquakes, and often the most abundant information for instrumentally recorded events. Using intensities allows longer observation periods for map performance evaluation, but has limitations in uncertainty and spatial coverage. Comparison of modern hazard maps and historical intensities also requires conversion between forecasted metrics such as peak ground acceleration (PGA) and intensity. Recent maps for California, Japan, Italy, Nepal, and France appear to consistently overpredict historically observed intensities. However, numerical simulations show that observed shaking is equally likely to be above or below predictions. The consistency of results from independently developed models and datasets in different countries and tectonic settings suggests a possible systematic bias in the hazard models, the observations, or both. Analysis of possible causes shows that much of the discrepancy is due to a subtle issue: the Ground Motion Intensity Conversion Equations (GMICE) equations used to compare the maps with historically observed intensities. Gallahue and Abrahamson (2023) showed that currently used GMICEs introduce a bias when used to convert hazard maps, overestimating the PGA-equivalent intensity value by as much as 1 intensity unit for above average ground motions that often control seismic hazard. Improved GMICE will be important for seismic hazard performance evaluation and ground motion modelling efforts. For mitigating earthquake risk, it is encouraging that much of the apparent overprediction of earthquake hazards results from the conversion equations rather than a systematic effect in the hazard modeling approach. Thus although any given hazard map may overpredict or underpredict shaking due to chance or parameter choice, we find no evidence for underlying systematic problems with hazard mapping.

POSTER 145

Hybrid Empirical Ground-Motion Models for the Island of Hawaii Based on an Updated Strong Ground Motion Database

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Due to different anelastic attenuation characteristics, the volcanic origin of some events, and the distribution of event depths, ground motion modeling on the island of Hawaii is challenging. The island of Hawaii has experienced several significant earthquakes, contributing to a growing database of strong ground motion observations. The development of Ground Motion Models (GMMs) for the island of Hawaii has been limited to only a few. In this study, we have proposed two separate GMMs using the Hybrid Empirical Method (HEM), one for shallow earthquakes (hypocentral depth ≤ 20 km) and one for deep earthquakes (hypocentral depth > 20 km) on the Island of Hawaii. Considering Western North America (WNA) and the island of Hawaii as the host and target regions, we utilized the stochastic point source model ratio in the host and target regions as adjustment factors. The adjustment factors have been applied to transform the GMMs from the host region to the target region. The models have been developed by the Ground Motion Intensity Measures (GMIMs) resulting from the HEM and nonlinear least-squares regression. We further calibrate the models using the observed database to adjust any bias between the GMIM estimates from the HEM and the Hawaii observations. The GMMs have been developed to predict PGA and 5%-damped PSA at periods T = 0.01–10 s for moment magnitudes (M) in the range of 3 to 7.5 and for Joyner-Boore distances in the $R_{jb} \leq 200$ km range.

POSTER 146

Empirical Models for Fourier Amplitude Spectrum of Ground-Motion Calibrated on Data From the Iranian Plateau

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Ground motion models (GMMs) are commonly employed in engineering seismology to predict ground motion intensities. Most GMMs typically predict the response spectral ordinates, such as spectral acceleration, for a single-degree-of-freedom oscillator due to their widespread use in engineering design. The functional forms of the GMMs for response spectra are constructed based on principles derived from the Fourier spectral concept. Presuming the applicability of Fourier spectral concepts in the response spectral domain might lead to physically inexplicable outcomes. This study employed a mixed-effects regression technique to introduce four models for predicting the Fourier amplitude spectrum. These models explore the influence of incorporating random-effect event and station terms and variations in employing the mixed-effects regression technique in either one or two steps, using either a truncated dataset or the entire dataset (nontruncated dataset). The models are developed based on data from Iranian strong motion. All datasets comprise 2581 three-component strong ground motion records derived from 424 events with magnitudes ranging from 4.0 to 7.4. These records span from 1976 to 2020 and involve 706 stations.

In contrast, the truncated dataset has fewer records, events, and stations, specifically 2071, 408, and 636. We employed simple functional forms for four models, incorporating a restricted set of predictors, which include moment magnitude (M_w), Joyner-Boore distance (R_{jb}), and time-averaged shear-wave velocity in the top 30 m (V_{S30}). The style-of-faulting term was omitted from the final functional forms based on statistical analyses.

POSTER 147

Methods to Evaluate and Improve the Modeling of Rupture Directivity in Assessment of Seismic Hazard

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In recent years, there have been advancements that model near-source effects of earthquake rupture on strong ground shaking, leading to an improved characterization of ground motions. Moving forward, modern techniques can be used to incorporate source characteristics and near-fault ground motion behavior that contribute to the azimuthally varying effects that result in rupture directivity. One example is the application of machine learning methods to support more automated integration of new predictor variables in model development and to allow more evaluation opportunities to assess residuals. Here, we utilize several techniques to take advantage of the plethora of synthetic data and its ability to supplement trends observed in data. We showcase two examples of how models can be developed using artificial neural networks (ANNs). We evaluate the performance of the ANN with existing methods, comparing misfit and evaluate how to improve upon these methods in the future.

One ANN approach uses a set of simulations with synthetic ground motions from the Southern California Earthquake Center (SCEC) CyberShake study to develop a ground motion model adapted to incorporate seismic directivity information using an ANN. This large database (TBs) enables us to train the model to better capture magnitude, period, and distance variations and how they relate to amplification from hypocenters located along finite-faults during training. In some cases, there is reduced misfit from better representing source features that aren't included in base ground motion models that neglect hypocenter location (e.g., azimuthal variation, source-to-site terms). Another ANN method uses a shallow-layered neural network model to better fit a hypocenter-independent model. This method adjusts the median and aleatory variability to account for the averaged impact of various hypocenter distributions to fit the underlying directivity adjustment model. This method serves as a template to apply to other directivity models, improving computational efficiency and more readily enabling integration in hazard codes.

POSTER 148

A Fault-Based Crustal Deformation Model With Buried Dislocation Sources for Slip-Rate Inversion of the Alaska Faults

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I apply a fault-based crustal deformation model with buried dislocation sources to estimate on-fault slip rates and off-fault moment rate distribution in Alaska for the long-term National Seismic Hazard Model (NSHM). This model uses the method of Zeng and Shen (2017) to invert for slip-rate and strain-rate parameters based on inputs from Global Positioning System (GPS) velocities and geologic slip-rate constraints. A time-dependent postseismic deformation correction is applied to the data to account for the viscoelastic responses from the 1964 Great Alaska earthquake. I modify the Alaska subduction model from the block model of Elliott and Freymueller (2020) using the USGS Slab2.0 model (Hayes et al., 2018). Faults in Alaska are obtained from the 2023 NSHM Alaska geologic fault model (Powers et al., 2023). The model slip rates are determined using a least-squares inversion. The resulting on-fault model slip rates are compared with the geologic slip rates in Alaska, and the off-fault moment rate is compared with the regional seismicity rate.

3D Wavefield Simulations: From Seismic Imaging to Ground Motion Modelling

Oral Session • Thursday 2 May • 8:00 AM Pacific

Conveners: Ebru Bozdag, Colorado School of Mines (bozdag@mines.edu); Rebecca Fildes, University of California, Davis (rfildes@ucdavis.edu); Menno Fraters, University of Florida (menno.fraters@ufl.edu); Lorraine J. Hwang, University of California, Davis (ljhwang@ucdavis.edu); Andrew Lloyd, Lamont-Doherty Earth Observatory, Columbia University, (andrewl@ldeo.columbia.edu); Brandon VanderBeek, Università di Padova (brandonpaul.vanderbeek@unipd.it)

High Frequency (2+ Hz), 3D Wavefield Simulations of Large Earthquakes on the Southern Whidbey Island Fault, Washington State

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We directly simulate large magnitude crustal earthquakes (Mw7.0-7.5) on the southern Whidbey Island fault in Washington State to better constrain the possible extent and distribution of strong shaking in the Puget Sound region. Simulations employ a 3-D seismic velocity model and kinematic, finite-fault sources, and are run using a spectral element method code (SPECFEM3D) on a mesh with a 30m-sampled topographic surface. We also implement targeted updates to the seismic velocity model at shallow depths to improve accuracy of high-frequency shaking (i.e., modeled up to ~2.5 Hz). These include adding a region-specific, shallow (~100m-thick) soil velocity model and surface topography. Model quality is assessed by comparing results to empirical ground motion models (NGA-West2) and records from the 2001 Mw6.8 Nisqually earthquake. We test the sensitivity of ground motion estimates to a variety of source parameters, including hypocenter location, fault dip direction, and source location. We find that all Mw7.0 scenarios produce strong shaking in the city of Everett, Washington, and produce peak shaking greater >10 cm/s in the cities of Seattle, Bellevue, and Tacoma. For larger magnitude events, strong shaking can extend as far north as Victoria, British Columbia, and as far south as Olympia, Washington. In addition, the sedimentary structure of the nearby Everett Basin encourages the generation of high-amplitude, intermediate- and long-period surface waves. We also observe a strong dependence of long-period amplification in the Everett, Seattle, and Tacoma Basins on rupture directivity and source location. The inclusion of a shallow soil velocity model impacts site effects at periods of 1-2 s, with the greatest impact observed at sites with VS30 < 400 m/s. The results indicate that the potential strong shaking from large southern Whidbey Island fault earthquakes will be greatest in the central Puget Sound region, though the exact distribution and intensity of shaking will be highly dependent on local geology and earthquake source parameters, like hypocenter location and dip direction.

3D Kinematic Models of Ground Motions of Cascadia Megathrust Earthquakes: Preliminary Results and Comparison to Paleoseismic Subsidence Data

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The Cascadia Subduction Zone (CSZ) is anomalously quiet, with a dearth of moderate-to-large magnitude seismicity in the instrumented record. However, paleoseismic evidence indicates that the CSZ ruptures in large (~M8-9) megathrust earthquakes, with the last great event occurring in 1700. To quantify the seismic hazard due to great CSZ earthquakes, we employ numerical methods to simulate ground motions of many M8.7-9.2 megathrust earthquake scenarios. Here, we present preliminary results from the next generation of 3D broadband (up to 10 Hz) ground motion simulations for the CSZ, building off the work of Frankel et al. (2018) and Wirth et al. (2018). These broadband ground motions are generated using a hybrid approach, where low frequency (<1 Hz) waveforms are simulated in a 3D seismic velocity model using SPECFEM3D and are combined with high frequency (1-10 Hz) waveforms modeled stochastically. We build these scenarios using a logic tree approach, varying the event magnitude, the down-dip and up-dip limits of slip, including rupture onto secondary splay faults, and the slip distributions, which are varied both randomly and based on interseismic geodetic locking. Ultimately, these ground motions may be coupled with simulations of tsunami inundation to achieve a time-dependent understanding of seismic and tsunami hazard in coastal communities. These simulations will also be used to quantify the impacts to infrastructure and cascading hazards, such as landslides, liquefaction, and land-level change, with a focus on coastal communities in the Pacific Northwest. In addition, we highlight a subset of earthquake scenarios to evaluate how different rupture properties, as well as methods for calculating static displacements (i.e., 3-D simulations vs. a 1-D Okada model), impact estimates of coastal vertical land-level change and their comparison to paleoseismic estimates from past earthquakes. We show that the method used to calculate vertical displacements influences the distribution of coseismic uplift and subsidence, and therefore has implications for comparisons to paleoseismic data from previous Cascadia earthquakes.

Broadband Ground Motion Simulations for a Türkiye-like Earthquake "Doublet" on the Hayward and Calaveras Faults

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The occurrence and impact of the February 2023 earthquake doublet in Türkiye, where an M_w 7.8 event was followed roughly 9 hours later by an M_w 7.5 event on an adjacent fault, begs the question: What would be the impact of such a sequence in California? Here, we consider a comparable doublet scenario on the Hayward and Calaveras faults in the San Francisco Bay region. The first phase of this work involves characterizing the fault ruptures and simulating the ground motions. We base the fault locations and orientations on the 2023 USGS National Seismic Hazard Model. Both faults have creeping zones, so we use a simple scheme in our kinematic rupture generator to taper the coseismic slip in the upper 10 km based on the ratio of long-term creep rate to long-term fault slip rate along each section. The resulting magnitudes are M_w 7.15 for the 95-km Hayward rupture and M_w 7.16 for the 100-km Calaveras rupture. We compute broadband motions using a combination of deterministic and stochastic approaches for the lower- and higher-frequency components, respectively. Our deterministic calculations use the USGS 3D San Francisco Bay region velocity model (v21.1) with a minimum shear velocity of 400 m/s, and our stochastic simulations use a 1D reference model with Vs30-based site-specific adjustments using period-dependent factors. We saved waveforms on a 1.2 km by 1.2 km grid of points, and we extracted PGA, PGV, and spectral accelerations at periods of 0.3, 1.0, and 3.0 s to produce scenario ShakeMaps. Additionally, we save ground acceleration time histories at other sites corresponding to locations of mid- and high-rise buildings for later use in structural response analysis. Comparison of the simulated motions with empirical ground-motion models (GMMs) are generally favorable; however, noticeable differences exist due to rupture directivity and basin response effects. Furthermore, simulated motions along the creeping fault sections are generally smaller than GMM predictions. The second phase of this work is ongoing and involves analyzing potential impacts on the built environment using the simulated ground motions.

Toward High-Frequency Three-Dimensional Green's Function Databases

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An effort is underway at national laboratories and universities to compute new 3D Green's functions. To inform choices for production Green's function simulations, we present ~1 Hz comparisons between elastic solvers and preliminary 3D moment tensor inversions for 6 historical underground explosions.

Among the results of the comparisons, we show that, even with extremely conservative meshing, differences of practical significance can persist between finite-difference and finite-element synthetics. More subtly, source-dependent amplitude errors related to finer meshing requirements for shear relative to compressional waves can give rise to systematic biases, motivating detailed convergence checks.

Guided by the above, we computed finite-element Green's functions and corresponding moment tensors for the historical explosions. Our results show that meaningful patterns can persist in moment tensor uncertainty surfaces even when best-fitting moment tensor solutions become unreliable. For low-magnitude or sparsely-recorded seismic events, 3D Earth models may provide new source constraints different from the usual Rayleigh-wave radiation pattern constraints that tend to dominate 1D inversions, with implications for improved source-type estimation in particular.

Iterative Global 3D Centroid Moment Tensor Inversions Using Stored Global Green Functions From Glad-M25

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Though the synthetic seismograms used for Global CMT inversion are based on modern 3D Earth models, their accuracy is limited by the validity of the path-average approximation for mode summation and surface-wave ray theory. Inaccurate computation of ground motion amplitude and polarization, and other effects that are not modeled, may bias inverted earthquake parameters. Synthetic seismograms of higher accuracy will improve the determination of seismic sources in the CMT analysis, and reduce concerns about this source of uncertainty. However, traditional forward computation of 3D synthetic seismograms for iterative source inversion remains computationally prohibitive. The calculation of a strain-tensor database has recently been implemented for the spectral-element solver SPECFEM3D (Ding et al., 2020), based on theory from previous work for regional inversion of seismograms for earthquake parameters (Zhao et al., 2006). The main barriers to a global database of Green functions have been storage capacity, I/O, and computation speed. We show that subselecting necessary elements can efficiently overcome these issues when storing reciprocal wavefields for 183 stations of the Global Seismographic Network. Here, we apply this framework of Green Function storage to the set of GCMT solutions used for the CMT3D catalog Sawade et al. (2021) and compare GCMT, CMT3D, and CMT3D+ solutions, the latter of which are iteratively inverted for moment tensor and centroid location and time until converged.

SPECFEM++: A Modular and Portable Spectral-element Framework for Seismic Wave Propagation

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SPECFEM represents a suite of computational tools based on the spectral element method used to simulate wave propagation through heterogeneous media. Over the years, SPECFEM has been developed as a set of 3 Fortran packages (SPECFEM2D, SPECFEM3D, and SPECFEM3D_GLOBE) with partial support for GPUs (NVIDIA and AMD). The central premise of SPECFEM has always been achieving highly optimized performance on traditional and modern architectures by implementing domain- and dimension-specific algorithmic optimization. However, this approach has also resulted in a codebase with a high technical overhead, heavy use of conditional branches, architecture-specific implementations, code duplication, and isolated feature implementations.

In this talk, I will present our recent efforts to unify the suite of SPECFEM packages under a single modular framework, SPECFEM++, while maintaining the performance characteristics of the original packages. The key feature of SPECFEM++ is a formulation that separates the physics from the parallelism of the spectral element method. We describe this parallelism using the Kokkos programming model and the physics using C++-templated spectral element types. The flexibility of C++ templates and the performance-portability of Kokkos programming model has let us design a modular package that is highly versatile and performant.

Forward Simulation of Air and Ground Vibration Induced by Series of Wind Turbines Using the Spectral-Element Method

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Amidst the ongoing energy transition, wind power, harnessed via turbines, has been identified as a viable renewable energy source capable of generating clean, sustainable power. As wind turbines harness the wind's energy to produce electricity, they introduce sub-aerial and subsurface vibrations that can be observed in seismic and acoustic recordings. Elastic and acoustic wave propagation from turbine sources was simulated using the spectral-element method implemented in SPECFEM3D across a spectrum of frequencies ranging from 1 to 10 Hz across a diverse set of subsurface conditions. Numerical results were compared with observations from turbine installations in Wolfe Island, Ontario for validation. Comprehensive synthetic modelling of these coupled wavefields allows us to characterize the noise introduced by these power-generating structures and to assess their impact on nearby people and infrastructure. Further, the wavefield characterization allows for the investigation of turbines as a seismic source that can lead to monitoring solutions for structural foundation and installation integrity.

Multiscale Rupture Modeling: Bridging Laboratory Acoustic Emissions and Earthquake Ground Motions

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Rupture phenomena occur at multiple scales, ranging from laboratory failure experiments to real-world earthquakes. This study introduces a novel hybrid approach combining quasi-static and dynamic rupture modeling to explore the initiation and propagation of fracture events. This method is applied to three distinct scenarios: a laboratory stick-slip experiment, a hydraulic fracture experiment, and the 2022 M6.7 Luding earthquake in Sichuan Province, China.

The models for each scenario are validated using real waveform observations from laboratory Piezoelectric Transducer (PZT) sensors and an array of dense field strong motion stations. The results from these applications demonstrate the robustness and versatility of the hybrid rupture modeling technique. The study provides insights into the intricate mechanisms of fracture initiation and growth at different scales, highlighting the correlation between micro-scale laboratory acoustic emissions and macro-scale earthquake ground motions. Furthermore, our findings reveal the critical role of various physical parameters in rupture dynamics, such as stress concentration, material heterogeneity, and fault geometry. These insights have significant implications for understanding earthquake mechanics and improving seismic hazard assessment.

Local Geological Changes and Simplicial Remeshing for Wave Propagation

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Realistic geological models of the subsurface often hold thin layers, tangential contacts, and horizons shifted by faults. Such features are difficult to handle in seismic wave propagation simulation because they lead to gigantic computation costs when using explicit time-schemes. As a consequence, studying the impact of geological structural uncertainties on wave propagation remains out of reach in most cases. In this work, we propose two strategies to modify a geological model locally and provide a good-quality simplicial mesh of it. The first strategy aims at better balancing accuracy and efficiency of wave propagation simulations by expanding or contracting the problematic aforementioned geological features. Relying on an exclusion zone associated with each horizon and fault, our approach locally modifies the geometry and the connectivity of geological layers in an automatic way. When applied to ground motion modelling in the lower Var valley basin (France), this approach allows to decrease the computation cost of a discontinuous Galerkin simulation by a factor of 55 while keeping an excellent accuracy. The second strategy we propose aims at inserting a new geological interface in a given model while avoiding to remesh this latter completely. To do so, we rely on a level-set function to describe the interface to be inserted and on the Mmg software to remesh the vicinity of the interface, with a special care of its intersections with previous discontinuities. Using this approach, we study the impact of the depth of a gas-water contact on a seismic wavefield. This illustrates how our method might open the path to the inversion of waveforms for the estimation of geological structural parameters.

3D Multiresolution Velocity Model Fusion With Probability Graphical Models

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The variability in spatial resolution of seismic velocity models obtained via tomographic methodologies is attributed to many factors, including inversion strategies, ray path coverage, and data integrity. Integration of such models, with distinct resolutions, is crucial during the refinement of community models, thereby enhancing the precision of ground motion simulations. Toward this goal, we introduce the Probability Graphical Model (PGM), combining velocity models with heterogeneous resolutions and non-uniform data point distributions. The PGM integrates data relations across varying-resolution subdomains, enhancing detail within low-resolution domains by utilizing information and a priori knowledge from high-resolution subdomains through a maximum likelihood problem. Assessment of efficacy, utilizing both 2D and 3D velocity models—consisting of synthetic checkerboard models and a fault zone model from Ridgecrest, CA—demonstrates noteworthy improvements in accuracy. Specifically, we find reductions of 30% and 44% in computed travel-time residuals for 2D and 3D models, respectively, as compared to conventional smoothing techniques. Unlike conventional methods, the PGM's adaptive weight selection facilitates preserving and learning details from complex, non-uniform high-resolution models and applies the enhancements to the low-resolution background domain.

Multi-Scale Seismic Imaging of Fault-Zone Structures in Southern California With Full-Waveform Inversions of Regional and Dense Array Data

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We discuss several methodologies for constructing multi-scale seismic velocity models for crustal fault zones at seismogenic depths with full-waveform inversion of earthquake and ambient noise data recorded by regional and dense sensor configurations. We first discuss applications for the area around the rupture zone of the 2019 Ridgecrest earthquake sequence in California, leveraging data from the regional network and dense 2D and 1D deployments with station spacings of ~5 km and ~100 m, respectively. To build self-consistent multi-scale models, we begin with pre-existing regional velocity model earthquake locations, and refine these results through iterative inversions of waveforms recorded by regional and 2D array stations. The improved results provide a structural context of small-scale fault zone models with resolutions up to the tens of meters using high-quality aftershock waveforms captured by dense linear arrays with frequencies up to 10 Hz. As a second focus area, we develop multi-scale imaging for the southern San Andreas fault using data recorded by a dense deployment near the Thousand Palms Oasis in the Coachella Valley at a time with very few local earthquakes. To utilize regional and teleseismic earthquake waveforms, we use double-difference kernels with the FK-injection SPECFEM3D solver to image the fault-zone structures beneath the dense array. The multi-scale results on fault zone and crustal structures contribute significantly to improved understanding of earthquake processes and seismic hazard assessments. The developed methodologies are broadly applicable to research on fault zones worldwide.

Global Source-Encoded Waveform Inversion: Preliminary Results

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We present the latest update on applying source encoding on a global scale. Our source-encoding technique enables us to compute Fréchet derivatives for all events with only a few forward and adjoint simulations and shows promising results for a hemispherical-scale study. In this study, we introduce four improvements. First, we start with the GLAD-M35 model, which is our latest global adjoint tomography model and provides a low-rank approximation of the full Hessian. This enables us to properly scale partial velocity Hessian terms as the preconditioner and determine the smoothing length based on the resolution length estimation. Second, we expand the dataset to a total of 9,382 events with corrected source mechanisms from 3D numerical simulations. The dataset is selected using a combination of FLEXWIN and new frequency-domain criteria, which restrict the difference between source-encoding and inversions using the full-frequency band. Third, by re-running forward simulations for all events every 10 iterations, we introduce a 'windowing' technique that removes unwanted parts of the time-domain observed data even when we only have a few data points in the frequency domain. Finally, we adopt new optimizers that better fit the varying nature of the source-encoded objective function. The optimizers we are testing include ADAM, stochastic conjugate gradient, and stochastic BFGS.

LLNLGlobeFWI: First Iterations Using a Semi-Automatic FWI Framework Applied to the Globe With Spiral as the Starting Model

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Building on the global anisotropic travel time tomography model, SPiRaL (Simmons et al., 2021), we present the first global full waveform inversion (FWI) updates to SPiRaL using an initial set of 103 events distributed throughout the globe at a period band from 40 s to 200 s. We employed LLNLGlobeFWI which is a python-based framework for semi-automated global full waveform inversion using the adjoint method. LLNLGlobeFWI was developed at Lawrence Livermore National Laboratory (LLNL) and used SeisFlows (Modrak et al., 2018) as a starting point for the development. LLNLGlobeFWI was executed on LLNL's Quartz supercomputer and 90-minute seismograms were computed for the events to capture seismic phases at global distances. Seismograms were windowed with Pyflex, multitaper misfits and associated adjoint sources were computing using Pyadjoint, and the L-BFGS method was used for the optimization within the custom semi-automated workflow. Accurate prediction of waveforms and onset arrival times at all distances with a single global model is the overall goal of this project. Here, we present the first full waveform inversions aimed at reaching that goal starting with the SPiRaL model and an initial set of global events. Future work will include the incorporation of a larger data set, period band reduction, and benchmarking with SPiRaL to ensure the onset times are improving as well.

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Homogenized Full Waveform Inversion : Application to Earth Model for Long Period Seismic Waves

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In order to understand the structure and dynamics of the Earth, seismic tomographic models are a precious tool. However the building of such models may be biased by such an interpretative goal. Switching paradigms, we can relax the interpretation aim to focus on building data-predictive models only, designed to perform source properties inversion for instance.

To proceed to the construction of such an Earth model, we applied a modified version of the classical Full Waveform Inversion (FWI), considering a full anisotropic setting of mechanical properties (21 elastic parameters and density), and a Gauss-Newton algorithm. Numerical simulations are performed using a spectral-element solver (SEM3D) in order to solve for both forward and adjoint wavefields, that give access to sensitivity kernels. Then, considering that the best model obtained by FWI is at best an effective model of the true one (as proposed by Capdeville & Métivier, 2018), a filtering step (whose operator comes from homogenization theory applied to nonperiodic media) provides a spatial regularization for the inverted model. With this in mind, a test-case is performed on a starting simplified Earth model with largely buried mantle heterogeneities. The resulting inverted, homogenized model, is very close to the homogenized starting model, as expected. The inverted model can therefore be considered as a good data-predictive model.

Adjoint-State Traveltime Tomography (tomoatt.com)

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Adjoint-state traveltime tomography is an efficient approach for determining subsurface seismic structures (Vp, Vs, anisotropy) and earthquake locations using body wave traveltime data. One remarkable feature of this approach is its independence from ray tracing. TomoATT is the software package that implements adjoint-state traveltime inversions. The package's first version, designed for non-commercial use in scientific community, is now ready for release. TomoATT grants users the flexibility to choose the specific type(s) of traveltime data they wish to employ. Whether it be absolute arrival times, common-source differential arrival times, or common-receiver differential arrival times, users can utilize them simultaneously or separately to infer velocity structures and/or earthquake locations. TomoATT stands out for its multilevel hybrid parallelization technique, which incorporates source parallelization, subdomain parallelization, hyperplane stepping parallel fast sweeping, and Single Instruction, Multiple Data (SIMD) optimization for multiple CPU architectures (AVX2, AVX-512 and ARM-SVE). This innovative approach significantly enhances computational efficiency and empowers the package to tackle super large-scale problems effectively. TomoATT is a user-friendly software package. Users only need to input traveltime data in a pre-defined format, and the software will execute with minimal user interference. The usage of the software package, TomoATT, can be found at www.tomoatt.com. Notably, adjoint-state traveltime tomography has also been extended to invert surface wave traveltime data for seismic velocity and anisotropy.

3D Wavefield Simulations: From Seismic Imaging to Ground Motion Modelling [Poster Session]

Poster Session • Thursday 2 May

Conveners: Ebru Bozdag, Colorado School of Mines (bozdag@mines.edu); Rebecca Fildes, University of California, Davis (rfildes@ucdavis.edu); Menno Fraters, University of Florida (menno.fraters@ufl.edu); Lorraine J. Hwang, University of California, Davis (ljhwang@ucdavis.edu); Andrew Lloyd, Lamont-Doherty Earth Observatory,

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POSTER 107

A Detailed Analysis of Seismic Waves Amplification for Basins Using 3D Seismic Simulations

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Sedimentary basins trap seismic waves, leading to amplification and long-duration shaking. This seismic response of a sedimentary basin can be relevant both for understanding active tectonics and for assessing seismic hazards relevant to society. Using 3D seismic wavefield simulations with different models, we can explore how the basin depth and the basin's geometrical boundary affect the seismic waves, amplitudes, and radiation patterns. Nenana basin in central Alaska is a promising region for studying basin wave propagation because its basement surface has been estimated from detailed active-source imaging and because there were about 15 broadband seismic stations in the region, enabling comparisons between simulation results (synthetics) and observations (data). We have created four Nenana basin region models: 1) the Berg et al. (2020) 3D tomographic model, 2) the Berg model with an embedded basin model, 3) a simplified model of an elliptical basin embedded in the Berg model, 4) a model with upper 8km from 1D velocity profile from Brocher2008 and bottom from the Berg model. By comparing and analyzing the seismic simulation results in both time and frequency domains from these models, together with the real data collected in this region, we can investigate the detailed mechanism of basin amplification for a variety of different seismic sources, basin geometries, and frequencies.

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POSTER 108

Estimating Ground Motion Intensities Using Simulation-Based Estimates of Local Crustal Seismic Response

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It is estimated that 2 billion people will move to cities in the next 30 years, many of which possess high seismic risk, underscoring the importance of reliable hazard assessments. Current ground motion models for these assessments typically rely on an extensive catalogue of events to derive empirical Ground Motion Prediction Equations (GMPEs), which are often unavailable in developing countries. Considering the challenge, we choose an alternative method utilizing physics-based (PB) ground motion simulations and develop a simplified decomposition of ground motion estimation by considering regional attenuation (Δ) and local site amplification (A), thereby exploring how much of the observed variability can be explained solely by wave propagation effects. We deterministically evaluate these parameters in a virtual city named Tomorrowville, located in a 3D layered crustal velocity model containing sedimentary basins, using randomly oriented extended sources. Using these physics-based empirical parameters (Δ and A), we evaluate the intensities, particularly Peak Ground Accelerations (PGA), of hypothetical future earthquakes. The results suggest that the estimation of PGA using the deterministic decomposition exhibits a robust spatial correlation with the PGA obtained from simulations within Tomorrowville. This method exposes an order of magnitude spatial variability in PGA within Tomorrowville, primarily associated with the near-surface geology and largely independent of the seismic source. In conclusion, advances in PB simulations and improved crustal structure determination offer the potential to overcome the limitations of earthquake data availability to some extent, enabling prompt evaluation of ground motion intensities.

POSTER 109

Effects of the Distribution of Ambient Noise Sources in Subsurface Models Inverted From Noise Correlations

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Cross-correlations of seismic ambient noise are often used to image subsurface structure. Although it is possible to account for the distribution of noise sources and treat noise correlations as self-consistent observations, most studies currently assume that noise sources are uniformly distributed and interpret noise correlations as empirical Green's functions. However, this assumption is not always correct, as noise sources are often localized and unevenly distributed. In this work, we investigate how the treatment of the noise source distribution changes subsurface models obtained from noise correlations. Our main focus is to study how inverted models change if a realistic heterogeneous noise source distribution is either incorrectly assumed to be uniform or properly taken into account. Furthermore, we explore the consequences of ignoring distant noise sources in a regional tomography, which may be necessary to avoid excessive computational requirements. To reach these objectives, we conduct a series of 2-D synthetic inversions for local subsurface structure, and thereby imitate a local-scale experiment exploiting ocean noise. The synthetic dataset consists of noise correlations computed with a large-scale noise source distribution and a laterally heterogeneous Earth structure model. We invert this dataset using three approaches, each dealing with the noise source distribution differently. Additionally, we repeat the experiments using a second synthetic dataset generated with a different noise source distribution to investigate how the estimated subsurface varies artificially due to the Green's function approximation. Our results demonstrate that the Green's function approximation introduces errors in the inverted models with a magnitude that depends on the distribution of noise sources. Since the location of noise sources changes over time, this suggests that model errors are also time-dependent. In contrast, source-related errors are avoided if the noise source distribution is accounted for. However, all noise sources, including those located away from the area of interest, must be properly considered.

POSTER 110

Southern Italy: An Intricate Litosphere

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High-resolution adjoint tomography stands out as a valuable method for comprehending the complexities of the Earth's lithosphere. This paper offers an overview of the seismic images resulting from IMAGINE_IT adjoint tomography in the study of the lithosphere beneath Southern Italy and the Adriatic region.

The Adria plate plays a crucial role in the geodynamics of the Central Mediterranean, serving as the foreland of non-coeval mountain ranges. Its margins are subjected to subduction systems beneath the Alps to the north, the Apennines to the west, and the Dinarides to the east. The intricate behavior of this system, combined with geographical data heterogeneity, has led to a fragmented understanding of the Adria plate. The lithospheric structure, specifically Vp and Vs profiles, remains poorly understood due to limited seismic stations, compromised earthquake location quality, and a lack of coverage by traditional seismic tomography methods. These uncertainties complicate the assessment of seismic hazards along the Adriatic coasts, including tsunami hazard evaluation. We present a preliminary analysis incorporating seven years of supplementary data beyond IMAGINE_IT original timeframe (limited to data until 2015). Noteworthy contributions come from the deployment of dense regional arrays of broadband seismic stations, such as AlpArray and the ongoing AdriaArray initiative.

Furthermore, the focus extends to southern Italy, covering the L'Aquila region up to the Calabrian Arc. The analysis of images produced by high-resolution adjoint tomography IMAGINE_IT reveals details of the lithospheric architecture, including crustal thickness variations, seismic velocity anomalies, and clear support of a significant interruption of delamination/subduction-related features.

POSTER 111

Synthetic Inversions for Anisotropic Structures using Wavefield Simulations and Adjoint Methods

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Laboratory measurements confirm the presence of complex (low-symmetry) elasticity in a wide range of materials. The presence of anisotropy in the uppermost mantle is well established. In subduction settings, anisotropy is complex, with different elements—the subducting plate, the mantle wedge, and the crust—potentially having different forms of anisotropy. Seismic imaging problems generally offer non-unique solutions, due to extreme heterogeneity and sparse coverage of stations and source. The addition of parameters due to the consideration of anisotropy makes the problem even more challenging. Here, in preparation for real seismic imaging problems, we perform a series of synthetic tomographic inversions, whereby a synthetic target model is used to generate synthetic data for a given source-station geometry. An initial model, different from the target model, is used to generate initial synthetic seismograms. Through formal minimization between initial and target seismograms, we iteratively perturb and improve the initial model toward the target model. We consider different target model blocks, each having a predefined type of homogenous anisotropy, and we test their recovery with a source-station geometry designed to have good, yet realistic, coverage of the medium. We test the limits of recovery of these synthetic anisotropy models by changing: 1) the size of the anomaly, 2) the degree of symmetry of the anomaly, 3) the strength of anisotropy (angular distance from isotropy), 4) the density of station coverage, and 5) the portion of waveforms to use in the inversion. Our study prepares us for realistic synthetic inversions for complex anisotropic structures, which will guide efforts for performing adjoint tomography in the Alaska subduction zone.

POSTER 112

Analysing Alpine Fault Earthquakes Through Ambient Seismic Noise

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The Alpine Fault is the primary seismic hazard in Southern New Zealand, rupturing in M7-8 earthquakes roughly every ~300 years, with the last event in 1717 AD. Yet, empirical data on ground shaking does not exist due to the absence of recorded Alpine Fault earthquakes. Numerical models that simulate shaking from possible Alpine Fault earthquakes provide key information to assist in hazard mitigation but current state-of-the-art models are too computationally expensive, limiting their ability to compute a comprehensive range of potential earthquake source scenarios.

Our approach sidesteps these limitations by estimating ground shaking using ambient seismic noise for modelling wave propagation. Ambient noise, often seeming random and incoherent in seismograms, can reveal coherent energy travelling between two seismic stations through cross-correlation, deconvolution, and coherency analyses. We apply the Virtual Earthquake method, which uses ambient seismic noise to compute empirical Green's functions between station pairs. These empirical Green's functions are modified from a surface point-force source to a double-couple source at depth. This method allows us to investigate ground shaking from many rupture scenarios comprising a broad suite of possible Alpine Fault earthquakes.

We use ambient noise records of both permanent networks and the novel SALSA (Southern Alps Long Skinny Array), a network of broadband seismometers strategically deployed every ~10 km along the Alpine Fault, which facilitates a comprehensive investigation of diverse rupture scenarios. This study showcases the potential of using ambient seismic noise to unravel seismic behaviour, offering a valuable tool for predicting and mitigating seismic hazards.

POSTER 113

Selection of a Starting Model for Adjoint Tomography of the Pacific Northwest

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High-resolution seismic tomography models are invaluable in characterizing subsurface geologic structures, quantifying seismic hazards, and understanding broader tectonic processes. Theoretical and computational advances over several decades have enabled full-waveform inversion techniques that extract more information from recorded seismograms than classical methods. In parallel, numerical methods have facilitated the rapid calculation of the forward and adjoint (time-reversed) wavefields in earthquake seismology, their interaction allowing the construction of the gradient of a chosen misfit function and the iterative improvement of the velocity model. It is well known that starting models play a crucial role in the success of full-waveform inversions. Here, the Stephenson et al. (2017) Cascadia seismic velocity model is systematically tested as a candidate starting model for future adjoint tomography of the Pacific Northwest. We use SPECFEM3D Cartesian (Komatitsch & Tromp, 1999) to calculate synthetic seismograms using the candidate starting model and a catalog of over 500 M4.0+ regional earthquakes recorded from 2012–2023. We assess starting model quality by comparing travel time anomalies between the synthetic and observed waveforms. We explore modifications to the starting model based on physical *a priori* constraints and make comparisons with a one-dimensional Earth model (ak135; Kennett et al., 1995). We focus on crustal and uppermost mantle structure which spans depth ranges (0–60 km) that are important to accurately estimate ground motions and seismic hazards, but may be poorly resolved in existing velocity models. While similar analyses with alternative candidate starting models remain necessary, this work will ultimately enable the development of future Pacific Northwest adjoint tomography models.

POSTER 114

Rupture Dynamics and Ground Motions Characteristics of the 2023 Türkiye Mw 7.8 and Mw 7.6 Earthquake Doublet

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Earthquake doublets have been observed globally in various tectonic regimes. Their occurrence disagrees with general aftershock evolution laws and thus challenges common approaches for seismic hazard assessment. A better understanding of the rupture evolution and interaction of faults involved in earthquake doublets is thus needed to improve earthquake forecasting and seismic hazard analysis. On February 6, 2023, the destructive earthquake doublet with magnitude 7.8 and 7.6 successively rocked south-central Türkiye and northwestern Syria. Here, we use data-constrained dynamic rupture modeling to investigate the rupture process and ground motions of the earthquake doublet. We find that the complex 3D fault geometry and the regional stress regime generates a distinct pre-stress loading on the multi-segment fault network and leads to complex rupture dynamics, including rupture branching and arresting, forward and backward rupture triggering, transitions between subshear and supershear. Our dynamic models well reproduce InSAR, GPS, local strong motion and teleseismic data. The synthetic ground motions show heterogeneous distribution with strong directivity amplification by subshear ruptures. Supershear rupture elevates the ground motion intensity off the fault, but mitigates the directivity amplification. Our synthetic ground motions illustrate the same distance decay pattern with the observations. In summary, our work highlights the importance of fault geometry and pre-stress loading in determining the complexity in rupture dynamics, and indicates that physics-based modeling can complement the ground motion models for assessing the seismic hazard.

POSTER 115

Lithospheric Structures of the Central Cascadia Subduction Zone Resolved by Full-waveform Inversion of Ambient Noise and Receiver Functions

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Lithospheric Structures of the Central Cascadia Subduction Zone Resolved by Full-waveform Inversion of Ambient Noise and Receiver Functions Nanqiao Du1, Bin He2,3, Ting Lei1, Tianshi Liu1, Qinya Liu1,2 1 Department of Earth Science, University of Toronto, Toronto, Canada 2 Department of Physics, University of Toronto, Toronto, Canada 3 Department of Geosciences, the University of Texas at Dallas, Richardson, TX, USA

The Cascadia subduction zone is one of the relatively young and warm endmember subduction systems, mainly due to the subduction of the Juan De Fuca plate underneath the North American Plate. Studies have shown the complex fluid migration processes in the crust and mantle while the tremor activity could also be partly attributed to fluid migration in this region. In this study, we aim to obtain high-resolution velocity structures of the crust and upper-mantle of this region based on full-waveform inversion. Particularly, high frequency P receiver functions (P-RF) are sensitive to sharp discontinuities and velocity variations beneath dense seismic arrays, and ambient noise data can be used to constrain fine-scale crustal structures. By using hybrid spectral element method (FK-SEM), we jointly invert could combine the P-RF waveforms and ambient noise cross-correlation data of the CASC93 array (Trehu et al., 1994) to obtain a detailed shear-wave velocity structure of the central Cascadia subduction Zone. Our model shows strong variations in the crust and upper-mantle in the central Cascadia subduction zone, and may further improve our understanding of the subduction and fluid migration processes geodynamics in this region.

Reference

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POSTER 116

Ambient Noise Attenuation and Differential Adjoint Tomography Applied to the Hongkou Linear Array Across the Longmenshan Fault Behind the 2008 M 7.9 Sichuan Earthquake

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The Longmenshan Fault is responsible for the 2008 M 7.9 Sichuan earthquake. In this study, we investigate the structure of the thrust fault zone using amplitude and phase information derived from ambient seismic noise. We analyze seismic noise data collected by a dense linear array of 51 3-C sensors across the Longmenshan Fault Zone at Hongkou Town, which is approximately 28 km northeast of the epicenter of 2008 Sichuan earthquake and within 100 km from the center of Chengdu, a metropolitan city with 16 million population. We extract amplitude decay information from the noise interferometry functions across the linear array by finding different combinations of station triplets (Liu et al. 2021), which cancel the effects of noise sources and unknown attenuation structure between the far-field noise sources and the linear array. In addition, we perform phase velocity tomography and convert the phase velocity map to S wave velocity in the top 5 km depth using Monte Carlo Markov Chain (MCMC). The results delineate the thrust-fold fault structure near Hongkou and suggest that the WFSD-1 drilling hole did not reach the main fault plane at Hongkou, which is situated further southeast and is associated with an asymmetric fault damage zone at ~1 km depth in the footwall of the Pengguan thrust fault. Our results agree with previous observations from seismic reflection profiles, InSAR data and WFSD drilling holes along the same line. Finally, we utilize ambient noise differential adjoint tomography (Liu et al. 2023) to improve velocity structure inversion, and the updated results will be presented at the meeting.

POSTER 117

Validating Tomographic Models of Alaska Using 3D Wavefield Simulations

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The EarthScope Transportable Array of seismic stations in Alaska and western Canada peaked in 2017 and has provided excellent data coverage in Alaska and western Canada, inspiring a wave of interest in the seismic structure of Alaska. Seismologists have utilized ambient noise waveforms as well as body waves, surface waves, and arrival time data from local earthquakes to produce several tomographic models that characterize the elastic structure (Vp, Vs) of the region, and several of these models have been archived at the EarthScope IRIS EMC for others to utilize. We have chosen five of these models of Alaska to compare and contrast their utility for wavefield simulations and for generating Green's functions for moment tensor inversions. We present synthetic waveforms made in the software package SPECFEM3D_Globe in comparison with recorded waveforms for a selected earthquake in Alaska. We then use the Python-based package MTUQ to perform moment tensor inversions using Green's functions generated in each of the five models. This testing will allow us 1) to investigate the effects of 3D structure on moment tensor inversions and 2) to carefully choose the best starting model for a future adjoint tomography study in Alaska.

POSTER 118

High-Resolution Surface Wave Tomography of the Hayward Fault in the Berkeley Region Using Ambient Noise Recorded by a Dense Nodal Array

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The ~70-km-long Hayward Fault (HF), capable of generating earthquakes exceeding magnitude 6, poses a critical threat to major cities in California, such as the San Francisco Bay area and Berkeley. Prior research revealed fault zone head waves near the HF, indicating a bi-material interface with distinct crustal blocks (slower P wave velocity on the eastern side). Clarifying if the entire HF is a continuous bi-material interface and obtaining a high-resolution crustal structure image surrounding the fault can greatly improve ground motion predictions in nearby urban areas.

To better understand the Berkeley section of the HF, Taira et al. (2022) deployed a 2-D dense nodal array across the campus of the UC Berkeley (UCB) and Lawrance Berkeley National Laboratory (LBNL). The dense deployment consists of 182 three-component nodal sensors with an average station spacing of ~100m and recorded continuously for about one month. Preliminary analyses of the nodal array recordings indicate the potential for reconstructing clear surface waves from the ambient noise data. In this study, we first reconstruct surface waves from ambient noise cross-correlation of each station pair. Then, Rayleigh wave group and phase velocity maps at different frequencies are constructed by inverting the picked travel times. Finally, we obtain a high-resolution shear wave velocity model for structures across the HF beneath the campus of UCB and LBNL in the top 15 km, by jointly inverting the Rayleigh wave group and phase velocities. The resolved fault zone image can improve our understanding of the HF in the Berkeley region.

POSTER 119

Computational Challenges of Large-Scale Numerical Simulations and Full-Waveform Inversion Workflows

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Parallel to the advances in HPC, computational requirements for seismic imaging techniques have increased in order to obtain a higher spatial/temporal resolution in a numerical full-waveform modeling, and to utilize larger databases of seismic events and multi-parameter inversions to improve the resolution of tomographic images, and our understanding of Earth's interior and dynamics. FWI workflows are well-defined involving numerical wave simulations to compute synthetic seismograms and data sensitivities to model parameters, pre-processing, and post-processing stages. However, different scales and problems may need different treatment of data, parameterization of the inverse problem, and model updates, potentially complicating the workflow. Moreover, improving the resolution of tomographic images, specifically large-scale inversions such as global-scale FWI, require dense computations and high-volume and high-frequency I/O. Thus maximizing the benefits of ever increasing available seismic data and computational resources, while harmoniously combining large and heterogeneous data in large-scale seismic inversion workflows, is crucial to obtain a high resolution and accurate tomographic images which is still a scientifically and technically challenging topic.

In this research, we focus on continental and global FWI workflows on CPU and GPU architectures, specifically to address storage and I/O bottlenecks in large-scale numerical simulations with the SPECFEM3D packages (i.e., large seismic and computational data, specifically attenuation snapshots in adjoint simulations, etc.) towards exascale computing. We will present our results and current efforts on data compression and asynchronous I/O to reduce the required storage size and I/O bandwidth. The research is supported by the NSF funded SCOPED project and simulations and the tests are performed on Texas Advanced Computing Center's Frontera system.

POSTER 120

Homogenization of Sedimentary Basins for the Simulation of Lithological Site Effects

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With the constant increase of computational power, the numerical modelling of lithological site effects can now handle 3D, geologically complex settings. However, a computational overburden is reached when, e.g., uncertainties have to be quantified. A possible pathway towards decreasing the cost of seismic wave simulations in complex media is the non-periodic homogenization. This method is known to provide accurate effective media for wave propagation. In this work, we apply it to 2D sedimentary basins and explore its efficiency and accuracy in terms of amplification simulation. Two homogenization strategies are investigated: the Backus' one, which considers the geological medium as a juxtaposition of 1D profiles, and the more general 2D homogenization, which involves the resolution of a partial differential equation. Using various velocity contrasts and geometries, we emphasize cases which require the general homogenization for an accurate modelling of amplification effects.

POSTER 121

Rapid 3D Green's Functions Using Reduced-Order Models of Physics-Based Seismic Wave Propagation Simulations

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Elastodynamic Green's functions are essential in seismology, and form a connection between direct observations of seismic waves and earthquake sources. They are key to enabling various seismological tasks, including physics-based ground motion prediction and kinematic or dynamic source inversions. In regions with comparably well-constrained 3D models of the Earth's elastic structure, such as Southern California, approximate 3D Green's functions can be computed using physics-based numerical simulations of seismic wave propagation. However, these simulations are computationally expensive, which presents a challenge for real-time ground motion prediction (e.g., ShakeMap and ShakeAlert), physics-based probabilistic seismic hazard assessment (PSHA, e.g., CyberShake), and uncertainty quantification in source inversions. Here, we address this challenge by using a reduced-order model (ROM) which enables rapid computation of approximate Green's functions by using the proper orthogonal decomposition combined with radial basis function interpolation. We train the ROM using three-component seismograms for six elementary moment tensors, computed with SeisSol, selecting 500 source locations to calculate 1.0 Hz elastodynamic Green's functions for approximately 10,000 sites in Southern California. Using leave-one-out cross-validation, we assess the accuracy of our Green's functions for the SCEC CVM-S4.26-M01 velocity model in both the time domain and frequency domain. We show that the ROM can accurately and rapidly reproduce simulated seismograms for generalized moment tensor sources in our 3D region, as well as kinematic sources by using a finite fault model of the 1987 Mw 5.9 Whittier Narrows earthquake as an example. In these demonstrators, the accuracy is quantified using the mean absolute error of the velocity waveforms and the Fourier amplitude spectra. We envision that our rapid Green's functions would be useful for physics-based PSHA, improving the uncertainty quantification in earthquake source inversions, and constructing rapid ShakeMovies with high spatial resolution.

POSTER 122

Comparison of Fundamental Fault Green's Functions (GFs) Computed Using Frequency-Wavenumber and Finite-Difference (SW4) Techniques for 1D Velocity Models

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It has been noted that use of the green's functions (GFs) computed using the three-dimensional (3D) codes such as SW4 and SPECFEM3D produce more reliable moment-tensor solutions compared to those when the GFs of the one-dimensional (1D) models are used. However, none of the studies explored if the GFs computed by the 3D and 1D are similar when they are computed for the same 1D velocity models. In this study, we have used the Dirac and Gaussian source time function in SW4 to compute regional seismograms up to 6Hz for one 1D model. We used three 1D codes, namely the Filon_AS-03, FK_PROG, and zengSAIKIA to compute high-frequency seismograms, ensuring that the wavenumber domain discretization is small enough to reduce the spatial aliasing in the synthetics. The 1D codes uses the delta function as the source time function. To establish the source time equivalence, f_o (the frequency parameter) needed to be set quite high (say about 20Hz) especially when the Gaussian source function is implemented. In this study, we will illustrate the equivalence high-frequency SW4 seismograms with those computed using the 1D code for the fundamental faults except for those computed for the 45º dipping dip-slip (DD) fault. For seismograms to be similar in amplitude for this fault, the corresponding moment-tensor elements have to be 2 time larger than those that are required by the 1D codes. This also involves the Mxy component, but the contribution from this component is many order lower than other moment-tensor elements, especially for the surface receivers.

POSTER 123

A Sparse Fault Parametrization for Large-scale Ruptures Based on Moment Tensor Interpolation

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Modeling and characterizing earthquake sources can be challenging when they fall outside the point-source approximation. Typical finite fault models assume that the rupture surface can be represented as a discretized planar fault or a combination of planes, segmented into discrete patches. This assumption requires committing to a specific fault plane geometry and discretization before performing inversion. To address this limitation, we propose a sparse yet robust fault representation that leverages the geometrical properties of the moment tensor, based on tensor interpolants and procedural surfaces. This approach enables the representation of slip surfaces with a few key point sources rather than an entire discrete surface and dynamically adjusts the discretization density for numerical modeling. We show that spherical linear interpolation is a natural interpolant function for moment tensors and showcase a preliminary application: the interpolant function is used to redistribute point sources from a pre-existing sparse rupture model to obtain a denser fault discretization, which we then use as a smooth source for waveform modeling, demonstrating interest for both the forward and inverse problem.

Advancements in Forensic Seismology and Explosion Monitoring

Oral Session • Thursday 2 May • 8:00 AM Pacific

Conveners: Richard A. Alfaro-Diaz, Los Alamos National Laboratory (rad@lanl.gov); Louisa Barama, Lawrence Livermore National Laboratory (barama1@llnl.gov); Jorge A. Garcia, Sandia National Laboratories (jgarc26@sandia.gov);

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Seismology in Support of Negotiation, Implementation, and Verification of Nuclear Test Ban Treaties and Science Diplomacy: Where It Started and DOS R&D Challenges

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In the late 1950s, scientists, diplomats, and policy makers recognized that improved seismological knowledge and capabilities were crucial for the detection and identification of underground nuclear explosions. The Eisenhower Administration initiated a comprehensive research and development program in seismology, known as Project Vela Uniform, based on the recommendations of the Berkner Panel Report filed by top national experts in seismology. From the Vela program's inception, DoD entities led by DARPA, developed the technical basis for all U.S. test ban treaty negotiations. In 1994, DoD transferred the programmatic and funding responsibility for Applied Seismological R&D to DOE, with the understanding that DOE would establish an applied nuclear explosion monitoring (NEM) program at national laboratories, while continuing to support academia and industrial communities through open-and-full competitions.[1] In parallel to these major DoD and DOE efforts, there was a small, yet operations-centric program at the former Arms Control and Disarmament Agency and then later at the Department of State, focusing on prompt transition of products to operations, for advancing national and international arms control verification goals, as well as for assessing compliance with nuclear test ban treaties and commitments. The seismic portion of DOS "verification research" reached peak in 2018-2021. Central to this seismic research program was region-specific geophysical calibration research, which was highlighted as a national priority in a 2019 OSTP policy report. In this talk, I describe how U.S. seismic research activities have evolved over the decades, how the DOS-funded projects augmented major nuclear monitoring R&D and operational efforts through international cooperative activities, often called "science diplomacy", and how DOS is seeking a sustainable solution to move forward in this fiscally challenging environment and time.

[1] John Keliher (Director, Nonproliferation and National Security, DOE) memo to John Deutch (Deputy Secretary of Defense), April 22, 1994.

Three-dimensional Nonlinear Calculations of Explosions at the Novaya Zemlya Nuclear Test Site

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We performed a series of three-dimensional nonlinear finite element calculations to model explosions at the former Soviet Novaya Zemlya nuclear test site. We organized all the available data from Novaya Zemlya explosions, including depth, topography and yield information. Many of these events are multiple simultaneous explosions. We performed calculations for six multiple events at the Northern Novaya Zemlya test site and five events at the Southern Novaya Zemlya test site. The Northern Novaya Zemlya test site has steep topography, so we performed equivalent calculations in a flat topography for comparison. The Southern Novaya Zemlya test site is nearly flat, so topography is not an issue, however these events are strongly affected by tectonic release, and are in an area of compression. We performed calculations with and without compressive tectonic stresses. From each of the calculations, we generated surface waves, full waveform regional seismograms and far-field body waves. We collected all the available seismic data from the calculated events and remeasured all of the surface wave magnitudes. We find that without tectonic stresses, the calculated surface waves are larger than the observed surface waves, but when compressive prestress is included the calculated surface waves are close to the observed values. Multiple simultaneous explosions also generate Love waves and non-isotropic Rayleigh waves. Multiple explosions may cause more surface wave variability than topography. Down going P-waves are almost unaffected by either topography or tectonic release. The reflected pP phase is distorted by topography which can reduce interference with the initial P-wave. Multiple explosions cause small but distinct variability in the P-waves at higher frequencies.

Discriminating Collapses From Explosions and Earthquakes

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The sudden collapse of an underground cavity produces seismo-acoustic signals that may potentially identify these events and discriminate them from explosions and earthquakes. In moment tensor space these collapses are modeled as gravity driven closing cracks (e.g. Bowers and Walter, 2002; Chiang et al., 2018, Pasyanos et al., 2023). Using body waves, they may show less high frequency energy than nearby earthquakes and explosions (e.g., Walter et al., 2018). The creation of cavities with the potential for collapse can follow from mining activities or underground nuclear explosions, making understanding their source an important part of geophysical nuclear test monitoring. The conditions leading to a possible cavity collapse vary with geology and depth. During the historic period (prior to 1993) of nuclear testing at the former Nevada Test Site (now the Nevada National Security Site), collapses following explosions were common as documented in Springer et al. (2002). The collapse following the September 2017 North Korean announced nuclear test is the best documented case at other nuclear testing locations (e.g. Wang et al., 2018).

To better understand and identify collapses as a unique source type we are examining a set of several dozen collapses following nuclear tests from the 1970's and 1980's in southern Nevada. We are comparing these collapse events with recent chemical explosions that were part of the Source Physics Experiments (SPE - e.g., Snelson et al., 2013), which have helped provide insight into how explosions generate shear waves (e.g., Pyle and Walter, 2022). We want to understand how much of the relative lack of high frequency energy observed in the historic Nevada collapse ATRISCO and the 2017 North Korean collapse studied in Walter et al. (2018) is due the shallow nature of the collapse source occurring in lower velocity materials, and how much may be due to the gravity driven collapse mechanism itself. As part of this work, we also plan to compare the nuclear explosion cavity collapses with those from mining areas at different depths and geologies, in various parts of the world.

Source Characterization and Uncertainty Quantification of the North Korean Nuclear Tests 2006-2017

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We introduce a novel and transportable technique to determine yield and depth of burial from seismic source spectra of underground nuclear explosions. We demonstrate the application of the technique on the six declared North Korean nuclear tests. This approach derives source spectra in absolute units for regional phase (Pg) amplitudes by correcting observations for spreading, attenuation, and site amplification. This approach stands out as an innovative use of broad-area propagation models, making it transportable and across various geologic settings. The method is applicable in situations with multiple or limited station observations where depth of burial is unknown. We present new independent estimates of absolute yield and depth of burial consistent with prior assessments, underscoring the potential of this method in enhancing nuclear explosion monitoring capabilities and transportability

Regional Characterization of Natural and Anthropogenic Seismic Events for Monitoring Efforts With Machine Learning

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Seismic monitoring and event characterization provides useful information about seismic events to assist in earthquake emergency response and for international monitoring efforts of explosions and nuisance events. In this presentation, we expand on the efforts of Barama et al. (2023) and Kong (2022) for explosion discrimination at regional distances using data from both digital and historical (formerly-analog) seismograms, including the full waveforms, initial seismic phase arrivals, their derivative products like radiated earthquake energy, coda wave envelopes, and phase-ratios. Using both seismograms and physics-based features we trained regional seismic source classifiers, testing approaches of a Convolutional Neural Network (CNN), Random Forest (RF), and Deep Neural Net (DNN) for both per-event (network) and per-station predictions. We anticipate that machine-learning models we developed can be robust tools for both regional characterization and gaining insight on what drives the models' prediction determinations.

Source-Type Discrimination Using Phase and Amplitude Metrics Derived From Nonlinear Alignment Methods

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Seismic monitoring agencies rely on metrics to distinguish event class (i.e., source type discrimination) to inform earthquake hazard or treaty compliance, depending on stakeholder interest. Conventional discriminant approaches are rooted in fundamental, physics-based differences in the source properties, but waveform path complexity can effectively erase higher frequency signal characteristics. In this study, we explore a combination of new methods for seismic signal discrimination, dynamic time warping (DTW) and the elastic shape analysis of curves (ESA). DTW focuses on phase differences whereas ESA separates both phase and amplitude signal variations using a novel transformation applied to functional data. We demonstrate the ability to distinguish underground point-sources using synthetic waveforms calculated for a realistic Earth model and various source mechanisms. We then apply these tools to recorded events in the Korean Peninsula, which include declared nuclear explosions, a collapse event, and naturally occurring earthquakes. We compare DTW, ESA, and P-to-Lg amplitude ratio analysis (Tibi, 2021) to demonstrate the limitations and effectiveness of novel signal space metrics for source discrimination.

Seismic Observations and Aftershock Analysis from a Fully Coupled Chemical Explosion in Layered Tuff

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On October 18, 2023, as part of the Low-Yield Nuclear Monitoring Program (LYNM), a multi-organization research team executed a fully coupled underground chemical explosion in Aqueduct Mesa on the Nevada National Security Site (NNSS). Experiment objectives were to investigate both prompt and non-prompt source and signal propagation signatures of underground explosions. To this end, measurements were recorded using a variety of geophysical sensors including geophones, accelerometers, seismometers, and distributed acoustic sensing (DAS), among several other sensing modalities. Signatures of elastic deformation were recorded across spatial scales from 10s of meters out to greater than 100 kilometers.

Here, we focus on the data collected within the tunnel complex where the experiment was conducted and at surface ground zero (i.e., the mesa surface) restricting our analysis to radial distances of ~ 1.5 kilometers. Our work targets explosion source signature and the numerous aftershocks recorded by the multi-modal sensing network. Regarding the explosion source signature, we compare in-tunnel and surface recordings on both geophones and accelerometers, as well as comparison of co-located measurements across the different modalities (i.e., DAS and accelerometers). We compare our measurements to pre-experiment predictions of ground motion and strain rate. Additionally, we report on aftershock magnitudes, Omori decay rate, frequency content, and productivity to compare with pre-experiment predictions and aftershock sequences from previous underground explosions and natural earthquakes.

Seismic Source Parameters and Scaling Relations for Microseismic Lower-Yield Military Explosive Events

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The ability to determine and assign a magnitude to a small microseismic lower-yield military explosive event can be advantageous in characterizing its source. This process involves the determination of its seismic moment which can be accomplished by modeling the ground motion's spectrum. However, the question remains as to whether the models available for earthquake simulation apply to much smaller ground motions from sources other than earthquakes. In this study, Brune source models are fitted to actual small ground motions from military explosive events using the Stochastic Method Model and the source parameters are determined for these events. The seismic waves generated by these lower-yield military explosions were recorded by a local network of seismometers/geophones for twenty-one events collected at two different distances. In addition to acquiring the source parameters for these ground motions, an investigation into their scalability and compliance with self-similarity laws for earthquake source relations is also investigated.

Discriminating S-Wave Polarization Angles of Explosive and Earthquake Sources

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Distinguishing whether a recorded seismic event is an earthquake or explosion is a core problem in explosion monitoring. In a 1D flat layer model, earthquakes produce a predictable S-wavefield based off their radiation pattern while an explosion source will not produce a direct S-wavefield. However, observations from nuclear tests have shown they can produce significant S wave energy on both the radial and transverse components. In this study, we perform 2D and 3D numerical experiments using SPECFEM (2D and GLOBE) to better constrain the conditions in which an S-wavefield generated from an explosion might differ from one sourced from an earthquake. We demonstrate that anomalies in rigidity and anisotropic parameters near the source can cause an explosion to produce a large S-wave field. The key to producing an S-wavefield is that the wavelength of heterogeneities must be smaller than the wavelength of the wavefield and extremely close to the source. The S-wave radiation pattern is highly sensitive to the source's proximity to the anomalies and moving the source sightly can produce a significantly different pattern. We do not observe the same high sensitivity near source structure has on far-field S-wave radiation pattern for earthquake sources. P-S ratios of explosive source change as a function of frequency and near source anomality size while earthquakes P-S ratios remain constant. Lastly, we compare our synthetic observations to S-wave polarization measurements that we made on nuclear tests conducted at the Nevada National Security Site and nearby earthquakes. S-wave polarization angles depend on the ratio of energy the incoming wave has on the radial and transverse components. Our initial results show that we can makestable measurements of the S-wave polarization angles for earthquakes as a function of frequency. We have also measured explosion S-wave polarization angles, but the measurements are not so common nor as robust. This method might prove useful for discriminating events of interest which have clear S-waves. LA-UR-24-20147

Simulations of Local Wave Propagation Effects on the Performance of P/s Source Discriminant

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Analysis of seismic records of local earthquakes and a series of underground chemical explosions conducted during the Source Physics Experiment (SPE) at the Nevada National Security Site have shown that at local distances (<200 km) the effectiveness of the single-station P/S ratio source discriminant is reduced, especially when seismic recordings from a sparse network of stations is used.

We used high performance computing to simulate high-frequency (0-10Hz) waveforms of the recorded SPE-5 underground chemical explosion and one local earthquake for a network of seismic stations in the Yucca Flat, and a series of simulations of collocated isotropic and double-couple explosion sources in the Rock valley, to investigate the effects of source radiation and wave scattering effects on the simulated waveforms and P/S source discriminant at local distances. The wave propagation scattering was simulated

by using the Yucca Flat Geological Framework Model (GFM) with correlated small-scale stochastic perturbations.

The inclusion of correlated depth-dependent stochastic velocity perturbations in the GFM, improved the quality of simulated source radiation and local waveforms, which resulted in better reproduction of the observed spatial variations of the P/S discriminant. We found that the shallow wave scattering deforms the radiation pattern and amplitude of source generated P and S waves, thus reducing the efficiency of the P/S discriminant. Our simulations suggest that a good azimuthal stations coverage and the network averaging can improve the overall performance of the P/S discriminant at local distances.

Moment Tensor Inversion and Its Uncertainty from Green's Functions with Different Algorithms

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Moment tensor inversion (MTI) has been routinely used by the seismology community to study the characteristics and the identification of source types for earthquakes and explosions. MTI has been further used to quantify uncertainty surfaces associated with each event type obtained by the moment tensor decomposition. In this study we are investigating uncertainties resulted due to the use of Green's Functions (GFs) computed by the frequency wavenumber integration and finite difference techniques for the same velocity model. Our focus here is to investigate the isotropic moments, especially for the explosions at the Nevada Test Site. To this end, we are investigating effects of the GFs computed allowing the velocity models to have random fluctuations in the geophysical parameters. We are focusing on the estimating the uncertainties in each source type of the decomposed mechanism that is mainly due to the uncertainties in velocity models using a Monte Carlo approach. We are also attempting to compare the MTI solutions with those determined by using a grid-search technique for the double-couple (DC) mechanism. For explosion sources, we perform a linear-inversion for the seismic moments of the DC, isotropic and compensated linear vector dipole (CLVD) sources for each possible DC mechanism to minimize the misfit between the synthetic and observed waveforms.

Physics Experiment 1: Chemical Explosive, Gas Tracer, Electromagnetic, and Atmospheric Experiments for Improved Monitoring of Nuclear-Explosive Testing

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The challenge of monitoring low-yield nuclear explosions is being met by the National Nuclear Security Administration (NNSA) and the national laboratories through improved understanding and utilization of multi-physics signals generated by explosions and other sources. These research efforts develop full-physics simulation capability, new sensing methods, and advanced data analysis. All these efforts are based on and validated by experimental data. Legacy data, including historic nuclear detonations, provide critical information, but data gaps persist. The Physics Experiment 1 (PE1) fills data gaps with a series of non-nuclear experiments at and near the Nevada National Security Site (NNSS) Aqueduct Mesa P-tunnel. Taken as whole, PE1 experiments generate seismic, acoustic, electromagnetic, and tracer gas signals similar to those generated by nuclear detonations in varying underground emplacement and atmospheric conditions.

On October 18, 2023, PE1 Experiment A (PE1 A) commenced with detonation of 16.3 tons (TNT equivalent) of chemical explosive in P-Tunnel. In addition to shock-related signals, the detonation released gas tracers and chemical-explosive byproducts into the cavity formed by the explosion. Near-source instrumentation in the grout confinement plug, nearby boreholes, and P-tunnel recorded the explosive shock, electro-magnetic waves, temperature, pressure, and real-time migration of gases from the explosion cavity. Seismic, acoustic, and electromagnetic waves were also recorded by instrumentation atop and around Aqueduct Mesa, at select sites within NNSS, and by regional seismic networks. Clear signals were recorded by all sensor modalities, and seismic signals were recorded to at least 250 km. Gas tracers were detected in boreholes and in P-tunnel within an hour after the explosive detonation and concentrations were monitored for several weeks. This presentation will describe the PE1 experiment series, with emphasis on Experiment A. Scientific objectives, field layout, execution, and plans for data dissemination will be presented.

Seismo-Acoustic Signals From an Accidental Chemical Explosion in South Korea

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Seismo-acoustic analysis can be used to identify, detect, and locate sources that generate waves in the atmosphere and solid Earth and provide a basis for the characterization of distant phenomena, particularly explosions. On March 4, 2020, an accidental explosion occurred at a chemical plant in the southwestern city of Seosan in South Korea. The explosion generated both seismic and infrasound signals, recorded by various sensors to distances as great as 300 km across the Korean Peninsula. Data included signals at six seismo-acoustic arrays operated cooperatively by Southern Methodist University and Korea Institute of Geoscience and Mineral Resources (KIGAM). Additional data from KSRS seismic array data from the Comprehensive Nuclear-Test-Ban Treaty Organization and all available dense seismic network data were utilized. Nine infrasound sensors co-located at KSRS seismic arrays, three temporary infrasound arrays, and four infrasound stations operated by KIGAM were also included in the analysis. Seismic, infrasound, and air-to-ground coupled acoustic arrivals from the explosion are identified for this event based on array processing and analyst review. A small number of secondary detections were identified that are consistent with the source location and may be indicative of infrasound generated by the fire that followed the explosion by a few minutes. Network back-projection using both seismic and infrasound waveforms is consistent with the ground truth location of the explosion. Observed infrasound arrival times are well matched by ray tracing predictions using the Ground-to-Space atmospheric specification, with tropospheric arrivals at the multiple arrays to the east of the source and no arrivals at the array to the west. Lastly, the infrasound amplitudes from the explosion are used to estimate the source energy. The hybrid utilization of seismic and infrasound observations in the analysis enhances the confidence of source characterization for explosion monitoring.

Estimating Crustal Velocity Structure in Alaska From Acoustic-to-Seismic Coupling From the 2022 Hunga Eruption, Tonga

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The 2022 climactic eruption of the Hunga volcano in the Kingdom of Tonga generated broadband acoustic waves that were clearly observed over 10,000 kilometers away at numerous pressure sensors in Alaska. The University of Alaska Fairbanks and the Alaska Volcano Observatory operate over 150 stations in the state that are equipped with a single infrasound sensor, a colocated broadband seismometer, and a colocated barometer. The arrival of high-amplitude acoustic energy from the eruption at a regional network of colocated sensors provides a unique opportunity to examine acoustic-to-seismic coupling and to use these observations to estimate shallow elastic parameters in the Alaska region. We compute coherence between pressure and vertical seismic channels between 0.01 Hz and 2 Hz for all available colocated sites in Alaska and observe network-wide peaks and troughs in coherence. Notable troughs occur at around 0.2 Hz, and to a lesser extent, at 0.075 Hz. We interpret these troughs as interference imposed by the secondary and primary microseismic peaks on the relatively low-amplitude seismic signal from Tonga coupling. We compute coupling coefficients from seismic over acoustic amplitude ratios in passbands with high coherence, allowing us to relate acoustic-seismic coupling to bulk elastic parameters at different maximum crustal depths. We compare our results to existing shear-wave velocity estimates in Alaska, and observe good agreement, particularly for a depth of approximately two kilometers. Mean shear-wave velocity estimates from these derived elastic parameters provide an empirical dataset for investigating seismic site effects, station-specific velocity corrections, and augmenting Vs30 estimates for ground-motion modeling.

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Detection of Seismic and Acoustic Signals With Serial Network Data Fusion: Demonstration Against Atmospheric Explosions

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Explosion monitoring conventionally operates in siloes: seismic, infrasonic, and other ground or space based sensors process individual modalities to perform functions like detection. Such siloed detection excludes evidence collected by other modalities that may be leveraged to achieve greater detection rates, lower nuisance alarms, and lower thresholds. Work conducted at Los Alamos National Laboratory seeks to increase detection performance by removing these siloes to facilitate data fusion.

We thereby present a proto-type system to fuse multiple explosion-sourced ("target" sourced) modalities into a serial architecture that shares detector output and makes collective (system-wide) decisions regarding source identity. The system shares this data by coupling the thresholds of its constituent detectors. Decisions made by one detector then inform a downstream detector, which processes a second modality. This downstream detector then adjusts its threshold according to the decision made by the upstream detector. Our system selects the coupling strength between these thresholds to achieve a maximum system-wide true positive rate and maintain an acceptable, system-wide false positive rate. The resulting system-wide detector achieves a superior performance relative to that of the best, constituent detector. We present these performance characteristics on a real data recorded from an explosion sourced on the US East Coast.

Our system thereby exploits the theory of distributed detection (Viswanathan et al., 1988), which has been exploited in multiple sensor networks. It remains under-leveraged in explosion monitoring. If successfully demonstrated in explosion monitoring scenarios, we argue that such systems can provide a non-incremental gain to monitoring capability that mimics the teamwork that of humans at the analyst-review stage of processing.

Surface-to-Space Acoustic Propagation Model Validation Using Chemical Explosion Sources: The DARPA AtmoSense AIRWaveS Project

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Surface explosions of sufficient size create acoustic waves capable of propagating hundreds to thousands of kilometers. These waves can be detected and characterized by ground and balloon borne microbarometers, pulsed Doppler radar soundings of the lower ionosphere and, in exceptional cases, ionospheric total electron content (TEC) derived from GNSS signals. While this capability has been demonstrated for higher yield explosions, the threshold of detectability for smaller events is still uncertain. This ambiguity motivates targeted field campaigns against events of known yield. The combination of well-understood sources with a sensing network of large horizontal and vertical aperture permits robust assessment of acoustic propagation models and constraint on the spatial distribution of wave fields. Here we describe an acoustic signal recording campaign planned for Spring 2024, leveraging multiple sensing modalities, aimed at a set of surface chemical explosions in central New Mexico as part of Phase II of the DARPA AtmoSense program. The observations will be compared to model simulations, supporting their validation extending from sources, to acoustic propagation, and ultimately to alternate remote sensing modalities including measurements of the lower ionosphere. The objective is to validate whole-atmosphere (surface-to-space) acoustic propagation modeling capabilities, including estimates of uncertainty and syntheses of multiple sensor observables. We also welcome other participants to the next active-source campaign, currently planned for Fall 2024, on a minimal interference basis. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Solid/atmosphere Moment Partitioning in Hypervelocity Impacts on Mars From Seis Recorded Seismic and Acoustic Signals and High Resolution Crater Imaging.

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The SEIS VBB sensor detected 10 confirmed impacts on Mars, documented by both the seismic signal and the high-resolution imaging of the formed crater. For about half of them, a chirp in the seismic signal was also detected, which was generated by the ground shaking generated by infrasounds generated by the impact. At several detected impact sites, high resolution images show the imprint of the blast with a notable occurrence on Sol 1094, dated 12/24/2021, marking the largest impact detected by the *InSight* mission.

The seismic source is constrained by the amplitude of seismic body waves, or surface waves for S1094b, and the imaged crater diameter. The acoustic source is constrained by the amplitude of indirect infrasounds and the imaged diameter of the blast zone. This allows two different estimations of these two sources: the first is the one acting on the ground, therefore associated with the seismic source while the second is acting just above the surface therefore associated with the acoustic source, each being expressed by seismic or acoustic moment, respectively. Comparing the seismic and acoustic moments for those confirmed impacts will provide the first estimation of the energy partitioning between ground and air for high velocity impacts on Mars, characterized by speeds and energies furthermore never recorded on Earth.

We present here preliminary results of this analysis made with different seismic and hydrocode modeling and discuss the impact of seismic scattering, lateral variations, subsurface structure and atmospheric attenuation in our estimations of the seismic and acoustic moments and associated energy/moment partitioning.

End-to-End Numerical Simulation of Explosion Cavity Creation, Cavity Circulation Processes, Subsurface Gas Transport, and Prompt Atmospheric Releases

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A numerical study of conjugate flow, heat and mass transfer by natural convection of noble gases within an underground cavity partially filled with molten rock is presented. The molten rock is initially considered at rest at an initial temperature and concentration. The molten rock is viscous and possesses strength that is temperature, and crystal fraction dependent. Under natural conditions, convection cells are developed within the molten rock leading to circulation, mixing and degassing of the initially trapped gases. Furthermore, the molten rock as well the degassing enhances the conjugate convection flow in the air gap within the cavity. We illustrate the onset of the different regimes and their combined effect of flow, heat and mass transport of different gas species, the fraction of molten rock and their impact on the noble gas fractionation. We also present a sensitivity analysis of the effect of the outer cavity boundary condition on the heat loss and cooling to the adjacent rock formation and its eventual release to the atmosphere. We demonstrate several scenarios of underground prompt releases to the atmosphere using a first-ever fully coupled prompt subsurface-to-atmospheric transport without ad-hoc boundary conditions between physics-based domains, or handshakes between different numerical codes. We are exploring physics informed ML schemes for developing surface responses of the end-to-end simulation framework to anthropogenic explosions.

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Joint Inversion of Body and Surface Waves at the Rock Valley Direct Comparison (Nevada) Study Site

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The Rock Valley Direct Comparison project (RVDC - Phase III of the Source Physics Experiment) is centered on conducting a large chemical explosion that is co-located with the source region of the unusually shallow 1993 Rock Valley earthquake series in southern Nevada. The goal is to improve the understanding of similarities and differences among signals produced by explosions in comparison to shallow natural events, by minimizing location and path variables.

As part of this experiment, we are developing a Vp, Vs, and density model for the RVDC site and surrounding region, through the joint inversion of seismic body wave arrivals, ambient-noise-based Rayleigh wave dispersion measurements, and gravity anomalies. This model will serve multiple purposes. It will be used to constrain material properties in the RVDC source region. It will aid in the analysis of both legacy observations from the 1993 series and the upcoming chemical explosion. Seismicity between 1993 and the present will be relocated in the model, which will be used to identify fault locations and orientations, building knowledge of the tectonics of the study site and of the broader Nevada National Security Site (NNSS).

Joint Inversion Using Waveform, First-motion Polarities and InSAR Deformation for the 2007 Crandall Canyon Mine Collapse, Utah

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On August 6, 2007, a major underground collapse at the Crandall Canyon coal mine in Utah caused a 3.9 local magnitude (ML) earthquake (Pechmann et al., 2008). Ford et al. (2008) modeled regional waveforms for the full moment tensor finding the event consisted of a primary vertical collapsing crack and a secondary near-vertical shear at the western edge of the collapse. Significant deformation after the event was also measured using Interferometric Synthetic Aperture Radar (InSAR) (e.g., Lu and Wecks, 2010; Planttner et al., 2010). Recently, joint source-type inversions have been used to analyze underground North Korean nuclear explosions, combining regional waveform data, first-motion polarity, and InSAR deformation (Chi-Durán et al., 2021). This technique is effective at improving source type estimates, independently constraining location (and depth), and reducing uncertainties in scalar moment. Our joint inversion for the Crandall Canyon Mine Collapse identified the event as principally a closing crack, with a waveform variance fit of 60%, first-moment polarity fit of 45% and a line-of-sight deformation fit of 90%. Our joint inversion results are consistent with previous studies of this event, providing better constraints of the source-type, moment tensor and scalar moment. These results together with those for the 4th and 6th DPRK explosions (e.g. Chi-Durán et al., 2021, 2024) show the ability to distinguish explosions and collapses, which in the past have been problematic for traditional discrimination methods (e.g. Walter et al., 2018).

Advancements in Forensic Seismology and Explosion Monitoring [Poster Session]

Poster Session • Thursday 2 May

Conveners: Richard A. Alfaro-Diaz, Los Alamos National Laboratory (rad@lanl.gov); Louisa Barama, Lawrence Livermore National Laboratory (barama1@llnl.gov); Jorge A. Garcia, Sandia National Laboratories (jgarc26@sandia.gov); Carl Tape, University of Alaska Fairbanks (ctape@alaska.edu); Cleat Zeiler, Nevada National Security Site (ZeilerCP@nv.doe.gov)

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Moment Tensor Estimation and Uncertainty Quantification (MTUQ)

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Accurately estimating seismic source parameters is crucial to understanding a wide range of geophysical phenomena, from natural seismic events to anthropogenic activities. Seismic moment tensors, together with point forces, can represent a variety of source mechanisms and be estimated using seismic data. Here, we present the latest developments in our open-source Moment Tensor and Uncertainty Quantification (MTUQ) code, tailored for point source characterization, with an emphasis on uncertainty estimation and visualization. We showcase the code's capabilities by revisiting the DPRK nuclear test of September 2017 to evaluate the influence of various data sources on the misfit space, both using a conventional grid-search approach and leveraging the fast Covariance Matrix Adaptation Evolution Strategy (CMA-ES) method. We also demonstrate point-force inversion capabilities on a recent rock and ice avalanche on the Barry Glacier. MTUQ takes advantage of high-performance computing architectures, accommodates a wide range of Green's function databases (both 1D and 3D and receiver side Strain Green's Function), and offers various optimization strategies that are adapted to different computational resource scenarios, from single-core CMA-ES optimization to large-scale grid searches with up to 1,000,000,000 grid points. We underscore the importance of accurate seismic source parameter estimation and the significant role MTUQ can play as a versatile and reliable tool in this essential aspect of seismology. New users can engage with active users and developers via workshop resources and research projects.

POSTER 125

Observations on Explosion-Triggered Seismic Events via Fiber Optic Sensing at Small Scales

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We present an aftershock analysis on seismic events recorded by distributed acoustic sensing (DAS) fiber following a series of chemical explosive experiments at the Blue Canyon Dome (BCD) on the grounds of the Energetic Materials and Testing Center (EMRTC) located approximately 6 km west of Socorro, NM. These experiments were a series of eight identical small (~4.5 MJ) chemical explosive sources detonated in a borehole at different depths (< ~55 m) and emplacement conditions, ranging from virgin rock to areas of varied a priori subsurface damage. We additionally performed each experiment both with and without filling the borehole with water. Here, we investigate both the presence of aftershocks induced by explosive sources on the DAS fiber data and characteristic differences in the aftershock sequences resulting from different emplacement conditions. Both the number of aftershocks and their distributions in time and space may provide information regarding how chemical explosive sources' thermochemical energies are spent and converted to seismic waves.

DAS provides much higher spatial sampling density than traditional sensing methods, capturing seismic wavefields with considerably greater coverage and enabling detection of smaller events at close-in distances through trace-to-trace correlation. We visually detect aftershocks on the fiber waveforms for each chemical explosive source. Our apparent seismic velocity estimations find seismic velocities consistent with the rock velocities in the study area suggesting that the detected events are real aftershocks. Moreover, the explosion-triggered aftershocks follow Omori's decay law for wet explosive sources but results are less clear for dry sources. Observations of aftershocks from the experiments at BCD demonstrate the utility of DAS to contribute to our understanding of explosion-induced aftershocks.

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POSTER 126

Leveraging Infrasound Signals for Integration of Ground- and Space-Based Nuclear Explosion Monitoring Capabilities

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Nuclear detonation detection is typically conducted via analysis of a combination of phenomenologies including seismic, infrasonic, hydroacoustic, air sampling, and satellite-based observations (e.g., light, gamma ray, x-ray, neutron). The ground-based components of such monitoring systems are ideal for detecting and characterizing below-ground and near-surface explosions while space-borne sensors can reliably detect and characterize nuclear explosions in the atmosphere. Recent research at Los Alamos National Laboratory has focused on developing and improving physical and statistical frameworks to better integrate and communicate information between these individual phenomenologies for near-surface and atmospheric nuclear explosions. Specifically, infrasound source models for supersonic sources in the atmosphere have been developed and evaluated to distinguish infrasonic signatures from such sources compared with point source explosion sources. Ray-based weakly non-linear waveform analysis has been utilized to construct infrasonic detection statistics and investigate coupling of infrasonic energy in the immediate footprint of the airburst to the seismic surface wave field. These and other aspects of this ongoing effort to integrate ground- and space-based nuclear explosion monitoring capabilities will be presented.

POSTER 127

Influence of Local 3-D Structure at Degelen Test Site on Short-Period Teleseismic P-Wave via Reciprocal Hybrid Modeling

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The large historical Blacknest Kazakhstan dataset, including underground nuclear tests conducted at the Degelen test site, provides a valuable resource for exploring how structural effects in the immediate vicinity of the source are carried over at teleseismic distances.

It shows significant differences in the recorded waveforms across four arrays (EKA, GBA, WRA, YKA), up to 2 Hz frequency. The rugged topography of the Degelen mountain range and its heterogenous crust should serve as a marker for source parameters identification (location, depth, magnitude), through the scattering of the incident P-wave at the free surface.

We investigated these source properties using a hybrid modeling methodology to simulate the the teleseismic wavefield between the Degelen region and the 4 arrays. It is based on a reciprocal coupling of the DSM solver, for the 1-D Earth background wavefield, and the SEM solver, for the 3-D complex Degelen area. This coupling approach ensure the generation of full Green tensor waveforms throughout the Degelen area and accurate up to 2 Hz frequency.

POSTER 128

Far-Field DAS Recordings of a Chemical Explosion

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On October 18, 2023 an underground chemical explosion was detonated at the P Tunnel of the Nevada National Security Site (NNSS). The experiment used a broad suite of sensors to detect the motion the of chemical explosion . Part of the ground motion network included a past DAS fiber deployment located approximately 14 km southeast of P Tunnel. Helically wound fiber with a 60-degree wrapping angle was installed two vertical boreholes (E80 and SW80) at the Dry Alluvium Geology (DAG) site during Phase II of the Source Physics Experiment in 2018. During the 2023 experiment, a Silixa Carina interrogator was used to record DAS measurements in the 385m deep E80 hole. Data were sampled at 1kHz with a 2-meter gauge length and 1 meter channel spacing. Starting at approximately 3.1 seconds after the explosion was detonated several upcoming wave phases are observed followed by a train of surface waves. This observation is consistent with predictions made prior to the experiment. This is the first time that DAS has been used to monitor chemical explosion experiments at a distance greater than a few 100 meters. We present a comparison of the predicted strain-rates and travel-times to the measured data.

POSTER 129

Capturing the Spatial Variation of Seismic Observations in SW4 Simulations of the Dry Alluvium Geology Experiment Series at the Nevada National Security Site

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Improving predictive capabilities of seismic sources at varied distance and energy length scales is crucial to understanding whether or how the near-field geologic complexities influence seismic wavefield propagation. This presentation aims to illustrate simulation of ground motions induced in the Dry Alluvium Geology (DAG) experiment (Mission Support and Test Services, LLC, 2021) series in Yucca Flat to explore the effects of a diverse lithological composition and topographic features on the spatial variability of ground motion from chemical explosions. Numerous investigations in the past have utilized dense seismic arrays to explore the spatial variability of earthquake ground motion (SVEGM), highlighted by variations in amplitude and phase among recordings from the same earthquake at diverse locations within a specific region. One of the most significant large-scale experiments to identify

the behavior of SVEGM was carried out on natural seismic sources in Lotung, Taiwan (Abrahamson, 1992). A similar large-scale study on anthropogenic seismic sources was carried out for events in the well characterized geology of Yucca Flat at the Nevada National Security Site during the DAG experiment. Simulation of the observed ground motions at DAG will be carried out in SW4, a finite difference numerical code developed for seismic wave propagation by Lawrence Livermore National Laboratory. Finally, the accuracy of the physics-based chemical explosion model will be presented by comparing the simulated ground motions with the recordings from the DAG site. The ultimate goal of a precise model is to identify gaps in the instrumentation scheme for future explosion experiments.

POSTER 130

Time-Variable Moment Tensor Inversion of Seismic and Seismoacoustic Data at the Source Physics Experiment Phase II: Dry Alluvium Geology

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Seismic source inversions that assume each component of the moment tensor has the same underlying source time function (STF) are often unable to accurately categorize the complexity of a source as it evolves in time. However, a full-waveform, time-variable moment tensor inversion, where each component of the moment tensor is independently allowed to vary in time, allows for a better understanding of the dynamics of a source. One such example of a complex source that is difficult to accurately represent with a conventional moment tensor would be an explosion, followed by slip on near-source joints. When a single STF is assumed for all components, this may instead be approximated as solely an explosion source or a double couple source, oversimplifying the source mechanisms involved. If instead a time-variable moment tensor inversion was used, these two mechanisms can be differentiated in time and space. In this study, we apply a time-variable moment tensor inversion to seismic and seismoacoustic data recorded as part of the Source Physics Experiment Phase II: Dry Alluvium Geology (DAG). We develop a joint inversion to invert the seismic and infrasound waveform data from the DAG-4 experiment for the six independent, time-variable components of the (subsurface seismic) moment tensor, as well as a vertical force function, a term that approximates the surface spall source. We plot the source mechanism as a function of time on the fundamental lune to better interpret how the DAG-4 source changes with time. Additionally, we compare the seismic and seismoacoustic moment tensor results, estimating the sensitivity of both the seismic and seismoacoustic inversion formulations to the moment tensor and vertical force function results to gain a better understanding of how the addition of infrasound data in a joint inversion framework can affect our interpretation of a source. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

POSTER 131

Exploring Paired Neural Networks to Rapidly Characterize Aftershock Events

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Mainshocks and their aftershock sequences occur unexpectedly and increase the burden of seismic analysts. Cross-correlation methods show promise for detecting aftershocks but require careful curation of template libraries, which is challenging for in-progress sequences. Also, cross-correlation methods are more computationally intensive, in comparison to use of pre-trained, deep-learning models. We explore the effectiveness of using a paired neural network (PNN) to identify similar earthquakes, such as aftershocks. The PNNs were trained to recognize similar earthquake pairs from a global dataset of real earthquakes augmented with different levels of background noise. We test the PNNs with a suite of closely-controlled test datasets, including a subset of high-quality aftershock templates with their cross-correlation matches (Emry et al., 2023), a dataset of highly similar event pairs from China (Schaff and Richards, 2021), and a dataset of synthetic waveforms created with a 1-d velocity model. This approach allows us to discern where the existing PNN models succeed and where they struggle, with the goal to understand whether PNN models may be trained differently to better generalize to in-progress aftershock sequences. This Ground-based Nuclear Detonation Detection (GNDD) research was funded by the U.S. Department of Energy. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

POSTER 132

A New Tool to Integrate Instrument Responses From Seismological Databases Into Python Workflows

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Instrument response files referenced and stored in CSS3.0, KBCore, and similarly structured databases follow a file format that predates the release of the CSS3.0 database schema in 1990, and these response files are often referred to as pazfir files. Pazfir files have changed slightly since 1990, with the most recent definition having been released in 2002 by the International Data Centre (IDC), and they are primarily used within the explosion monitoring community. However, the wider seismological community uses the RESP and StationXML formats released by the FDSN, and open-source tools, such as ObsPy, support these FDSN formats but not pazfir files, making them difficult to incorporate into modern workflows. A pazfir file reader has been developed to ingest response information available from the appropriate database tables, read in the file with some basic QC, and output an ObsPy Response object. The Response object can then be attached to waveforms extracted from the database, allowing researchers to use ObsPy's response removal functions either to return a waveform in units of ground motion or pressure or to incorporate it into a StationXML file. This pazfir reader will allow researchers to fully retrieve and incorporate data and metadata from these databases into Python workflows or file formats usable by community-supported tools through its inclusion in Pisces (https://github.com/LANL-Seismoacoustics/pisces) an open-source python package available on GitHub from Los Alamos National Laboratory that was developed to facilitate the integration of data from CSS3.0 and KBCore databases into Python-based geophysical analysis workflows.

POSTER 133

Ambient Seismic Noise Tomography of Heterogeneous Geological Formations

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Ambient seismic noise tomography is a unique tool suitable for characterizing the velocity structure of various geologically complex regions. To demonstrate this capability, we analyzed 30 days of vertical component short period seismic data from the karstic Santa Fe River Sink-Rise system in north-central Florida. We applied power spectral density estimates and frequency-wavenumber analysis to characterize noise source biases in the tomography. We then extracted Rayleigh wave group velocity dispersion measurements from empirical Green's functions estimated through phase cross-correlation and phase-weighted stacking. Finally, we inverted the dispersion measurements at various periods, yielding a model of the aquifer's seismic velocity structure. Our results reveal layering with varying group velocities aligning with a priori hydrostratigraphic knowledge. Notable findings include the base of the aquifer and dolostone semiconfining units characterized by elevated velocities relative to the overall mean velocity. Furthermore, we identified low-velocity upper layers likely expressing zones of extensive karstification. We demonstrate that ambient seismic noise tomography is a robust tool applicable for the characterization and validation of the near-surface structure, including physical properties, identification of unknown features, and the location and continuity of units. Additionally, we are applying the capabilities of ambient noise tomography and signal analysis to the Nevada National Security Sites. Through this endeavor, we aim to enhance our knowledge of the site's subsurface velocity structure, contributing to a broader understanding of geological contexts with implications for various applications. This work was done by Mission Support and Test Services, LLC, under Contract No. DENA0003624 with the U.S. Department of Energy and the National Nuclear Security Administration Office of Defense Nuclear Nonproliferation. DOE/NV/03624--1843.

POSTER 134

Using Deep Learning Models to Characterize Subsurface Physical Parameters at Modeled Underground Chemical Explosion Sources

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The characterization of underground explosion sources is important for constraining seismic source features, such as yield and seismic moment. There is little understanding, however, of how subsurface characteristics at the source, such as emplacement or ground material (e.g., basalt, tuff, salt), affect the observed far-field seismic waveforms (FFSWs) we record and analyze or the methods through which we extract source features, such as source time function inversion. Additionally, it is not well studied how nonlinear phenomena near the source are affected by varying subsurface characteristics, and in turn, how these nonlinearities influence our often-linear source models. We present work that explores how subsurface characteristics at the source affect FFSWs by leveraging a nonlinear shock physics code coupled to a linear wave propagation code. Our methodology allows us to parametrically explore subsurface characteristics and generate many synthetic seismic data sets at the local scale (distances < ~700 m). We vary source depth, chemical explosion size, and receiver locations in addition to the physical properties at the source and some nonlinear modeling parameters.

We use our synthetic labeled data to train multiple deep neural networks (DNNs) to predict different subsurface characteristics that have been found to have the greatest effect on the FFSWs, including source emplacement, ground material, yield strength, and fracture pressure, and we explore different DNN architectures to optimize results. We then leverage our trained DNNs to perform a sensitivity analysis that quantifies how the subsurface characteristics affect the FFSWs. Once developed further, these DNN models can be used to better characterize explosion yield or moment by considering predicted near-source characteristics.

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POSTER 135

Comparing Observed and Modelled Station Terms from the Source Physics Experiments Phase 2 (Dry Alluvium Geology) Explosions

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Since 2011, a series of chemical explosions with a range of different depths and explosive yields have been detonated at two sites on the Nevada National Security Site (NNSS) to help further understanding of the seismic waves generated by underground explosions. In this study, *P*-wave amplitudes recorded from explosions in the second phase of the Source Physics Experiments (SPE) explosions at stations ranging from 2 km to around 36 km distance have been analysed and compared with model predictions. The model seismograms were computed using a visco-elastic wave propagation code and a high resolution 3D Earth model of the NNSS. For comparison model seismograms are scaled using two explosion source models, the Mueller-Murphy model and Denny and Johnson model. In order to assess how effective the 3D Earth model was at modelling path effects between the location of the explosions and the stations, a two-step inversion was carried out to estimate station and distance terms for the stations used in this study for both the observed data and model data scaled using both source models. Although there are some differences between the observed and modelled station terms, in general there is reasonable agreement and one of the main features in the observed data, negative station terms for stations at around 10 km distance from the location of the stations, is replicated in the model data. Distance terms which predict the fall-off of amplitude with distance were also estimated for the observed and model data and are found to be in good agreement.

POSTER 136

Comparisons Between Geophone Array and DAS Array Detections

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We applied an array-based detector on 14-days of continuously recorded Distributed Acoustic Sensing (DAS) and co-located nodal geophone array data. These data were repurposed from the 2016 PoroTomo experiment at Brady's Hot Springs, Nevada (e.g., Feigl et al., 2019). Since DAS is essentially a single component seismometer, we used a time-domain delay and sum technique modified to beamform only channels along linear portions of the fiber-optic cable with the highest coherency to measure the energy distribution in slowness space. The energies for each linear portion are then summed together to produce a final slowness image. We applied a moving window array detector on the geophone array using an optimal 1-3 Hz bandpass filter. The optimal DAS bandpass filter was 0.5-2 Hz. DAS was poor at estimating P- and S-wave BAZ and slowness compared to geophone array; however, we predicted using synthetics that the DAS array selected has cable broadside sensitivities. Future experiments using different fiber-optic cable geometries should provide better BAZ estimates. A persistent night-time local noise source toward the southwest was also observed by both geophone array and DAS. We correlated the duration of the noise signals to pumping schedules at the geothermal plant. Overall, the DAS and geophone array detection performance was similar over regional and teleseismic distances with the exception that DAS has many more false detections. Prepared by LLNL under Contract DE-AC52-07NA27344. LLNL-ABS-858924.

POSTER 137

Explosion Source Analysis and Discrimination From Regional Distance Seismic Observations

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This study utilizes regional seismic observations to investigate earthquakes and announced explosions in the Democratic People's Republic of Korea (DPRK). We compute the coda spectral ratios and Relative Source Time Functions (RSTFs) at common stations to isolate source information from additional path and site effects within the measurements. The resulting frequency-dependent amplitude ratios reflect source differences between the two seismic events, which can then be fitted with parametric models that map observations to seismic source parameters. In the case of the RSTFs, the results also provide a time-domain representation of the source-time function. This work allows us to identify spectral differences between explosions and nearby earthquakes. The measurements also agree with estimated earthquake and explosion source models for seismic events occurring at or near the DPRK test site. We analyze parameter trade-offs in these models and quantify the bias associated with source parameter estimation. The coda spectral ratios between explosions and earthquakes reveal that the explosive sources exhibit lower S-wave corner frequencies and S-wave spectral amplitudes (at high frequencies). These results show that a comparing spectra between different source types via spectral ratios provides valuable insights for seismic discrimination and source characterization efforts.

POSTER 138

Inferring the Focal Depths of Small Earthquakes in Southern California Using Physics-Based Waveform Features

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Determining the depths of small crustal earthquakes is challenging in many regions of the world because most seismic networks are too sparse to resolve trade-offs between depth and origin time with conventional arrival time methods. Precise and accurate depth estimation is important because it can help seismologists discriminate between earthquakes and explosions, which is relevant to monitoring nuclear test ban treaties and producing earthquake catalogs that are uncontaminated by mining blasts. Here we examine the depth sensitivity of several physics-based waveform features for ~8,000 earthquakes in southern California that have well-resolved depths from arrival time inversion. We focus on small earthquakes ($2 < M_L < 4$) recorded at local distances (< 150 km), where depth estimation is especially challenging. We find that differential magnitudes ($M_w/M_L - M_C$) are positively correlated with focal depth, implying that coda wave excitation decreases with focal depth. We analyze a simple proxy for apparent stress drop, $\log_{10}(M_0) + 3\log_{10}(f_c)$, and find that source spectra are preferentially enriched in high

frequencies, or "blue-shifted", as focal depth increases. We also find that two spectral amplitude ratios, $R_{g,0.5\text{-}2\ Hz}/S_{g,0.5\text{-}8\ Hz}$ and P_g/S_g at 3–8 Hz, decrease as focal depth increases. Using multilinear regression with these features as predictor variables, we develop models that can explain 11–59% of the variance in depths within 10 sub-regions and 25% of the depth variance across southern California as a whole. We suggest that incorporating these features into a machine learning workflow could help constrain focal depths in regions that are poorly instrumented and lack large databases of well-located events. The waveform features we evaluate in this study have previously been used as source discriminants and our results imply that their effectiveness in discrimination is partially because explosions generally occur at shallower depths than earthquakes.

POSTER 139

Providing Data for Nuclear Explosion Monitoring—WFNE Repository

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Usage of a high-quality data set is a key element for any geophysical analysis. The Waveforms From Nuclear Explosion (WFNE) is a comprehensive repository providing access to a large volume of information of potential interest to the nuclear explosion monitoring community. It was developed and is maintained by Leidos under sponsorship of the Defense Threat Reduction Agency (DTRA). WFNE provides convenient access to source parametric data (origin, bulletin and other geophysical parameters) on all the 2,157 atmospheric, underground and underwater nuclear explosions detonated in the world between 1945 and 2017, and to their associated waveforms and station/instrument information, as collected from many sources. Distance domain for waveforms ranges from local to teleseismic (0.8-179 degrees). Detailed presentations of the test sites and detonations in each test site are provided as "Event Summaries", including main results of studies and references.

WFNE is built as a trusted data set, starting from the previous data repository "Nuclear Explosion Database (NEDB)" that was accessed in the past by numerous users in the U.S. and international nuclear explosion monitoring community. Added information consists in a large volume of seismic, hydroacoustic and infrasound data collected from a variety of data sources, including the results of recent efforts on rescue of pre-digital seismic data via digitization. All data are collected from open sources; they are checked for completeness and quality and converted into a consistent format before being merged into WFNE, offering easy access to a correct and well-organized data set, ready to be used as input for research studies. Over 100,000 waveforms ranging from digitized analog recordings for the oldest explosions to recent International Monitoring System (IMS) data are included in WFNE. Data continues to be collected from newly identified sources. Using web-based access, users can search, visualize, and download data of interest for their own research. Access request is available at: *https://www.wfne.info/* .

POSTER 140

Investigating Shallow Subsurface Structure Near Legacy Nuclear Test Sites Using Single Station HVSR

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We investigate shallow subsurface structure near two legacy nuclear tests on the Nevada National Security Site. In the first analysis, we use open-source continuous seismic data collected from a single line of a temporary array deployed for the Source Physics Experiment Phase I. For the second analysis, we use continuous data collected as part of the active-source FREY experiment to investigate the HADDOCK legacy nuclear test. Shallow subsurface structure is important for understanding seismic site response and detecting subsurface anomalies. In this investigation, we focus on the use of ambient noise-derived horizontal-to-vertical spectral ratios (HVSR) to highlight frequency-dependent site effects, shallow velocity profiles, and total H/V spectral power. HVSR has several advantages, including repeatability, the need for only short periods of data collection, and application to single-station, high frequency measurements, which are particularly sensitive to the shallowest layers. In this comparison, we test the ability of single-station HVSR to measure changes in subsurface structure along a profile, and within an array, near two sites with potential structural features. We examine the correlation between a new method using the integrated spectral power of H/V and traditional resonance and forward modeling-based approaches for H/V ratios. Using these results, we compare the feasibility of these methods for understanding shallow structure using temporary seismic deployments at sites with potential shallow heterogeneities.

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POSTER 141

Detecting Subsurface Mining Activity using Cross-Correlation and Local Surface Arrays

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Detecting subsurface human and industrial activity from surface seismic observations remains a challenging task. Using data from two mines, the Redmond Salt Mine in central Utah and the Pleasant Gap Limestone Mine in central Pennsylvania, we test the extent to which we can identify, locate, and distinguish different human-generated seismic signals over different mining subsurface structures and local geologies. The Redmond Mine was instrumented with a local surface array of 15 nodal seismometers over one month in 2018. The Pleasant Gap Mine was instrumented with over 50 surface nodal seismometers over two month-long periods, one in the spring and another in the fall of 2023. Because many anthropogenic signals are persistent, rather than impulsive, we employ cross-correlation methods to characterize and track these persistent signals over time. To locate the cross-correlation signals, we implemented both array-based backprojection and single-station polarization methods. However, we also observe impulsive signals related to blasting which we locate with traditional seismic methods. In general, we find that anthropogenic signals at these mines are often periodic, distinct in frequency, characterized by their relative time of occurrence, and whether the source location is stable. Between the two operations, we compare the effects of site geology and structure, local noise levels, the density of observations, and proximity to presumed sources on the ability to understand these anthropogenic signals.

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POSTER 142

Investigation of Full Moment Tensor Solutions for Earthquakes and Announced Nuclear Tests at the Punggye-Ri Test Site, DPRK

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Event Screening is the rejection of the hypothesis that a seismoacoustic event is generated by a single explosion source. There are several methods used to screen events, including the ratio of body-wave to surface-wave amplitudes, the ratio of high frequency P-wave to S-wave energy, and source depth. However, these methods may not screen all relevant events and so forensic seismologists have looked for additional approaches. The full moment tensor solution (MTS) resolves the six independent components of the source moment tensor, and therefore fully characterises the source mechanism, including determining the proportion of deviatoric and isotropic energy released by a source. However, complications arise from sources at shallow depths where the moment tensor inversion becomes underdetermined. Furthermore, explosions can generate deviatoric energy, complicating the MTS. Here, we use the mttime inversion scheme (e.g., Chiang et al., 2021), utilising data from IRIS, the International Data Centre (IDC) and recently published additional datasets, to calculate MTSs for: six announced DPRK nuclear tests, the collapse event after DPRK6, and nearby earthquakes in the IDC Reviewed Event Bulletin (REB). After tuning of station-specific time-shifts and velocity models, all six announced nuclear explosions have large positive isotropic components, with significant deviatoric components in their final MTSs, whereas the collapse event has a large negative isotropic component. In contrast, the earthquake MTSs have larger deviatoric components in comparison to isotropic. However, in all cases the compensated linear vector dipole component (volume expansion along a plane) is substantial, and solutions are not always stable; small adjustments in the time shifts, velocity model and station distribution can produce highly variable seismic source interpretations. Thus, care must be taken in determining the cause of a seismic source.

POSTER 143

Relative Source Time Function Estimation, Applications to the Source Physics Experiments

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The Source Physics Experiment (SPE) are a series of chemical explosion experiments at the Nevada National Security Site (NNSS). SPE Phase-I (2011-2016) provided a wealth of dense, local- to regional-distance observations suitable for characterizing shallow chemical explosions located within the same borehole. SPE Phase-II (2018-2019) was emplaced in alluvium with a dense array network in both linear profiles, borehole emplaced accelerometers and a grid of geophones. We investigate the time-dependent source processes of each chemical explosion using relative source time function (RSTF) estimation. We characterize SPE Phase-I using data from five linear seismometer profiles located between 100 and 2000 meters from the shot location. For SPE Phase-II, we experiment with using surface and near-source borehole instrumentation within 100 meters to compute RSTF's, this is due to complexities of the source medium and propagation. We attempt to reconstruct the relative source time functions (RSTF) to improve the resolution of time-dependent source processes utilizing the lower yield events in the series as the green functions. The RSTF estimates do provide exceptional resolution to each explosion's time-history for SPE Phase-I. Preliminary modeling efforts suggest these measurements may be useful for precise characterization of explosion processes and spallation. Using the relative source time functions allow us to expand our understanding of the SPE Phase-I and Phase-II explosion series. Application of these techniques contributes to our understanding of source physics and facilitates future efforts to additional seismic source experiments and phenomenology.

POSTER 144

Transportability of a Convolutional Neural Network Seismic Denoising Model

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Machine learning algorithms typically follow the paradigm of training a model on compiled datasets with characteristics of the type of data that the model is designed to then evaluate. This has often led to model performance problems when taking a previously trained model and attempting to utilize it to evaluate a new dataset which differs in characteristics when compared to the training dataset. This problem of model transportability is pronounced in the field of seismology, as we typically train our machine learning models on data specific to certain regions, networks, or time periods, which then experience significant performance drops when those models are utilized in other regions. Here, we assess the transportability of our previously constructed Multi-level Wavelet-based Convolutional Neural Network (MWCNN) seismic denoising model and investigate whether techniques such as transfer learning may provide solutions to said transportability problems. The MWCNN model was originally trained on earthquake and explosion data from the Utah seismic region and will now be used to analyze data from the Nevada seismic network. To assess the degree to which transportability is an issue for the MWCNN model we will first evaluate the denoising performance of the Utah-trained model using data associated with the 2020 Monte Cristo Range, Nevada, earthquake sequence. Then, we will compare the denoising capabilities of the Utah-trained MWCNN denoising model with that of a denoising model trained exclusively on Nevada earthquake and explosion data to measure whether a performance gap exists and what its magnitude is. Lastly, our goal is to assess whether transfer learning techniques may provide an avenue towards accounting for transportability issues by examining the denoising performance of a model with weights initially assigned using Utah-based data that is then further trained on data from the Nevada region.

POSTER 145

Gravity Mapping to Validate the Rock Valley Geological Framework Model

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As part of the ongoing Source Physics Experiment, its third phase, known as the Rock Valley Direct Comparison (RVDC) effort is underway. This experiment seeks to compare the signatures recorded from a large chemical explosion emplaced very near to an historic earthquake, whose signatures were well recorded with nearby instrumentation. As part of this effort, a detailed Geologic Framework Model (GFM) was developed that included projections of the many known faults throughout Rock Valley. Efforts to improve seismic event locations include the use of the GFM and updates to seismic velocity, as well as a re-evaluation of the attitude and location at depth of relevant faults.

We have acquired several lines of relative gravity data using a LaCoste & Romberg portable gravimeter to improve the observation density over previous data available from the U.S. Geological Survey. Our aim is to validate or update the GFM and its fault projections as appropriate through these dense data, and to provide a Bouguer Gravity map to be used in future joint gravity/seismic inversion to further update the model and improve locations for previously recorded earthquakes. We present our observations, data reductions, modeling methods and comparison with the existing GFM. The gravity modeling is undertaken using open-source Python-based SimPEG software (Cockett et al., 2015).

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POSTER 146

Observations of Epicentral Infrasound From Shallow Low-Magnitude Earthquakes in the Permian Basin, West Texas

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Seismic waves emanating from earthquakes and underground explosions can disturb the Earth/atmosphere interface and generate acoustic waves that may propagate to local and even global distances. Epicentral infrasound (EIS) is generated directly above an event while local infrasound (LIS) is generated at or near a receiver. Both have been observed at distances of hundreds to thousands of km following explosions and moderate to large earthquakes (M_L 3.55 and greater). Proximal (<50 km) observations, however, are especially important for characterizing low-energy events. LIS has been observed for an earthquake as small as M_w 1.87. While laterally propagating EIS has been observed within 10 km of buried chemical explosions, to our knowledge there are currently no observations of EIS at such distances following earthquakes of any magnitude. The Pecos Infrasound Network observational campaign, during which infrasound was recorded on three arrays during a period of high seismic activity in the Permian Basin of West Texas, was designed to remedy this lack of observations. From January to June 2023, nearly 1000 earthquakes ($1.2 \leq M_L \leq 4.2$) occurred within 50 km of the network, all at depths <11 km. We analyzed 191 $M_L \geq 2.5$ events and identify coherent infrasound signals following 45 earthquakes. We highlight exemplary infrasound signals following three events. All three earthquakes generated LIS at or near the receivers. Two of the three (both M_L 2.9) also generated laterally-propagating EIS detected on an array about 3 km away, which is confirmed with array processing methods and comparison with seismic observations. To our knowledge, these are the first observations of laterally-propagating EIS at proximal ranges following an earthquake of any magnitude.

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POSTER 147

Seismic Soundscape of the Parks Highway Corridor, Central Alaska

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In February of 2019, 306 three-component nodal seismometers were deployed every 1 km along the Parks Highway in Alaska, from Nenana to Trapper Creek, for a period of 35 days. These nodes recorded a wide range of signals, including from local, regional, and teleseismic earthquakes, mining blasts, helicopters, planes, trains, and automobiles. Our overarching goal is to characterize the "seismic soundscape" for this region, represented by a large set of waveforms, identified by time windows and frequency windows, that are labeled by event type. Motivated by the findings of Meng and Ben-Zion (2018), we are particularly interested in characterizing the spectral signatures of various aircrafts and engine types, which is made possible by a ground-truth data set of all commercial flight paths within the time period of interest. Alaska offers an exceptional opportunity for the ground-based detection and characterization of aircrafts, because there are a wide range of different aircrafts in use in Alaska (about 100 different types for our region and time period) and because background noise levels (e.g., low car traffic, continental interior) are relatively low. Spectrograms of ground motion from passing aircrafts reveal characteristics that are unique to specific types of planes, such as plane-specific harmonics and doppler shifts. In characterizing the spectral signatures of various source types we hope to create a unique database of labeled waveforms to use as training data sets for future machine learning studies. We are currently working to establish detection thresholds and characterize spectral signatures of all signals. Our analysis is augmented by permanent seismic and infrasound stations, providing means for extrapolation outside of the 35-day time period of interest.

POSTER 148

Seismic Data Denoising Using Multi-Scale Mathematical Morphological Filtering

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Recorded seismic data are generally contaminated by noise from different sources, which masks the signals of interest. In the seismology community, frequency filtering is the standard method for noise suppression. However, frequency filtering is inadequate when the signal of interest and noise share the same frequency band. We implemented a new data denoising technique based on the mathematical morphology theorem. The method uses morphological opening and closing operations with respect to predefined structuring elements of varying scales, and decomposes an input noisy waveform into several time series with differing characteristics. Using weighted stacking the denoised waveform is constructed from the time series. The reconstruction factors used to perform the weighted stacking are chosen carefully based on the assessment of which scales are likely to enhance the signal of interest and which ones are likely to amplify the noise. We will discuss the implementation of the approach and its initial application to process high-frequency local and near-regional data.

POSTER 149

Evaluation of Multiple-Event Location Methods Using Ground-Truth and Synthetic Data

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We investigate the accuracy and effectiveness of several commonly used multiple event relocation techniques to recover accurate hypocenter and uncertainty information using sparse datasets involving mostly regional-distance phase readings from ground truth (GT0 or GT1) real event clusters and synthetic sources. The compared techniques include Progressive Multiple Event Location (PMEL, Pavlis and Booker, 1983), MLOC (Hypocentroidal Decomposition algorithms provided by Global Seismological Services, based on Jordan and Swerdrup,1981), HypoDD (Waldhauser et al., 2000), and GrowClust (Trugman and Shearer, 2017). These techniques employ different methods to account for structural heterogeneity along the ray paths from sources to receivers or locally within the cluster source region. We compare the results to traditional single event location using the best available 3-D structural information in the study regions. We evaluate the methods in terms of mislocation with respect to GT locations and the size and accuracy of the derived uncertainty regions. It is expected that multiple-event, cluster relocation techniques will resolve relative epicenter position better than single-event location; however, questions remain about their effectiveness in recovering absolute hypocenter positions, or accurate estimates of location parameter uncertainties (e.g., Lin and Shearer, 2005). In a nuclear explosion monitoring context, the validity of the uncertainty assessments is often more important than the accuracy of the estimated hypocenters. Initial results indicate that location uncertainty estimates obtained from relative location techniques can be unrealistically small in many cases. We comment on possible causes embedded within the relocation codes that explain the obtained results.

POSTER 150

Moment Tensor Inversions for Rapid Seismic Source Detection and Characterization of the North Korean Nuclear Tests

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The rapid detection and source characterization of any type of seismic events including earthquakes and nuclear explosions are two important missions of many monitoring seismological laboratories. Here, we extend the use of a technique already considered for earthquake monitoring in tectonically active regions to identify non-double-couple shallow events. This approach allows the rapid screening of such events. It can then be implemented in near real-time procedures and it can become the core of an easy-to-use interactive tool for seismic analysts. This rapid detector of seismic events provides the full information of the sources (origin time, location, magnitude, mechanism, and source decomposition) from full moment tensor inversions calculated on a grid of virtual sources distributed over a region of interest with a limited set of stations. Its overall performances on all past Democratic People's Republic of Korea (DPRK) nuclear tests and regional earthquakes are presented. This work also allows to confirm the nature of the first DPRK explosion in 2006 despite the low signal to noise ratio observed in the seismic data, as well as the characterization of the collapse in the Mantap mountain after the 2017 nuclear test. These rapid source parameters (location, magnitude, mechanism) are comparable to those derived from high-frequency data and more complete set of regional and teleseismic stations. Thanks to this designed tool rapid (i.e., within a few minutes) and complete event screening is possible and it opens numerous options for earthquake and explosion monitoring as well as for tsunami warning.

POSTER 151

Modeling the Ground Motions From Chemical Explosions in Proximity of a Fault

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The Source Physics Experiment (SPE) is being conducted at Nevada National Security Site (NNSS) to study the ground motion generated by underground chemical explosion sources in various geologies. Of particular interest is the understanding of mechanisms of shear wave generation observed during underground explosions, which may look like natural seismicity in the far field. SPE-III will be conducted in proximity to a fault. We have conducted numerical modeling of the ground motion from explosions at various depths to investigate a role the fault may play in the predicted ground motion. Various in-situ stress conditions were assumed at the fault as well as the fluid pressure which may affect the friction on the fault. A new constitutive model for porous saturated rock has been used which accounts for fluid pressure build up in a dynamic loading unloading cycle.

POSTER 152

Signal Arrival Databases for Ground Truth Infrasound Events

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Seismo-acoustic waveform model development serves to improve both precision and accuracy in event characterization estimates through the application of more robust travel time models for infrasound signal propagation. Development requires the ability to validate models with real data against meaningful metrics. Comparisons across a suite of ground truth (GT) events provides the ability to evaluate model performance across a broad spectrum in both space and time. Current infrasound GT data is limited for several

reasons, including but not limited to, a lack of acoustic signals from naturally occurring events and a lack of broad global network coverage. Data is particularly limited for regional networks where sensors are located between 100-600 km from a source of interest. Numerous boutique experiments have historically been conducted by researchers with varying degrees of openly available data; however, none of these datasets exist in a singular place. Here, we present a curated dataset of 119 GT infrasound events suitable for algorithm evaluation. Our database identifies signal arrivals and characteristics for each of the GT events, capturing all available regional signal arrivals in an open-source repository.

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Advances in Operational and Research Analysis of Earthquake Swarms

Oral Session • Friday 3 May • 2:00 PM Pacific

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Seismic Clusters as Markers of Crustal Stability

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Seismic activity is the mirror of local instability in the brittle crust. Each seismic event occurs because of stress accumulation at weak interfaces within crustal volumes and static and dynamic perturbations, so that earthquakes tend to be clustered in space and time. So, on one hand, seismicity trivially provides information about the state of stability of the fault patch where it takes place, on the other side, it is rather difficult to assess whether the occurrence of seismic events may be somewhat connected to the large-scale state of stability of a fault. Are foreshocks "fore-shocks" or simply markers of local instability without prognostic value? Is there difference between foreshocks and swarms? We analyse several parameters describing seismic clusters until the mainshocks in relocated seismic catalogues in relationship with the magnitude of the incoming mainshock in the range Mw 2.5–7.3 in Southern California and Italy (e.g., the involved area, duration, the p-value of the Omori-Utsu law, the b-value, the seismic rate, number of events, entropy, inter-event times distribution). We find differences in the distributions of some features; foreshocks tend to spread over larger areas, they are featured by larger and more energetic clusters with also higher variance of magnitudes and relative entropy. Others are not distinguishable. Moreover, foreshocks and swarms are found to share the same scaling behaviors. Theoretical modelling suggests that the combined effect of long-range correlations and fault memory makes the system sensitive to both mechanical details, structural properties of the fault system and its history. Therefore, it produces different future evolutions because of tiny changes in internal parameters or in past occurrences. We believe that foreshocks can be hardly distinguished from swarms using the structural and statistical properties of clusters. In this sense, foreshocks are likely of limited usefulness for short-term earthquake forecasting if considered alone, but they could be useful for the identification of regions featured by correlated seismic activity, a plausible marker of crustal instability.

Investigating Slow Slip Transients and Earthquake Swarms on the Blanco Transform Fault With Obs Data Mining

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Oceanic transform faults (OTFs) constitute one type of plate boundary accommodating deformation through quasi-periodic earthquakes, aseismic creep and seismic swarms. Recent studies suggest that earthquake swarms are driven by episodic slow slip, both of which can sometimes precede moderate-large earthquakes at OTFs. Here, we analyze data from an OBS network (X9 code, 55 stations deployed for 1 year in 2012-2013, Nabelek et al 2012) surrounding the Blanco Transform Fault (BTF) located offshore Oregon. We re-visit this dataset using two advanced data mining approaches. We thus conduct a comprehensive analysis of the BTF seismic wavefield, aiming to investigate slow slip phenomena and its role in generating earthquake swarms.

First, we apply a machine-learning (ML) workflow to detect microseismicity. We use the PickBlue CNN phase picker and GaMMA associator. After a quality assessment, about 40,000 earthquakes are retained, representing 4.5 times more than a previous seismic catalog for the same dataset. Our ML seismic catalog delineates the fault's along-strike segmentation, revealing distinct seismogenic behaviors: sections emitting nearly continuous microseismicity, aseismic areas, and portions characterized by seismic swarms, and mainshock - aftershock sequences. Second, we measure the seismic wavefield spatial coherence across the OBS network, by computing the covariance matrix spectral width, using CovSeisNet. An interesting finding includes very low-frequency earthquakes (VLFE) detection in the 10-30 s period range.

To better understand the spatio-temporal relations between slow earthquakes, foreshock swarms, and mainshock earthquakes, we are relocating seismic swarms and VLFE sources. Finally, we aim to extend the new insights gleaned using the year with OBS data on the fault, to improve and ground truth methods using only the permanent in-land stations near the coast. This would improve quality and reliability of multi-year analysis of BTF swarms when only in-land stations exist, aiding in the elucidation of their driving mechanisms, potentially involving slow slip transients.

Distant Seismic Monitoring of a Volcanic Earthquake Swarm Near the Manu'a Islands, American Samoa, with Deep-learning and Template-matching Event Detection

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From July to October 2022, an earthquake swarm occurred near the Manu'a Islands in eastern American Samoa. The swarm started in late July, with peak activity in August, before decreasing in late September and has fortunately been quiet since. Earthquake information was limited to felt shaking reports from local residents sent to the National Weather Service Pago Pago office, because of a lack of seismometers in the region when the swarm started. Residents were concerned about the unusual frequent shaking, making it essential to understand the source of these earthquakes in rapid response mode.

We show how modern seismological methods provided initial information and situational awareness of the evolving Taʻū volcano earthquake swarm, with limited available data. Using continuous seismic data from one Global Seismographic Network station located ~250 km west of Taʻū volcano, we applied the EQTransformer deep-learning model (Mousavi et al., 2020) to automatically pick P and S phase arrivals for earthquakes between 2022-07-01 and 2022-08-12, when seismic activity began and intensified. We used S-P times from events matching felt reports to identify additional likely Taʻū volcano swarm events, while excluding events from unrelated sources such as the Tonga Trench. Waveforms from these events were used in template-matching to detect additional events. Starting 2022-08-13, when continuous Raspberry Shake seismometer data from Taʻū Island became available, short (<3 second) S-P times output by EQTransformer constrained the swarm location to the northern submarine realm of Taʻū volcano. The Raspberry Shake data was essential in determining Taʻū volcano as the correct source of the swarm, ruling out the previously assumed Vailuluʻu seamount as a potential source. On 2022-08-20, the USGS Hawaiian Volcano Observatory commenced operational response seismic monitoring in American Samoa, estimating magnitudes of 2 to 4 for most subsequent earthquakes. Methods such as deep-learn-

ing and template-matching can improve monitoring and forecasts of swarms and aftershock sequences far from seismic stations.

Improving Template Matching Detections Using a Convolutional Neural Network

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The use of template matching to detect previously missed small earthquakes is widespread in seismology, due to its power in searching for similar signals. The newly detected earthquakes improve understanding of the geology, seismo-tectonics and seismogenesis of the area explored. The usefulness of template matching has sparked the development of many software tools (e.g. QuakeMatch; Toledo et al., 2024) that allow seismologists to easily apply them to their area of interest.

Like every detection technique, the performance of template matching shows a tradeoff between sensitivity and false detection rate that is dependent on the choice of the detection threshold. The value of the correlation coefficient between two earthquake signals is highly dependent on several properties such as the distance of the earthquake from the station, the noise level at the station, the magnitude of the earthquake, the focal mechanism of the earthquake, etc, making the selection of a specific correlation coefficient threshold hard. To detect a larger number of earthquakes, researchers often use a lower correlation coefficient detection threshold and manually inspect the detected events to classify them as true events (Toledo et al., 2024). This is a tedious task, especially when using a large number of templates. To reduce the human workload, which can be especially important during evolving earthquake sequences, we employ a Convolutional Neural Network (CNN) to discriminate between earthquakes and noise using the template matching detections as input. We use the data from several microearthquake natural and induced Swiss sequences (Simon et al., 2024, in prep.), to train and test the developed CNN model. Our CNN model uses single-station 3-component waveforms of any length and outputs an earthquake detection score. We demonstrate that the developed CNN can be used to significantly reduce the human workload with high accuracy, allowing the use of low correlation coefficient value thresholds for template matching detections. Furthermore, we show the implementation of the method inside the QuakeMatch software (Toledo et al., 2024).

Automated Detection and Characterization of Swarms and Mainshock-Aftershock Sequences in Southern Mexico

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Earthquakes in Mexico are frequent and dangerous. Over the last decade, there have been a dozen major earthquakes including two larger than M7.5. The Mexican subduction zone is considered a natural laboratory for studying slip processes due to the relatively short trench-to-coast distance which brings broad portions of the seismogenic megathrust inland. Using an automated detection algorithm that identifies clusters of events using the nearest neighbor distances in the space-time-energy domain (Zaliapin and Ben-Zion, 2013), we sought to characterize ~700 sequences detected from 2012 to 2020. Traditional methods are time-consuming and biased due to the number of events and human perception, so we developed an automated strategy to evaluate sequences on a spectrum of swarm to mainshock-aftershock (MS-AS). The automated algorithm uses quantitative forms of these attributes: 1) magnitude difference between the largest event and next largest events, 2) percentage of the sequence after the largest event, 3) slope of seismicity rate over time, 4) ratio of magnitude range to the number of events and, 5) rate of maximum magnitude decay over time. The automated method yields similar results to manual characterization and is effective at identifying average properties when there are discrepancies among manual ratings for complex sequences. We found more swarms than aftershock sequences despite the prominence of large megathrust MS-AS sequences over the past decade. Temporally, some swarm sequences show an interesting pattern where the seismicity shuts on or off depending on nearby megathrust activity. Spatially, swarms help define a vertically dipping fault in the upper plate indicating a strike-slip sliver fault may be closer to the coast than previously thought. We anticipate standardizing the characterization process will provide opportunities for more in-depth studies of seismic sequence types and their causes.

Seismological Study of the West Bohemia/Vogtland Swarm Region With Waveform and Catalog Data

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The Vogtland region is situated in the western part of the Bohemian Massif and extends over an area of 3500 km^2 across four state borders. It is intersected by the medium-sized Tertiary Eger Graben, Variscan terrain boundaries, and a small sedimentary basin. The area is a type locality for the study of mantle-derived, diffuse degassing of CO2 and the persistent occurrence of mid-crustal earthquake swarms. Quaternary maar volcanoes and crustal magmatic underplating indicate extended magmatic processes. Despite intensive research, the cause of the earthquake swarms has not been elucidated, and questions remain as to how shallow magmatic fluids penetrate, whether the apparent Moho upwelling and underplating zone correlates with an upwelling of the brittle ductile transition between 15-10 km depth. Another open question is why since 1985 the highest swarm energy release with Ml<4.5 occurs in a cluster below Novy Kostel, and why for about 15 years the swarm has been migrating with each new cluster in a well-defined fault zone to the north and south, reaching shallower levels in recent years. To date, the Novy Kostel swarm extends over 35 km in length and 12 to 8 km in depth. The sources cover strike-slip, normal and thrust mechanism.

We follow three approaches to explore the swarm region: (1) improve the existing dense seismic network by installing high-frequency 3D arrays as antennas to detect and locate the smallest events. So far, two swarm episodes have been recorded by this installation; (2) unify the existing seismic catalogues from different surveys using a common velocity model and modern relative locations; (3) use of machine learning phase detection, migration and stacking techniques with the dense network data for the preiod 2018 to 2024 to reduce the completeness magnitude and study the anatomy of swarms in the initial activity phases. This comprehensive approach will answer the question of whether the distribution of the deepest micro-earthquakes follow the upwelling brittle ductile transition over the region of CO2 degassing and swarms.

Systematic Measurements of Parameters During Earthquake Swarms

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The identification of processes causing earthquake swarms are long-standing problems in seismology. We are engaged in an ongoing comprehensive and systematic approach that examines a variety of parameters. Here we summarize recent results which have not been previously published. We investigated the difference in magnitude M between the largest and second largest events, which we call M1-M2. Large samples (67-174 swarms) of swarms in tectonic and volcanic areas (teleseismic data) each had similar distributions and variances and the same means of 0.16 M units. No swarms were found with M1-M2 equal to 0.7, which suggests a break in scaling. M1-M2 is systematically larger as M1 get larger, which suggests variability of conditions in the source regions. Swarm durations are longest for swarms on megathrusts, and shortest at volcanoes, although distributions overlap. The largest event occurs late in volcanic swarms, suggesting a growing source size. This trend is not observed for mid-ocean ridge swarms. A plot of number of events in swarms versus number of swarms shows two branches (sub-parallel trends), suggesting two dominant processes. An updated study of volcanic swarms that follow the Generic Volcanic Earthquake Swarm Model (GVESM) using local data show that the peak rate occurs near the onset of low-frequency events. This suggests that the peak rate is the culmination of development of a system of cracks, which then facilitate fluid (water, gas, or magma) movement. Overall, the suite of observations and measurements suggests that there are several mechanisms or processes involved in earthquake swarms.

Earthquake Swarms as a Window to Characterize Transient Processes

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Earthquake swarms are broadly defined as earthquake sequences without a distinct mainshock. Many different parameters have been proposed to characterize earthquake swarms and distinguish them from mainshock-aftershock sequences. However, there is no universal definition of swarms. In this study, we compile previously identified earthquake swarms in different tectonic regions, including tectonic strike-slip faults, volcanic and geothermal regions, and fluid-induced swarms in the intraplate region. We obtain a comprehensive set of physical and statistical parameters to characterize the swarm evolution in space and time and compare swarms from different tectonic regions. For two swarms driven by different external processes, we further characterize short-duration bursts within the swarm.

Preliminary analysis found no systematic difference in effective stress drop from different regions with values ranging up to 3 orders of magnitude. The range of effective stress drop is similar to static stress drop for individual earthquakes, suggesting the average stress release is nearly constant. The skewness of moment release history is mostly small, however, several prolific swarms from the Salton Trough have very high skewness, suggesting more concentrated moment release during the early stage of the swarm - a behavior that is more similar to foreshock-mainshock-aftershock sequences.

A systematic difference in the scale exponent between migration velocity and swarm duration separates swarms into different groups of different dominant triggering processes from pressure-diffusion dominant to shear-stress-transfer dominant regimes. An effective diffusivity is obtained based on the product of velocity squared and duration. Relatively narrow ranges of diffusivity are found for each group, with the Salton Trough being systematically higher and bridging the gap between crustal swarms and slow-slip events. We hypothesize that such observation suggests characteristic diffusion processes in different tectonic regions, and swarm parameters reflect characteristic transient processes in different environments.

Deep Learning Analysis of Transient Signals Preceding the 2023 Mw 7.8 Kahramanmaraş Earthquake in Türkiye

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Laboratory studies indicate that faults undergo damage and stress evolution before rupture, potentially leaving discernible signatures in seismic data. Before the 2023 M_W 7.8 Kahramanmaraş earthquake in Türkiye, an extended period of ~ 8 months displaying seismicity around the epicenter and the entire rupture suggested an extended preparation phase (Kwiatek et al., 2023; Picozzi & Iaccarino, 2023). This study analyzes low-frequency (< 5 Hz) recordings from regional broadband seismic stations near the future epicenter of this earthquake. Using a deep neural network, we extract key features from the continuous seismic waveforms and their spectral characteristics and employ an unsupervised clustering analysis to identify distinct classes in the continuous waveform recordings. Our analysis reveals two main changes in the spectral characteristics about 8 and 6 months before the mainshock, respectively, coinciding with the onset of elevated seismic rates and changes in *b*-values. Of particular interest is the emergence of numerous (N=3724) temporal episodes lasting about 12~30 minutes containing enhanced radiated energy in the frequency band 1-5 Hz, starting 6 months before the mainshock. These episodes are observed solely at five seismic stations within 46 km epicentral distance from the future mainshock epicenter, all located on the east side of the East Anatolian Fault Zone. The episodes are likely of tectonic origin, as their occurrence is not correlated with time of day, weather changes, construction processes, telemetry-related events, or instrument-related factors. Each episode comprises numerous small transient pulses resembling extremely small earthquakes. The pulses have a similar moveout to that from a local earthquake near the main rupture epicenter. We present the statistical analysis of observed episodes as well as their source properties and investigate their physical origin.

Enhanced Seismicity at a Geothermal Spot in Southern Tibet Following 2004 Mw 9.1 Sumatra and 2005 Mw 8.6 Nias Earthquakes and Its Implication for Rifting Process

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There are several north-south trending rifts in southern Tibet, indicating the extensional stress perpendicular to the convergence direction between the Indian and Eurasia plates. However, the rifting geodynamic process is under debate. Strong geothermal and seismic activities are observed all over southern Tibet. In particular, there is a geothermal spot west of Pumqu-Xianza Rift in the Lhasa Terrane, where there are nearly continuous seismic activity with magnitude 3-5 based on the global and regional catalogues. With such high seismicity rates, it is expected to observe dynamic triggering around the geothermal spot. Here we conduct a systematic search for dynamically triggered microearthquakes in southern Tibet following the 2004 December 26 Mw 9.1 Sumatra and 2005 March 28 Mw 8.6 Nias earthquakes. We find clear increase of high-frequency signals during the surface waves of the Sumatra mainshock, a clear hallmark for instantaneous dynamic triggering. To better quantify seismicity rate changes, we apply a Network Waveform Matched Filter Technique (NWMFT) to continuous seismic data recorded by the Hi-CLIMB 2D array to obtain more complete earthquake catalogues in southern Tibet. Using 213 hand-picked events as templates, we detect ~36 times more events 90 days before and after both mainshocks. The detected catalogs show that local seismicity in the geothermal spot west of Pumqu-Xianza Rift was enhanced after the Sumatra earthquake, but no significant change after the Nias earthquake. The enhanced seismicity lasted about 20 days following the Sumatra mainshock. The difference in triggering response following these two distant earthquakes could be related with the fact that the Sumatra mainshock excited long-duration surface waves with cumulative energy density 15 times more than that of the Nias mainshock or due to potential recharge time since relative short time interval between these two mainshocks. We will examine spatio-temporal evolutions of seismicity to better constrain the physical processes of dynamic triggering at geothermal regions and its implication for rifting process in southern Tibet.

Advances in Operational and Research Analysis of Earthquake Swarms [Poster Session]

Poster Session • Friday 3 May

Conveners: Kyren R. Bogolub, Nevada Seismological Laboratory, University of Nevada, Reno (kbogolub@unr.edu); Jeffery L. Fox, Ohio Geological Survey (jeffrey.fox@dnr.ohio.gov); Andrea L. Llenos, U.S. Geological Survey (allenos@usgs.gov); William H. Savran, Nevada Seismological Laboratory, University of Nevada, Reno (wsavran@unr.edu); Daniel T. Trugman, Nevada Seismological Laboratory, University of Nevada, Reno (dtrugman@unr.edu); Elizabeth A. Vanacore, University of Puerto Rico Mayagüez, Puerto Rico Seismic Network (elizabeth.vanacore@upr.edu)

POSTER 120

Feature-based Magnitude Estimates for Small, Nearby Earthquakes in the Yellowstone Volcanic Region

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Conventional methods of magnitude estimation for small, locally recorded events either rely on measurements of the maximum peak-to-peak amplitude to compute a local magnitude (M_L) or measurements of waveform decay to compute a coda duration magnitude. While at least one of these methods is generally able to produce an event magnitude in an automated framework, small events occurring as part of an earthquake swarm often pose a challenge. These events can occur rapidly and close by, causing overlapped event waveforms that make it challenging to accurately estimate the required magnitude parameters. This is particularly evident in Yellowstone, where ~50% of all seismicity occurs as part of a swarm. Additionally, only a subset of seismometers used to process events in the Yellowstone region have the station corrections

needed to compute M_L. This further limits the ability to produce M_L values for very small events (< ~1.5). The need for another approach to estimate magnitude is magnified for large, deep-learning enhanced catalogs.

We introduce a machine learning method that uses features derived from short-duration waveforms capturing individual phase arrivals and event source parameters to predict the catalog network M_L. We train one support vector machine (SVM) for each station-phase pair, resulting in 34 models using *P* features and 17 using *S* features. Producing a model for each station allows the SVMs to efficiently learn individual station corrections. We ensemble predictions from multiple models into a network-averaged magnitude. For each phase, we initially examine 48-potential features and narrow the final number used in each model to ~9 by applying feature selection techniques. Using these features, initial results produce an R^2 value of ~0.9 on the test sets when averaging the model predictions. This method will improve our ability to produce M_L values for Yellowstone swarm events and lower the M_L magnitude of completeness. While not directly transferrable, this approach may be beneficial to other seismic network operators who routinely process earthquake swarms.

POSTER 121

Analysis of Yellowstone Earthquake Swarms After Relocating Using Nonlinloc-Ssst and a 3D Velocity Model

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The Yellowstone region is the most seismically active area in the U.S. Intermountain West with an average of ~1,500–2,500 earthquakes per year. About half of Yellowstone seismicity occurs as part of earthquake swarms which have been attributed to processes such as hydrothermal fluid migration, magma injection or creep along faults. High-precision earthquake locations can be used to understand the structures where swarms occur and the underlying causes of the swarm seismicity. NonLinLoc (NLL) is a nonlinear high-precision earthquake location method that has been shown to produce higher-quality absolute locations than conventional methods. We have applied a more advanced version of NLL, NonLinLoc—Source Specific Station Terms with Coherence (NLL-SSST-coherence) to ~40 years of Yellowstone seismic data recorded from 1984 to 2024 to obtain high-precision absolute earthquake locations. The NLL source specific station terms are created iteratively using a 3D velocity model and waveform coherence is used to reduce arrival time errors. We will compare the absolute locations from NLL-SSST-coherence with 1D routine locations produced by the University of Utah Seismograph Stations and with 3D relocations using standard NLL. Initial results indicate that the NLL-SSST-coherence locations show an improvement over both the 1D routine and standard NLL locations, and some earthquake locations converge to linear features which could indicate fault structures. These findings suggest that using a more advanced location method for swarm events could be an important step in understanding the structures and dynamics of earthquake swarms. It also suggests that including the use of NLL-SSST-coherence in routine location analysis could improve the "realtime" interpretation of Yellowstone swarm activity.

POSTER 122

It's Swarmy Outside: Defining Swarms for the Purpose of Forecasting

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Compared to more common mainshock-aftershock sequences, earthquake swarms are difficult to define and are therefore often defined by what they lack in relation to aftershock sequences (e.g., a clear mainshock, Bath's Law, Omori-like temporal rate decay). However, such definitions can be difficult to quantify, particularly in more complex sequences of elevated earthquake rate. They also do little to describe what a swarm actually is, particularly for the general public who may never hear the term until they are in the midst of one and receiving earthquake advisories that could cause confusion or alarm. Definitions that focus on seismogenic processes due to fluid migration, slow slip, or volcanic processes may be more informative, but it is difficult to identify these processes early in a swarm's evolution. Because the U.S. Geological Survey (USGS) releases earthquake advisories and forecasts during some swarms, such as the 2016, 2020, and 2021 swarms near the Salton Sea in California (e.g., McBride et al., SRL, 2020), we propose a definition that helps us make better forecasts and reduces confusion.

Here we define a swarm simply as a sequence of earthquakes where changes in earthquake rates are driven by processes beyond typical mainshock-aftershock triggering. This definition allows a swarm to be described with a time-varying background rate term in the Epidemic-Type Aftershock Sequence model (Ogata, JASA, 1988), which is already used to produce aftershock forecasts in many regions. A swarm forecast can therefore be computed by adding a temporally varying background rate to the approach used for an aftershock forecast. Currently, the USGS forecasting method estimates this rate from the swarm so far observed and a swarm duration model (Llenos and van der Elst, BSSA, 2019). This procedure is applied using expert judgement when the inclusion of the extra rate improves the model. In general, we argue that the best definition of a swarm is one that helps us best forecast the future and is simple enough for people outside of our scientific sphere to understand.

POSTER 123

Event-Event Waveform Correlation and Multi-Event Multi-Channel Deconvolution Applied to Temporal-Spatial Patterns of Micro Earthquake Sequences (Swarms)

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Event-event multi-channel waveform correlation and multi-event multi-channel deconvolution is applied to two recent sequences of micro-earthquakes in South Carolina (Elgin and Monticello Reservoir). Clustering of events based on event-event multi-channel waveform correlation is used to identify separate spatial clusters of co-located events independent of prior localization procedures. That is, event-event waveform correlations identify repeated ruptures on individual localized asperities. The inferred hypocentral distances between the events on the same asperity may be smaller than the individual event location uncertainties. Small events with poor SNR with uncertain locations may be identified as belonging to localized spatial clusters. The clustered waveforms may then be used as matched-filter templates to further detect even smaller events related to the asperity. A statistical procedure is proposed to evaluate the probability of false event detection is presented. The resulting sequential pattern of event time series on the individual asperities then may be studied with more detail. A nearest neighbor temporal-spatial analysis is applied to characterize the sequences within and between asperities. Once decomposed into individual asperities, the event sequences on each asperity begin to resemble a fore-shock, main-shock after-shock sequences. A multi-event multi-channel deconvolution procedure of Der et al (1988) is applied to individual clusters to study more detailed temporal rupture variations on the individual asperities and reveal complex source functions.

Der, Z. A., R. H. Shumway, and A. C. (1988). Frequency Domain Coherent Processing of Regional Seismic Signals at Small Arrays, Bull. Seism. Soc. Am., 78, 326-338.

POSTER 124

Heterogeneous Seismic Swarm Activity in Central Utah: Triggering Mechanisms and Their Complex Interactions

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The complex geo-tectonic transition zone between the Basin and Range province and the Colorado Plateau results in a remarkable diversity of temporal and spatial characteristics of seismic swarms in central Utah. E-W extension, high heat flow, past volcanic activity, and hydrothermal processes form an exciting background to study forty years of seismic swarm activity based on the regional catalog of the University of Utah Seismograph Stations (e.g., duration, moment release over time, spatial variations). Alternating phases of very high and low activity are observed, as well as comparably continuous moment release, repeated activation of the same source areas as well as large swarms in previously seismically inactive areas. Subsequent in-depth analyses of exemplary, most recent swarm sequences, including event detections, relocations, MT inversions, waveform-based clustering, and repeater analysis, provide unique insights into the diverse faulting processes. We observe the following examples of diverse swarm activation processes: (1) swarm activity on a normal fault related to the regional Basin and Range extension but also (2) the activation of a local fault deviating from the recent regional tectonic regime. (3) The complex triggering of swarm activity by a mainshock and (4) years-long repeated activation of another swarm area. Combining the observations of the exemplary sequences and the catalog characteristics of the 40 years of swarm activity, we aim to expand the overall discussion on swarm activity and its relation to geothermal and tectonic processes.

POSTER 125

What Has Unimak Island in Alaska Witnessed in the Last ~30 Years?—a Seismic Recap

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Seismic swarms on volcanoes along a subduction arc could be reflective of a multitude of geophysical processes. These processes can broadly be volcanic, tectonic, or cryospheric in origin, or a combination of these. Unimak Island that exhibits subduction arc volcanism is located in the central part of the Alaska-Aleutian subduction zone where the Pacific plate subducts beneath the North-American plate, normal to the trench-line with low coupling between the plates. The island hosts several volcanoes such as Roundtop, Isanotski, Shishaldin, Fisher, and Westdahl. Of these, Westdahl, Fisher, and Shishaldin, are considered active due to historic volcanism, volcano seismicity, and deformation cycles. In this study, Unimak Island is divided into smaller regions based on the locations of the three active volcanoes and their seismic activity from 1990-2023, including the recent 2023 unrest at Shishaldin. The seismicity in these regions is categorized into multiple time windows depending on the length of activity and quiescence. The seismicity in each spatio-temporal unit is used to (1) characterize individual swarm clusters, (2) identify correlations with specific periods of volcanic unrest defined by different observations (eruptions, deformation etc.), and (3) identify signatures of possible interactions between the three volcanoes. The study uses relocated seismicity (Klein, 2002) from the Alaska Volcano Observatory (AVO) seismic catalog (available through USGS), and eruption history and geodetic observations curated by AVO.

POSTER 126

Correlations and Change Points Identification in Crustal Anisotropy, b-Value and Vp/vs, Time Series During Seismic Swarm Occurrences in the Alto Tiberina Fault Zone (Italy)

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We computed different seismological parameters from the analysis of the waveforms recorded during the seismic swarms activity occurred along the Alto Tiberina Fault (ATF) and surrounding regions (Northern Apennines, Italy) in the period 2010-2015: crustal anisotropy (in terms of time delay between the two S-waves generated by the shear wave splitting), b-value of the Gutenberg-Richter law, and vp/vs ratio. We obtained three time series of the corresponding measures for each station of the Italian Seismic Network operating in the study area. However only three of them show enough points along the entire 6-year period to obtain robust time series. Due to the sparse presence of values in the time series we thus apply a weighted likelihood approach to homogenize them, and finally we looked for both correlations and change points in their temporal trends. The times corresponding to aforementioned variations in one or more parameters/stations are then tested to highlight the statistical significance of their occurrence. We merge all observations for getting a more constrained interpretation of the ATF seismicity evolution. The statistical approach presented in this study for comparing seismological time series could more generally find application in comparing other types of time series, and is especially suitable for those derived from unevenly sampled measurements.

Advancing Seismology with Distributed Fiber Optic Sensing

Oral Session • Friday 3 May • 8:00 AM Pacific

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High-Resolution Analysis of Earthquake Sources and Subsurface Structures Using Downhole Optical Fiber Crossing Active Fault

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Distributed Acoustic Sensing (DAS) systems have proven effective in quantifying changes in frequency, amplitude, phase, and location of dynamic perturbations along the fiber, especially when installed with assured well coupling. Placing an optical fiber at the depth crossing an active fault holds potential for unraveling fault zone architecture. With the calibration of the co-site borehole-seismometers, we substantiate the reliability of DAS recordings. And, with this approach, coupled with high-resolution recordings in high seismicity region, constitutes our endeavor to uncover seismic insights, enhancing our comprehension of source and site heterogeneity in earthquakes across local to regional scales. Our exploration includes analyzing earthquake nucleation, source time functions, features in attenuation, and the generation of high frequencies within sub-surfaces. We employed source deconvolution, utilizing aftershocks as Empirical Green's functions up to 10Hz, to decipher slip heterogeneity within regional fault systems. On the advantage of the high spatial resolution DAS data, we directly apply the Q-operator to the time series at every channel to map the Q-structure crossing the fault zone and subsurface to avoid the influence from coda while apply seismic spectra analysis. The detailed mapping in attenuation could improve the uncertainties in earthquake source parameters estimations, namely the corner frequency and stress drop. As the feature of the attenuation in the fault zone might mainly related to fractured damage zone and thus the possible correlation to porosity and permeability, which led to the structure for the fluid flow in the fault zone, that is crucial for the understanding of the earthquake rupture dynamics, and its triggering. We demonstrated the application of meter scale spatial resolution and high sampling rate of in-situ downhole optical fiber could be beneficial to map the physical architecture of a waek zone, and good capability to decipher the slip and stress heterogeneity of regional fault system.

Dascore: A Python Library for Distributed Acoustic Sensing

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In the past decade, distributed acoustic sensing (DAS) has found many monitoring applications in disparate areas such as hydrocarbon exploration and extraction; glaciology; hydrology; urban geophysics; induced, regional, and global seismology; and several more. Many of these DAS applications have proven transformative to geoscience research. However, the lack of mature open-source software for working with DAS data has resulted in redundant efforts to implement data input/output (IO) and processing routines among various research groups. To help more new users quickly begin working with DAS data, we developed DASCore, an open-source Python library for analyzing, managing, and visualizing DAS data. DASCore provides IO support for various DAS file formats and file system archives, common processing routines, and static visualizations. It implements an intuitive object-oriented interface, has an extensive automated test suite, and is comprehensively documented. DASCore is a foundational package for the broader DAS Data Analysis Ecosystem (DASDAE) and as such its main goal is to accelerate the development of other DAS applications.

Characterizing South Pole Firn Structure With Fiber Optic Sensing

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The firn layer covers approximately 99% of Antarctica's ice sheets and critically protects glacial ice from the external environment. Its accurate physical and geophysical characterization is thus crucial for understanding ice sheet evolution, including issues critical to glacial mass balance and the effects of climate change. Our study utilizes Distributed Acoustic Sensing (DAS) technology to transform an 8-km fiber-optic cable between the Amundsen-Scott South Pole Station and the QSPA Global Seismographic Network station into a dense, low-maintenance, and continuously interrogated seismic array. With its 1 m spatial and 1000 Hz temporal resolution, this array successfully resolves a significant number of seismic wave propagation modes, providing detailed insights into both P and S wave velocities with depth. Comparing our data with the South Pole Ice Core, we have formulated a more precise, East Antarctica-specific empirical relation, significantly enhancing firn density estimations in the region. In addition to isotropic structures, we employ co-located geophones to also resolve the firn's anisotropic structure. Moreover, continuous year-round DAS monitoring enables the investigation of temporal firn variations. Our results underscore the transformative potential of DAS technology in glaciology and firn analysis, providing new insights into ice sheet seismology.

Assessing Distributed Acoustic Sensing (DAS) for Moonquake Detection

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We present how DAS could greatly enhance geophysical networks on the Moon. Moonquakes can provide valuable insights into the lunar interior and its geophysical processes. However, extreme scattering of the lunar seismic wave makes seismic phase identification and source characterization difficult on individual seismic stations. DAS, on the other hand, can detect the full waveform even in especially high scattering environments to pick up scattered phases that were previously unidentified by standard low-density seismic networks. We explore the potential of DAS to detect moonquakes if installed on the lunar surface by answering two questions: How could DAS advance Moon seismology? Can DAS detect moonquakes? To answer, we first generate synthetic DAS recordings to show that DAS is especially suited to measuring moon quakes in highly scattered environments with low seismic velocity on the Moon's near surface. Then, we compare the real Apollo seismometer recordings to the minimum resolution of DAS on the Earth in the very low-noise environment of Antarctica. We find that all thermal moonquakes previously recorded by the Apollo geophones can be detected by current DAS. Current DAS sensitivity will also allow for 60% of the meteoroid impacts and moonquakes that were recorded hemisphere-wide on all the Apollo seismometers to be detected. Our results show that this detection percentage should increase to over 90% with achievable and expected improvements in DAS equipment. Overall, we show that current DAS technology would be able to detect on average about 15 moonquakes per day, with large fluctuations depending on recording during lunar sunrise/sunset and the moon's distance from perigee/apogee. Utilizing DAS for lunar seismology promises a transformative advance in analyzing wave propagation on the moon, paving the way for significant insights into the Moon's internal structure.

Rupture Imaging of Firn Quakes with Distributed Acoustic Sensing

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A firn quake is an unusual seismic event resembling an earthquake but occurring in the snowfields and often accompanied by an audible "whumpf" sound. This intriguing phenomenon is explained to be caused by the collapse of a weak snow layer. However, historic reports and quantitative measurements of firn quakes are limited. Here, we report the most distinct firn quakes ever recorded, with their seismic signals clearly captured by a distributed acoustic sensing (DAS) array near the South Pole. The DAS array, deployed in January 2023, extends about ~8 kilometers from the South Pole station to the QSPA seismograph site and consists of ~8,000 channels. The firn quakes, induced during seismic surveys, were both felt directly during the fieldwork and recognized on the DAS records. The seismic records of firn quakes show distinct surface waves with multiple Rayleigh modes generated by the propagating source, with rupture durations varying from a few seconds to about 15 seconds. To investigate the kinematic features of firn quakes, we develop a novel back-projection rupture imaging method, utilizing Rayleigh waves together with an iterative mode striping technique. Our method yields an accurate estimation of rupture speed, depth, and magnitude, which provides critical insights into the physical mechanism of firn quakes.

SUBMERSE Project Paves the Way for Continuous Fiber-optic Monitoring in the Oceans with Submarine Telecommunications Cables

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In the last few years, a number of technologies to use fiber optic cables as sensing devices have been established, among them Distributed Acoustic Sensing (DAS) and State-of-Polarisation (SoP). The potential of these technologies for monitoring a range of Earth System parameters in submarine cables has been demonstrated through several pilot experiments, but full integration with telecommunication infrastructure has not yet been achieved. The SUBMERSE (SUBMarinE cables for ReSearch and Exploration) project links Research and Education Networks (RENs), universities, research institutes and industry to establish multi-method monitoring along submarine optical telecommunication cables at several key oceanic cable routes branching off from Sines in Portugal, Madeira, Svalbard and in the Ionian Sea (cable linking Preveza, Greece to Crotone, Italy), and in addition the Transatlantic cable between Fortaleza and Sines. Those pilot sites should serve as a blueprint for establishing continuous monitoring services along many more cables.

The project comprises technical developments for integrating DAS and SoP measurements, for establishing differential SoP measurements between repeaters and for operating DAS in a co-existence mode, i.e., in fibers also carrying telecommunications traffic. Furthermore, a range of geoscientific and marine biology use cases are included, which seek to establish code/services for monitoring earthquakes and tsunamis, tracking whales, measuring the sea state and other Earth System variables.

The data collected by SUBMERSE will be distributed according to FAIR principles through established community-specific distribution channels such as EIDA for seismological data, with exceptions for security-sensitive time periods, and spatial or frequency ranges.

The first data from test sites are now being delivered and will be presented in this presentation. Furthermore, an outlook on the seismological real-time and archive products will be provided.

Monitoring Soil Moisture With Distributed Acoustic Sensing in the Agricultural Setting

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Distributed Acoustic Sensing (DAS) emerges as a non-intrusive and high-resolution method for monitoring crucial agricultural soil properties. The deployment of fiber optic cables in the soil ensures minimal disturbance to the soil environment, enabling the comprehensive monitoring of soil health parameters, including moisture, density (compaction), temperature, and organic content through high-resolution ambient seismic signals. Each of these properties involves dynamic processes from multiple perspectives, posing challenges for extraction from a single observation type. In this study, we conducted a two-day DAS observation spanning approximately 150 meters in a farmland setting with diverse agricultural treatments. Employing ambient noise interferometry, we derived seismic velocity variations in both space and time, revealing a notable correlation between relative seismic velocity and soil moisture. A spectral analysis confirmed that ambient noise power spectral density serves as reliable proxies of precipitation intensity for shallow farmland soil. In addition to DAS, we co-located a Distributed Temperature Sensing (DTS) observation system to record the high-resolution temperature of the near-surface soil, influenced by soil moisture and air temperature diffusion. By combining the precipitation and surface temperature data with independently measured soil temperature, we developed a model representing the physical system of rainfall elastic load, diffusion in the soil, and evaporation. Our findings indicate that rainfall leads to an abrupt increase in soil moisture and a sudden drop in seismic velocity, followed by gradual recovery during the downward diffusion process (drainage). Notably, the substantial rise in seismic velocity, up to 60% at some plots depending on the tilling treatment, is best explained by thermoelasticity. We explore how the degree of tilling affects drainage and soil temperature. DAS exhibits substantial potential for real-time precision agriculture monitoring, offering opportunities to enhance resource management, sustainability, and crop productivity in the face of a changing climate.

Spatio-Temporal Fidelity of DAS Arrays to Compression Seismic Signals: Impacts on Real-Time Source Estimates

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DAS recordings of P waves have traditionally been associated with the shear component of oblique arrivals resulting in axial phase shift along the cables. However, careful examination of the records created by 478 local events in Japan reveals modal perturbations along the cable resulting from normal incidence of both P and S waves. We model this phenomenon as large scale oscillations (typically over a few kilometers) of the cable under localized forces with the cable axial and torsional tensions as restoring agents. Based on our model, spatial and temporal frequencies of the oscillations are determined by cable properties, almost regardless of earthquake magnitude. This is while modal amplitudes are significantly affected by the velocity structure of the deployment site, as well as earthquake radiation pattern on second order. The modal property of these waves has significant implications in both detection and magnitude estimation of earthquakes and as such needs to be considered in hazard assessment and early warning in active subduction zones.

Understanding the Rupture Process of the Mw 7.6 2022 Michoacán Earthquake With Distributed Acoustic Sensing

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Mexico City, the most populated city in the Americas, undergoes significant seismic hazards. Yet, the city is sparsely instrumented compared to other populated and seismically active regions. Therefore, we installed a DAS interrogator in Mexico City in the summer of 2022 to collect one year of data for observational studies in the region. On Sep. 19, 2022, a Mw 7.6 earthquake occurred in Michoacán, approximately 450 km away from the city. The DAS system provides us with a high-quality, ultra-dense, and unique dataset that can be used to study the rupture process of the earthquake, which is essential to refine our understanding of regional fault systems and potential seismic hazards.

We apply a recently developed higher-frequency back-projection method to obtain a novel 3-D earthquake rupturing image and test the limit of DAS for earthquake source characterization. We integrate DAS recordings with data from regional and global seismic stations to investigate the rupture process of the Michoacán earthquake at different spatial scales at a frequency range of 0.2-1 Hz. With preliminary analysis, we successfully identify and locate two subevents in a 3D rupturing space, and we further validate the outcomes with conventional seismometers. These results demonstrate the great potential of enhancing rupture imaging by integrating DAS arrays in earthquake source studies.

Distributed Environmental Sensing Using Trans-Oceanic Subsea Cables

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We present a distributed fiber optic sensing (DFOS) prototype capable of measurements beyond the first repeater of subsea cables. The cable spans approximately 6,400 km and includes more than 80 optical repeaters. Our system is capable of distributed measurements of both phase and polarization of the backscattered signal, including the Rayleigh backscattering from the silica fiber and point reflections from fiber Bragg gratings (FBGs) present within the optical repeaters. Each point along the cable is measured in real-time, with zero dead time and covering a frequency range from mHz to kHz. This measurement spans all degrees of freedom supported by the fiber and therefore completely characterizes its linear response over the measurement bandwidth.

During a 1 month measurement period, all world-wide earthquakes with >6 magnitude were detected. Here we present a detailed analysis of the measured signatures from two earthquakes and ocean swells. The first event is a 6.3 magnitude earthquake with an epicenter in California, while the second event is a 7.1 magnitude event located in Indonesia. The recorded signatures from our about 80 points along the ocean floor are compared with data from the two available seismic stations in the North Atlantic ocean. Our measurement results show good quantitative agreement with the waveforms recorded by the land-based seismic stations. In addition, we show real-time tracking of the seismic waves as they propagate along the cable and use this to determine their relative speed. This technology is a major step towards 3D beamforming and imaging using multiple subsea cables. We also show measured cable movements from the mid-Atlantic ridge, whose origin to date is not fully understood.

Finally, this sensing prototype does not disrupt telecom traffic and uses commercial off-the-shelf components, thereby providing a scalble path to realize distributed fiber optic sensing over the entire subsea network.

Enhancing Seismic Monitoring in Cook Inlet, Alaska: Integration of Distributed Acoustic Sensing with the Existing Seismic Network for Advanced Earthquake Denoising, Detection and Location

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Offshore Distributed Acoustic Sensing (DAS) has emerged as a powerful technology for seismic monitoring, complementing the existing seismic networks in coastal regions. However, the offshore DAS data often combine signals that are new to the eyes of seismologists, including new types of instrumental noise, fiber coupling issues, ocean waves, and microseism that overprint earthquake signals. The overlap of these signals hinders accurate detection and location of earthquakes. In this study, we propose an advanced architecture for earthquake monitoring in Cook Inlet, Alaska, by integrating the offshore DAS with the Alaskan regional seismic network. The proposed architecture incorporates machine-learning-based denoising, phase picking, and event relocation, leveraging an ensemble approach with DAS and broadband observations. A denoising neural network, employing self-supervised learning, is trained on randomly masked real DAS recordings for 2000 earthquakes. The trained denoiser effectively removes DAS signals lacking spatial-temporal coherence. Subsequently, the denoised DAS data enables the detection of lower-magnitude earthquakes and provides significantly more phase picks than the original noisy data, particularly for the smallest events. We then apply the trained denoiser to the M0.6+ earthquakes in the Cook Inlet region. The ensemble-learning approach is applied to pick P and S arrival times on both the denoised DAS and broadband recordings. In the final step, we relocate the detected earthquakes using their P and S phase picks of the integrated DAS and broadband seismic network. We quantify the improvement of adding DAS to a regional network by quantifying uncertainties earthquake source parameters This comprehensive approach results in more efficient and robust earthquake detection and location compared to traditional seismic networks in the offshore region. The proposed architecture holds significant promise for earthquake early warning and hazard mitigation, demonstrating the potential for enhanced seismic monitoring networks in offshore environments.

On DAS Recorded Strain Amplitude

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Distributed Acoustic Sensing (DAS) has become popular for recording seismic waves in recent years. The ability to record waveforms with useful phase information has been demonstrated in numerous studies. Validation of the sensitivity factor with respect to strain is commonly done by application of fiber stretching-devices in laboratory environment. The lack of in-situ calibration with respect to actual rock strain leaves room for unknown amplitude loss caused by imperfect coupling of the cable jacket to the rock and the loss through several layers of coating of the fiber in the cable. We use DAS-recordings together with recordings of the colocated invar-wire strainmeter array at BFO and an STS-2 broad-band seismometer to investigate the coupling of DAS fibers in situ. Two types of optical fiber cables are installed in parallel. One is a conventional telecommunication cable, where fibers are embedded in a gel-type substance to avoid damage potentially caused by straining the cable jacket. The other is a dedicated tight-buffered DAS cable. We compare recordings from a section where the cables are simply unreeled with recordings from a section, where sandbags are densely put on the. We use signals from the Mw 7.7 and 7.6 East Anatolian Fault earthquakes on February 6th 2023. A comparison of signals from all three instruments is possible in the frequency-band between 50 mHz and 0.2 Hz. At lower frequencies the DAS signal-to-noise ratio is insufficient. At higher frequencies the invar-wire strainmeters show a parasitic response to vertical ground motion. We find that the DAS fibers do not pick up the full amplitude of rock-strain. Amplitude loss depends on the type of cable. The tight-buffered and the telecommunication cable pick up about 1/2 and 1/4 of the amplitude, respectively. Surprisingly the application of sandbags has little effect. Both sections show similar discrepancy in amplitude. The signal loss apparently is not due to the imperfect coupling of the cable jacket to the rock, but due to reduced internal coupling of the fiber to the cable.

Evaluation of Passive Source DAS Methods on the Source Physics Experiment (SPE) Phase II

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Distributed Acoustic Sensing (DAS) is an emerging technology capable of recording the acoustic wavefield at unprecedented spatial resolution. However, this new tool requires significant refinements before it becomes operational for explosion monitoring objectives. Recent studies have shown significant development of array processing with DAS data. In this contribution we explore three such array processing methods including DAS strain-rate data versus geophone measured ground motion, beamforming for event parameters, and machine learning based denoising. We first validate the methods on published results and then apply to high SNR data from the Source Physics Experiment Phase II. We further investigate these methods as a function of DAS array design and SNR through the use of synthetic signals and noise.

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Lossy Compression and Reconstruction of Distributed Acoustic Sensing Data Using Deep Learning

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Distributed Acoustic Sensing (DAS) is a new seismic observation method. DAS dramatically expands the ability of dense seismic observation and has been used for ocean observation, sub-surface imaging, volcano monitoring, and earthquake characterization. While the high rate of data benefit research analysis, they are problematic for data transmission and storage and limit the real-time or large-scale application of DAS. Data compression algorithms can accelerate the transmission by transforming the raw data into smaller size , however, at the cost of more computing time and/or data distortion. Current state-of-the-art data compression techniques for DAS involve either a low compression rate (40%) for a lossless compression (Dong et al., 2022) or lossy compressions (Issah and Martin, 2023) that retain the low rank representation of the data.

In this study, we compress and reconstruct an ocean bottom fiber-optic sensing dataset using Deep Learning, particularly Implicit Neural Representation and Shallow Recurrent Decoder. The dataset recorded on two seafloor telecommunication cables in Alaska's Lower Cook Inlet samples ~16k channels at 250 Hz. On the 2.5 Hz decimated dataset, we reach a 8x (12.5%) and 10x (10%) compression ratio while retaining a maximum mean square error of 0.03 and 0.05, respectively. In the reconstruction, ocean surface gravity waves that are dominantly observed in the raw data are effectively reconstructed by both methods and can be further used for physical oceanography. We test the methods on earthquake waveforms and demonstrate feasibility of the compression for seismological use cases. At last, we evaluate these methods by comparing their accuracy, adaptivity, computing expense and generalizability on the near real-time data transmission using our edge computing experiment in Alaska Cook Inlet.

Exploring Urban Distributed Acoustic Sensing Datasets With Scattering Networks

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Distributed Acoustic Sensing (DAS) probes fiber-optic cables with repeated laser pulses to measure the Earth deformation along the cable. The extended spatio-temporal nature of DAS time series provides a vast amount of information about the seismic wavefield and the related processes occurring at the Earth's surface and interior. Urban DAS datasets have been shown to contain various types of natural (e.g., earthquakes) and anthropogenic (e.g., carry blasts, car traffic) signals, but new signals and/or hidden patterns are still likely to be discovered. We mine continuous DAS data in urban areas in

an unsupervised manner using a deep scattering network — a convolutional neural network with convolutional filters restricted to wavelets. Deep scattering networks allow us to directly build an accurate representation of each DAS dataset from which we extract the most relevant information with independent component analysis (ICA) and Uniform Manifold Approximation and Projection (UMAP) algorithms. The ICA representation of the data is then clustered with dendrograms together with UMAP to provide a 2D representation of the data. We use external measurements, such as earthquake catalogs and weather stations to understand the output of the clusters and the UMAP representations. This study shows the potential of unsupervised methods to investigate the extent of the nature of signals contained in terabytes of data recorded by DAS.

Advancing Seismology with Distributed Fiber Optic Sensing [Poster Session]

Poster Session • Friday 3 May

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POSTER 1

Matched-Filter Earthquake Detection Applied to City-Scale DAS Fibre-Optic Systems in Aotearoa New Zealand: What More Can We Detect?

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Matched-filters have been successfully applied to detect earthquakes recorded using Distributed Acoustic Sensing (DAS) systems in multiple settings including to detect geothermal seismicity and aftershocks. This previous work has demonstrated that matched-filters applied to DAS systems can be used to detect additional seismicity missed by standard cataloguing methods applied to standard sensor networks. Similarly, matched-filters and recently developed machine-learning enhanced workflows have been shown to provide enhanced detection performance on seismic recordings made using standard seismometers. Thus far, little work has been done to ameliorate these methods and datasets to provide optimal earthquake detection datasets and workflows.

In this work we test the sensitivity of matched-filters applied to two city-scale DAS arrays in Aotearoa New Zealand to reliably detect small aftershocks from a M 5.9 earthquake above the Hikurangi subduction zone. We also compare the sensitivity of the DAS arrays to multiple standard and state-of-the art earthquake detection methods applied to standard seismometer data. Using this case study, we provide a logical comparison between advanced methods applied to high-quality data and relatively simple matched-filter methods using high-fold data from DAS arrays to evaluate the relative benefits of each approach. We also explore a combined approach using DAS data alongside traditional seismic data to attempt to achieve an optimal detection solution.

POSTER 2

Using AIS Data to Determine the Location of Ocean Bottom Fiber Optic Cables

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Undersea fiber-optic cables form the backbone of global telecommunication networks, facilitating rapid data transmission across continents. However, the correct location of telecom subsea cables is generally inaccurate, if not completely unknown, or even sometimes undisclosed for safety reasons, as fiber optic cables represent a crucial geopolitical asset. Unlike on land, where tap tests with precise GPS data can be performed, subsea cables are not easily and inexpensively accessible. This limits their potential for proper seismic and environmental monitoring of near-coastal regions using Distributed Acoustic Sensing (DAS).

This study presents an approach to enhance the geolocation of undersea fiber-optic cables using Automatic Identification System (AIS) data from ships and large vessels transiting above subsea cables. We use a 4-month dataset from a cable located offshore Florence, OR. The first 50 km of the cable were probed with a Febus A1R interrogator unit using a 20 m channel spacing, a 100 Hz sampling rate, and a 40 m gauge length. During this experiment, we identified 186 vessels of different types and sizes, many crossing the cable multiple times. We precisely determine the location of some channels using the noise generated by ships and correlate it with AIS data. This study allows us to provide additional constraints on the location of fiber-optic cables and DAS channels.

POSTER 3

Near-Source T-Wave Observations in the North Atlantic Using Distributed Acoustic Sensing

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T phases are acoustic waves that propagate in the low velocity zone of the oceanic sound channel that acts as a waveguide, the SOFAR channel. They are generated by earthquakes through the conversion of seismic energy at the solid-liquid interface, but the exact processes involved are still under debate.

Due to their low attenuation and slow propagation velocity, these arrivals are especially useful for the detection and characterisation of small earthquakes in marine basins, as they can improve the location of the event while their waveforms can yield information on source rupture.

In October 2023, a Distributed Acoustic Sensing (DAS) interrogator was installed on the GeoLab dark fibre in the Atlantic, starting at the Praia Formosa CLS, in Madeira Island, Portugal. The instrumentation of this cable is part of a project by ARDITI and the Oceanic Observatory of Madeira where oceanographic data recorded by buoys and autonomous vessels are combined with DAS data to obtain a global view of the underwater environment of Madeira Island in all its physical, chemical and biological aspects, including the characterisation of regional seismicity. This initiative is also linked to the SUBMERSE project, as the Madeira cable is a pilot site to establish continuous DAS monitoring along many more submarine fibre-optic cables.

On October 27th, a near-source (<40 km) M2.9 earthquake was recorded by the DAS interrogator along the entire cable. The epicentre of the earthquake was east of the Desertas Islands, southeast of Madeira. Besides the P and S phases, very clear T phases are also visible. The recorded T waves have strain values larger than those of P and S waves. However, multiple T phases are identifiable, suggesting different points of conversion or even possible reflections.

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POSTER 4

Geolocalization and Preliminary Surface Signals of Cascadia DAS Array, Port Angeles, Washington

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In April 2023 our team conducted a Distributed Acoustic Sensing (DAS) experiment using dark (unlit) fiber from a 4.5 km telecommunication cable in Port Angeles, Washington, situated above the Cascadia Subduction zone. Despite the infrequency of megathrust earthquakes on this margin over the past centuries, it is an area of concern due to the high seismic hazard present. Our project focuses on leveraging onshore DAS for seismicity monitoring and gaining insights into the shallow subsurface of Port Angeles. This presentation outlines the geolocalization methods employed for channel mapping along the array, including performing and processing a tap test to map out the channel locations of the array, which is essential information for future research with this data. Additionally, preliminary findings regarding the ambient seismic noise field recorded by the high-resolution DAS array will be discussed. The continuous sampling along the fiber allows for both high spatial and temporal resolution, making it valuable for monitoring the subsurface along the array. The array has picked up a myriad of cultural and noise signals, including traffic from a nearby highway and bike/foot traffic along an adjacent path. These passive seismic signals will be used for ambient noise tomography to deduce information about properties and structures of sediments below the array, but the appropriate use of ambient noise first requires careful characterization of the noise prior to interferometry and tomography. We will examine the characteristics of these ambient/cultural seismic signals including their spatial and temporal distribution and the variations in their frequency content. This analysis sets the groundwork for utilizing ambient noise tomography to estimate shallow shear wave velocities in the subsurface, crucial for assessing ground motion hazard in the Port Angeles area.

POSTER 5

Fiber Optic Wellbore Installation for Distributed Acoustic Sensing at Los Alamos National Laboratory

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Optical Fiber Distributed Acoustic Sensing can be used in wellbores for a number of applications including to monitor production, monitor wellbore integrity, and for vertical seismic profiling. The optical fiber is robust in harsh environments, allows for a dense network of sensors, and is compact. At Los Alamos National Laboratories (LANL) and the surrounding area, there are wellbores previously installed for geothermal research and groundwater monitoring. While these wellbores provide easy access for research related to seismic monitoring and wellbore integrity monitoring using optical fiber, coupling of the fiber to the wellbore casing presents a challenge since the optical fiber is installed well after installation of the wellbore itself. Here we present efforts to couple, collect, and analyze wellbore optical data recorded on at LANL and the surrounding area.

POSTER 6

Use of Distributed Acoustic Sensing as a Tool for Monitoring Geohazards at Mt. Rainier

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Distributed Acoustic Sensing (DAS) is a new and expanding technology used to monitor seismic events with optical fiber cables as a distributed array of one-dimensional strain sensors. In this work, we investigate the potential of using a dark fiber, an optical fiber deployed for telecommunications purposes, to monitor seismic activity in and around Mt. Rainier, a glaciated, active stratovolcano in the Cascades Volcanic Arc, USA, and is monitored by the Cascades Volcano Observatory (CVO) and the Pacific Northwest Seismic Network (PNSN). Mt. Rainier hosts a broad spectrum of geohazards such as earthquakes, debris flows, landslides, and various cryospheric hazards such as icequakes or avalanches that present a risk to nearby urban areas.

In this study, we use DAS recording on a 48 km long cable, with more than ~ 4,000 channels, buried under the road between Ashford, Washington and Henry M. Jackson Memorial Visitor Center on the flank of Mount Rainier.

We apply template matching to the DAS data, using events in the PNSN earthquake and surface-event catalog to search for events not detected by the permanent monitoring network. We use the USGS catalog to select a big magnitude event and then search for it on DAS data; after that, we process that event as a template to do the continuous search on the data. In addition to the activity at the volcano, our dark fiber experiment recorded a tectonic earthquake swarm in August 2023, located in the Western Rainier Seismic Zone. This more complete earthquake catalog will be used to perform double-difference relocation and tomography to improve our understanding of fault structures within the Western Rainier Seismic Zone. We also perform preliminary analysis to detect and identify other event types, including surface events, volcano tectonic earthquakes, and other volcanic events. Our study presents the groundwork for the use of DAS to monitor volcanoes in near real time.

POSTER 7

Signal Detection With Neural Networks in Dark Fiber Seismic Data

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Distributed Acoustic Sensing (DAS) provides continuous and high-resolution spatial monitoring capabilities along the entire length of the optical fibers where the ground deformation caused by seismic activity is measured in strain or strain rate. Telecom cables, known as dark fibers, offer a spatially dense and cost-effective alternative for seismic data collection in urban areas. We demonstrated recording seismic signals with a telecom cable provided by the Istanbul Metropolitan Municipality along the Sea of Marmara on the Anatolian side of Istanbul from February to mid-March in 2023. The collected data involves various seismic signals, such as teleseismic and local earthquakes, including the East Anatolian earthquakes in February 2023 and their aftershocks, controlled explosions, traffic, and other cultural noise.

This research aims to demonstrate the detection of local seismic activity in and around Istanbul using DAS data. Monitoring local seismicity is essential to better understand the tectonics and seismic activity in a region. However, it is challenging to detect or discriminate small earthquakes where the higher spatial resolution of DAS may be advantageous. To this end, we first visually inspect all earthquakes (local and teleseismic) and compare our observations to data recorded by nearby strong-motion seismometers. Our goal is to generate a training set to detect local events with natural networks, specifically those that are difficult to observe by visual inspection. Since we have a limited data set from Istanbul, which makes the training challenging, we explore generating additional data from nearby strong-motion seismometers to be included in the training set by converting them to DAS units. To test the robustness of our tools, we will also demonstrate them with a larger data set collected in Athens by the ETH Zurich group. We will present our observations in DAS data compared to those recorded by classical seismometers in Istanbul and the initial results of our seismic event detection with neural networks for DAS.

POSTER 8

Modelling Wavefield Complexity for Submarine DAS Data From Santorini (Greece)

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Distributed Acoustic Sensing (DAS) with existing telecommunication cables has contributed significantly to the seismological exploration of difficult-to-access regions such as the ocean bottom. In contrast to the relative simplicity of deployment of a DAS interrogator on dark fibres, the data can be challenging to analyse and interpret, particularly in geophysically complex areas, as the wavefield becomes much more complex. In our study focused on the region around Santorini in the Aegean Sea, we interrogated a 45 km long dark fibre extending from Santorini along the ocean bottom to the neighbouring island of Ios from mid-October to mid-December 2021. This region is of great geophysical interest because of its historical and recent seismic and volcanic activity, especially along the Kolumbo volcanic chain. Alongside the anthropogenic noise on Santorini, we directly observe the time-variable primary and secondary microseisms along the submarine section of the cable, the latter inducing slow-moving Scholte waves. Throughout the experiment, we recorded 1021 seismic events with varying strengths and locations.

To better understand the complex wavefield in the region, we take advantage of the latest developments in DAS wave propagation modelling using the spectral-element solver Salvus. We run simulations with varying levels of complexity, from a simple layered model to the inclusion of topography, bathymetry, and a heterogeneous velocity model. Furthermore, the fully complex model allows us to perform backpropagation with the aim of locating seismic events near the Kolumbo volcanic chain. The simulations with varying complexity and backpropagations for four different earthquakes highlight the complicated wavefield in the region and the challenges of recovering a source location, even when all complexities are taken into account.

POSTER 9

Earthquake Detection of the MiDAS Seismic Monitoring System Containing Downhole Optic-Fiber Distributed Acoustic Sensing and Borehole Seismometers

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Milun fault Drilling and All-inclusive Sensing (MiDAS) project initiated after the destructive 2018 M6.4 Hualien, Taiwan, earthquake. The project successfully drilled through the Milun fault, which was one of the main rupture faults in the Hualien earthquake, in Hole A (700 m deep) on the hanging wall. In addition to this primary hole, a 500-m-deep hole (Hole B) was done on the footwall 700 m away from Hole A. After drilling, the MiDAS group deployed a 7.5-km-length optic-fiber cable perpendicular to the Milun fault, passing through Hole A (from top to bottom), the main fault zone on the surface, and Hole B (from top to bottom) orderly. The downhole triaxial seismometer arrays were installed in both holes. In this study, we search earthquakes from the continuous seismic records by two methods; one is manually picking and another is by the deep-neural-network-based seismic arrival-time picking method, PhaseNet. The study period is from March to May, 2023. We group earthquakes into 5 classifications by the S-P arrival time differences (ts-tp). Class S, A, B, and C demonstrate events with ts-tp ranges < 1s, > 1s & < 2s, > 2s & < 6s, and > 6s, respectively. Class D collects events with unclear P- or S-wave identification. Compared both detected results of human made and from PhaseNet, we recognize that those from PhaseNet have high accuracy (80 ~ 98%) in local events (Class A-C). However, the accuracy drops to 22% for Class S, which includes ultra-close events on the fault. It is possibly due to lack of ultra-close event templates in the PhaseNet model training. Next step, we will improve the PhaseNet model and develop a labor-saving procedure in earthquake detection for the MiDAS seismic monitoring system.

POSTER 10

HD-TMA: A New Fast Template Matching Algorithm Implementation for Linear DAS Array Data

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Distributed Acoustic Sensing (DAS) technology, combined with existing telecom fiber-optic cable, has shown great potential in earthquake monitoring. The template matching algorithm (TMA) shows good detection capabilities but depends on heavy computational costs and diverse template events. We developed a program named HD-TMA, which accelerates computation by 40 times on the CPU platform and 2 times on the GPU platform. For linear DAS array data, we introduced a fast arrival-picking algorithm based on the Hough transform to pick time windows of template waveforms. The HD-TMA algorithm was successfully applied to the 2022 Menyuan Ms6.9 earthquake's aftershock sequence recorded by a DAS array and several optimization strategies were discussed based on this dataset. 1) Using SNR in choosing the location and aperture of the subarray and the time window of the template waveforms. 2) Considering the decrease in template events' marginal utility, we proposed applying a neural network to build a template event library, followed by HD-TMA scanning. Such strategies can effectively reduce computational costs and improve detection

POSTER 11

2-D Shear-Wave Velocity Profile of Shallow Sediments Using Ocean Bottom Distributed Acoustic Sensing and Ambient Noise Probabilistic Inversion

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Ambient noise tomography is a well-established technique that estimates the physical properties (i.e., thickness and shear-wave velocity) of the crust and upper mantle through the inversion of surface-wave dispersion curves. Imaging the shallow crust and sediment layers can be difficult, especially offshore, due to the limited number of ocean bottom seismometers. A more accurate sediment mapping on the continental shelf can help identify potential risks like underwater landslides that could damage telecommunication cables or trigger tsunamis. The recent development of the Distributed Acoustic Sensing (DAS) technology presents an opportunity to achieve higher-resolution imaging of the offshore sub-surface using dense station spacing distributed along a fiber-optic cable. We probed 50 km of a telecommunication fiber deployed offshore Cordova, Southern Alaska, and recorded continuous data for four months in 2022. The sediment cover on the continental shelf is likely to have a significant portion of glacial sediments originating from the Copper River, which is situated a few miles to the south. Although no large earthquake (Mw>7.0) has occurred in the region since the 1964 M9.2 Prince William earthquake, the area remains seismically active and susceptible to underwater landslides. We use the data collected from May 04 to May 15, 2022, to compute cross-correlation functions between station pairs along the fiber. From a frequency-time analysis, we estimate surface-wave phase velocity between groups of station pairs and invert to produce a 2-D shear wave velocity profile. In this work, we propose to use a Bayesian Monte Carlo inversion framework to build our final velocity profile. The inverted shallow velocity profile provides new constraints on the nature of the sediments in this seismically active region. We will discuss the implications in terms of sediment transport and mixing but also the potential of underwater landslides associated with these sediments.

POSTER 12

Towards a Metadata Standard for Distributed Acoustic Sensing (DAS) Data Collection

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With increasing use of Distributed Acoustic Sensing (DAS) technology, there is a need to implement a metadata standard specifically for DAS to facilitate the integration of DAS measurements across experiments and increase reusability. We propose a transfer metadata standard which may be adapted for storage. The schema describes the five key components of a DAS experiment: (1) interrogator, (2) data acquisition, (3) channels, (4) cable, and (5) fiber. The proposed metadata schema is hierarchical based, with a parent 'overview' metadata block describing the experiment, and child branches describing the instrumentation (i.e., interrogator and acquisition parameters) and the fiber sensor (i.e., cable installation and fiber properties). The metadata schema is designed to be independent of the time-series data so that corrections and updates can be applied to the metadata, without having to manipulate large volumes of time-series data. Unique identifiers are used as pointers that map different components within the metadata schema; they also provide a natural basis to the naming convention (i.e., source identifier) of the time-series data, where the time series data is uniquely defined by the metadata standard. Where possible, the identifiers are consistent in naming conventions with ProDML. We use GitHub to implement version control for the metadata standard, to enable community collaboration and facilitate sustainable development of the metadata standard. Examples are shown for common deployment scenarios. The path forward including technical issues and strategic path will be discussed.

POSTER 13

Exploring the Potential for Joint Monitoring of Tectonic Tremor Using Dark Fiber and Seismometers

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Tectonic tremor has been found among various plate boundary settings using observations from permanent seismic networks and/or temporary dense array deployments. Studying the behavior of tremor is important for understanding the physics behind a wide spectrum of fault slip behaviors, and for constraining the spatial extent and state of stress of a plate boundary's seismogenic zone. Experiments in recent years have demonstrated that dark (unlit) fiber from telecommunication cables can be used for distributed acoustic sensing (DAS) to enhance our ability to monitor regular earthquakes. This new tool is especially valuable where seismometers are sparse, absent, or challenging to deploy and maintain long term. Fortunately, telecommunication fiber is spatially extensive across the Earth, especially onshore in (and between) urban environments that often reside near major active faults.

Here we extend the application of onshore DAS to the study of slow earthquakes as represented by non-volcanic tremor, to explore its potential for joint monitoring with seismometers. In April 2023 we conducted a small-aperture (4.5 km) DAS array experiment using dark fiber during an episodic tremor and slip event in Northern Cascadia (Port Angeles, WA). Using the PNSN tremor catalog for reference, we find that the array detected tremor signals generated down-dip of the seismogenic zone (>35 km depth), and validate these observations with the timing and shape of similar signals from nearby seismometers. Next, to evaluate the efficacy of DAS for tremor location, we perform a comparative analysis of epicenter estimates derived from traditional methods using seismometer only data and from seismometer plus DAS data. Given the large number of sampling points when using just one cable of fiber, the hope is that DAS has the ability to leverage seismometers with additional spatial resolution and constraints during heightened tremor activity. At a broader scope, we aim to demonstrate how these two instruments may be used harmoniously for enhanced monitoring of regular and slow earthquakes, and general seismological investigations.

POSTER 14

A Metadata and Time-Series DAS Workflow Using Cloud Computing

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The high spatial and temporal resolution that DAS provides has the potential to transform how geophysical network monitoring is performed. DAS provides strain measurements at a spatial resolution of meters along cables that can be tens of kilometers in length at kilohertz sample rates, surpassing the resolution provided by setups of traditional seismic instrumentation. The sensitivity of DAS in the 10-1 to 100 Hz bandwidth combined with its operational capability on land and on the seafloor means that it not only provides a mechanism to track the change in frequency and amplitude of seismic signals over distance, but it can supplement recordings from conventional observatory-quality sensors in regions such as the ocean floor where station density is extremely sparse. However, two issues impede the systematic study of DAS to quantify its benefit: (1) the vast volumes of data generated by the system makes it difficult to telemeter and, once at a datacenter, analyze efficiently and (2) the lack of consistently compiled metadata inhibits the comparison of correlated signals across geographically separated fibers. Both issues need to be addressed to provide calibrated and quality-controlled DAS data sets suitable for downstream ingestion into event detection techniques such as template matching and machine learning algorithms. We show our progress with respect to the second research question (i.e., metadata standardization, Lai et al., 2023) across the 32 data sets collected for the 2023 Global DAS project and show how this enables comparison of DAS data across networks. We build off pioneering DAS time-series data workflows (Ni et al., 2023) and discuss how cloud computing technologies can be leveraged for DAS data storage and seismic event monitoring.

POSTER 15

Exploring Source and Structure Sensitivity Kernels of DAS Ambient Noise Correlations

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Distributed Acoustic Sensing (DAS) technology has transformed seismic monitoring and imaging by converting standard optical fiber cables into dense arrays of virtual seismic sensors, offering continuous, well-distributed, and high-resolution seismic records. This study investigates the sensitivity of DAS ambient noise cross-correlation for several fiber configurations and compares them with standard seismometer ambient noise cross-correlations.

DAS directional response is sensitive to the angle of incidence of seismic energy with respect to the orientation of the fiber. Consequently, the DAS ambient noise cross-correlation spatial sensitivity is influenced by factors such as the geometry of the fiber-optic cable and the location of seismic sources of noise. To improve our understanding of DAS passive seismic interferometry responses to noise source distributions and cable setups, we model their source and structure sensitivity kernels using full waveform modeling and an adjoint approach. This exploration sheds light on the challenges and potential biases associated with employing DAS in passive seismic interferometry, underscoring the importance of understanding DAS responses to diverse noise sources.

By studying these aspects, we can effectively optimize DAS-based experimental setups and bolster the reliability of passive seismic imaging applications. This work lays the foundation for the full waveform inversion of ambient noise cross-correlation of DAS data.

POSTER 16

Distributed Fiber-Optic Magnetic Sensing for Subsurface Imaging and Monitoring

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Distributed fiber-optic sensing (DFOS) technology offers a cost-effective, versatile solution for geophysical applications, with advantages such as extended sensing range, high spatial resolution, durability, and flexibility. While electromagnetic (EM) sensing holds promise for improving fluid saturation mapping to complement seismic imaging and monitoring, distributed EM sensing systems are still in early development stages. This study introduces an optical-fiber-based distributed magnetic sensing (DMS) system, simultaneously recording acoustic and magnetic wavefields. The DMS system uses a standard distributed acoustic sensing (DAS) interrogator, probing a specialized single-mode fiber optic cable embedded with magnetostrictive wires. These wires, responding to EM fields, induce strain in the fiber core in addition to mechanical strains detected by standard single mode fiber. By measuring backscattered light, the strain-induced phase variation between two sensing fiber segments is detected. In validation experiments, prototype DMS fibers, with and without fiber Bragg gratings (FBGs), exhibited expected spectral responses to controlled EM and acoustic sources, consistent with theoretical predictions. The DMS system achieved sub-millitesla (mT) magnetic field intensity resolution over a bandwidth of 10-2000 Hz. Cross-well EM time-lapse simulation and inversion of CO_2 injection demonstrated the proposed DMS system's potential sensitivity, highlighting its potential to augment seismic monitoring in realistic scenarios. Preliminary results showcase valuable insights into this multi-physics optic sensing system, indicating its potential for monitoring subsurface fluid changes. These findings set the stage for further research and development of an integrated DAS and DMS system, enabling more comprehensive and cost-effective geophysical applications.

Anisotropy Across Scales

Oral Session • Friday 3 May • 8:00 AM Pacific

Conveners: Frederik Link, Yale University (frederik.link@yale.edu); Eric Loeberich, Yale University (eric.loeberich@yale.edu); Walid B. Mansour, Washington University in St. Louis (walid@wustl.edu)

A Seismic View of the Stress Field

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The stress field in the Earth's crust, often represented as the orientation of the maximum horizontal compressive stress (S_{Hmax}), is an important parameter for a wide variety of investigations in solid-earth geophysics. The orientations and magnitudes of the principal stresses determine faulting types and the orientation of new fractures, are related to anisotropy in elasticity and permeability, and can affect wave propagation. Our understanding of the stress field in the Earth's crust is built mostly upon earthquake source characteristics, borehole-based measurements, and modeling. Observations are sparse and unevenly distributed, and the level of heterogeneity is not well known. Compliant features in rocks, such as grain boundaries and small fractures are very sensitive to the stress field and changes in the stress field. Due to an asymmetry in the way that rocks relax during extension and compression, we observe stress-induced anisotropy in the behavior of compliant features in rocks due to the horizontally anisotropic stress field in the Earth. Thus, we can infer the orientation of the horizontal principal stresses using differential travel time measurements of differential Green Functions taken at different azimuths. We applied this method to Rock Valley at the Nevada National Security Site for building geophysical models associated with discriminating underground explosions from earthquakes.

Seismic Anisotropy and Stress-Field Variations Along the Dead Sea Fault Zone in Northern Israel

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Geological observations based mainly on stress (strain)-indicating meso-scale markers suggest that the local maximum horizontal compressive stress (S_{Hmax}) direction along the Dead Sea Fault (DSF) system in northern Israel changes considerably over short distances from a ~N-S, fault-parallel orientation in the south to an ~E-W, fault-perpendicular orientation in the north. However, the association of the meso-scale markers to the present-day stress field is not well constrained as many of them could have formed at any stage during the DSF evolution. In this study, we use a large dataset of Shear-Wave Splitting (SWS) measurements, taken from local DSF-related earthquakes, to characterize the azimuthal seismic anisotropy of the upper-crust at this critical turning point of the DSF system, near the Lebanese Restraining Bend. The SWS directions commonly align parallel to the inferred local S_{Hmax} as revealed by the meso-scale markers, supporting their association with the current stress field. In several stations, SWS fast directions indicate azimuthal anisotropy at high angles to the trace of the master fault, indicating that stress-induced anisotropy represents a more plausible mechanism for SWS than structure-controlled anisotropy. The SWS measurements suggest that a northward counterclockwise rotation of the crustal S_{Hmax} is present along this segment of the DSF, supporting previous notation on the transition from divergent to convergent strike-slip faulting in this area.

Imaging Los Angeles Basin via Directional Dependent Rayleigh Wave Ellipticity Using Data From the Lab2022 Nodal Array

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We deployed a temporary nodal array in the Los Angeles basin, comprising ~300 nodal geophone seismometers, composed of two dense lines (inter-station spacing of ~0.6 km) and a 2D distributed/shotgun array (spacing of ~2 km). We compute multi-component ambient-noise cross-correlations between all stations available in the area, including both regional broadband and nodal stations. We observe clear fundamental mode Rayleigh and Love waves in the period band of 1-10s, where higher mode Rayleigh waves are also observed for periods shorter than ~4s. We use array processing techniques to measure both surface wave phase velocity and Rayleigh wave ellipticity, or H/V (Horizontal-to-Vertical) amplitude ratios. The measured Rayleigh wave ellipticity clearly depicts the basin's lateral boundaries. Moreover, at each station, we examine the azimuthal dependency of the ellipticity measurements. We show that strong Rayleigh wave H/V azimuthal anisotropy is evident within the basin, which is potentially related to the stress-induced crack alignment. We compare our findings with the SCEC Community Velocity Model (CVM) and regional stress field model and discuss how the models can be further improved. As an accurate basin model is important to earthquake ground motion prediction, our newly acquired results demonstrate the utility of dense nodal arrays for shallow imaging in a densely populated urban setting for seismic hazard assessment.

Anisotropy in Flowing Firn and Ice: Insights from Ambient Noise and Active Source Studies in Antarctica

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Antarctic firn, which covers 99% of the Antarctic ice sheet, promotes a variety of exotic seismic behaviors owing to its porosity, extreme shallow velocity and density gradients, and highly dynamic and evolving nature. Ambient noise excitation of firn through wind forcing creates patterns of spectral amplifications that are sensitive to both static shallow structure and surface environmental forcing effects. Spectral peaks demonstrate pervasive offsets across seismic components, pointing to a sensitivity to azimuthal anisotropy as well. Here, we show that spectral peak offsets can be interpreted in the context of flowing ice and snow and can be systematically used to determine frequency-dependent anisotropy. We show example results from Ross Ice Shelf seismic arrays and preliminary nodal networks from the TIME project, validated by direct comparison to active source experiments. Flowing firn and ice demonstrate multiple kinds of anisotropy that vary with depth, with brittle fracture accommodation of stress dominating in solid ice and plastic foam-like extension in shallow firn. We also present preliminary results from recent large-N nodal arrays deployed in the TIME project during the 2022 and 2023 field seasons.

Broadband Rayleigh and Love Wave Phase Velocity Maps Based on Double-Beamforming of Ambient Noise Cross-Correlations

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Ambient noise tomography has become a popular method in the past two decades to image the crust and uppermost mantle structure. To date, broadband Rayleigh wave signals can be obtained from ambient noise, which can be utilized to study the earth's interior structure from the surface down to ~200-300 km depths. However, it is hard to extract intermediate- and long-period (>50 s) Love wave signals from ambient noise using conventional data processing techniques for ambient noise. Array-based data processing techniques can enhance weak signals. In this study, we adopt an algorithm of the double-beamforming method to extract broadband Love wave signals from ambient noise. We validate the accuracy of the dispersion curves measured from our method by comparing them to those measured from the conventional method. Then, we use a finite frequency ambient noise tomography method to construct broadband Love wave phase velocity maps across the contiguous USA. These phase velocity maps are consistent with those obtained from conventional methods at short periods (<40 s). Finally, we analyze the resolution of our double-beamforming method based on checkerboard tests and find that the resolution of phase velocity maps based on our method is close to the aperture of the subarrays used in our double-beamforming method.

Flow in the Mantle Beneath Eritrea and Yemen: Evidence From Seismic Anisotropy

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To investigate the role of magmatism and mantle flow in continental breakup, we analyse mantle anisotropy beneath Eritrea and Yemen, regions on either side of the Red Sea Rift ;near the Afar Triple Junction. We use teleseismic data recorded on temporary regional arrays to calculate SKS shear-wave splitting parameters at six seismic stations in Eritrea and 71 seismic stations in Yemen. Our results show moderately high delay times (1.18 -- 1.85 s) and fast polarisation directions oriented NE-SW to NNE-SSW in Eritrea. We observe little backazimuthal variation in the splitting parameters, providing confidence that there is a single layer of anisotropy beneath the stations. This single layer of anisotropy is attributed to asthenospheric flow oriented NE-SW, channelled from the Main Ethiopian Rift through Afar to the Red Sea. We interpret this flow as originating from the superplume beneath Africa. Our results support the hypothesis that the latter stages of continental breakup in Eritrea involve magma-assisted rifting.

Modeling Layered Anisotropy in the Alaska-Aleutians Subduction Zone

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A major limitation of shear wave splitting is its path-integrated nature. The most commonly used core-refracted teleseismic phases traverse thousands of kilometers from the core-mantle boundary to the receiver, complicating interpretation of the signal. Contributions from multiple layers of anisotropy can be determined using forward modeling. Yet these forward models often do not consider more than two layers of anisotropy, the effects of dipping layers, or the statistical robustness of the results.

We present multilayer shear wave splitting modeling along the Alaska-Aleutians Subduction Zone (AASZ). With an updated splitting catalog, we are able to identify six regions with sufficient density of splits to forward model. We model these splits with two- and three-layer cases, including with tectonically derived middle dipping layers. Based on our modeling and previous anisotropic studies using shear wave splitting and tomography, we ultimately choose a three layer model with a dipping middle layer with the axis of anisotropy oriented parallel to paleospreading. At five of the six regions, we identify a suite of models that is statistically better than a single-layer case. These models oftentimes differ from the "best-fitting" model, implying that only considering the model with the lowest misfit will provide an inaccurate representation of layered anisotropy. We also argue that the inclusion of tectonically-derived fabrics in these models is an important step, especially in regions such as subduction zones where these fabrics are well constrained.

Depth-Dependent Seismic Azimuthal Anisotropy Beneath the Aleutian Subduction Zone and the Juan De Fuca-Gorda Plates

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Benefiting from the deployment of ocean-bottom seismometer arrays in the Aleutian subduction zone (Alaska Amphibious Community Seismic Experiment (AACSE)) and the Juan de Fuca-Gorda plates (Cascadia Initiative (CI)), researchers have constructed high-resolution surface wave dispersion databases (e.g., Zhang, et al., 2021; Liu et al., 2022). Based on the Rayleigh wave phase speed azimuthal anisotropy databases from these two regions, we construct depth-dependent azimuthal anisotropy models for both the crust and uppermost mantle beneath the Aleutian subduction zone and the Juan de Fuca-Gorda plates.

These models of depth-dependent seismic anisotropy reveal distinct tectonic features of the subduction zone forearc and the young oceanic plate. In the forearc region of the Aleutian subduction zone, we observe a correlation between the along-strike variation in fast directions above the slab and the spatial changes in the orientation of local faults. Deeper within the subducted slab, we observe a trench-perpendicular pattern of anisotropy fast directions, suggesting the existence of fossil anisotropy. In contrast, on the Juan de Fuca-Gorda plates, we find that paleo-spreading directions may account for the anisotropy fast directions in most of the study region. Additionally, the dominant fast directions in the asthenosphere appear to be influenced by mantle flow, which is partially reflected in the absolute plate motion directions.

Exploring Mantle Dynamics of the Cascadia Subduction System Through Anisotropic Tomography With Transdimensional Inference Methods

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The Cascadia subduction system is an ideal location to investigate the nature of mantle flow and associated driving forces at a convergent margin owing to the dense network of on- and off-shore seismic instrumentation. While numerous shear wave splitting and tomography studies have been performed with these data, they have produced conflicting views of mantle dynamics collectively referred to as the Cascadia Paradox. On the overriding plate, splitting observations are consistent with large-scale 3D toroidal flow while off-shore splitting patterns are more easily explained by 2D plate-driven flow. Either geometry is difficult to reconcile with seismic tomographic models that image a fragmented Juan de Fuca slab descending beneath the Western USA. However, these observations offer only an incomplete image of Cascadia mantle structure. Shear wave splitting provides a depth integrated view of anisotropic fabrics making inferences regarding the 3D nature of mantle deformation difficult. Prior high-resolution body wave tomography typically neglects anisotropic effects which can in turn yield significant isotropic imaging artefacts that complicate model interpretation. To overcome these limitations, we invert P-wave delay times for a 3D hexagonally anisotropic model with arbitrarily oriented symmetry axes using the reversible jump Markov chain Monte Carlo algorithm. This stochastic imaging approach is particularly well-suited to the highly non-linear and under-determined nature of the anisotropic seismic tomography problem. The resulting ensemble of solutions allows us to rigorously assess model parameter uncertainties and trade-off between isotropic and anisotropic heterogeneity. We investigate whether the fragmented nature of the subducted Juan de Fuca slab is a well-resolved feature and to what extent its geometry trades off with anisotropic parameters. In light of our new 3D anisotropic model, we re-evaluate the Cascadia Paradox and attempt to reconcile disparate views of Western USA mantle dynamics.

Segregated Melts Below the 660 in the Central Pacific: Implications on Water Transport in Mantle Upwellings

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Global water cycle has been of great interest to the community in the past several decades, and the majority of seismic observations, along with experimental studies, appears to support the transport of water down to the deep Earth through mantle downwelling near subducting slabs. In contrast, there is limited seismic observation in facilitating the argument for or against the transport of water from the deep Earth back to the upper mantle. As a consequence, the key mechanism(s) or/and mineral(s) responsible for potential water transport during mantle upwelling remain enigmatic.

In the context of receiver function technique, here we present a novel observation of P660sP and PS660P phases, which involve P-to-S conversion at the 660 and arrive as postcursors of surface reflected PP waves. Specifically, we present robust detection of PP postcursors, P660sP and PS660P, in teleseismic receiver function stacks that sample the 660 beneath the central Pacific near Hawaii. Interestingly, their amplitude systematics against the epicentral distance are inconsistent with the predictions from isotropic media. Since the receiver function stacks in different distance ranges effectively sample the same proximity and such unique amplitude systematics is unlikely caused by heterogeneous sampling and lateral variation of the structure.

We search for an effective VTI (vertically transversely isotropic, or radially anisotropic) layer either below or above the 660-km discontinuity through a Markov Chain Monte Carlo method and validate the model against other observations of P660s, SS precursors, and ScS multiples in neighbouring regions. We find that the properties of such anisotropic layer can only be reconciled with a tilted segregated melt layer beneath the 660, presumably due to strong shear deformation induced by the mantle upwellings against the 660. We propose that such deep melts are likely hydrous melts induced by the breakdown of hydrous aluminous poststishovite, carried by hot mantle plume, into the less-soluble stishovite in the uppermost lower mantle.

Anisotropy Across Scales [Poster Session]

Poster Session • Friday 3 May

Conveners: Frederik Link, Yale University (frederik.link@yale.edu); Eric Loeberich, Yale University (eric.loeberich@yale.edu); Walid B. Mansour, Washington University in St. Louis (walid@wustl.edu)

POSTER 46

Analysis of Anisotropic Characteristics in the Valley of Mexico

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We obtained preliminary results of an anisotropic seismic study based on the Shear Wave Splitting parameters from microearthquakes that occurred in and around the Valley of Mexico (VM), recorded by the Valley of Mexico Seismic Network from June 1996 until July 2023. These analyses focused on determining the effects of both local and regional tectonic stresses and deformation regimes from the behavior of common anisotropic alignments (e.g., faults, fractures, or cracks). In most cases, fast polarizations follow the orientation of already known local fault systems with preferential orientations of NE-SW, NNE-SSW, and E-W, along with other NW-SE fast polarizations that could show particular cases of unknown alignments in certain areas. Temporal variations of anisotropy could show deformations in the upper crust for specific regions due to changes in the tectonic environment and possible variations of pore-fluid pressure. Observations of splitting delays presented range mainly between 0.015 s to 0.07 s in most stations, with some individual values overpassing these values with important values of percentage of anisotropy, which can be considered systems bordering on critical fracturing systems. The areas with high values of anisotropy percentage (> 4.0%) allow for the characterization of the main fracture routes in the Valle of Mexico, which could be evidence of routes of internal deformation and important zones of ground motions.

POSTER 47

S Wave Velocity and Azimuthal Anisotropy From Ambient Noise Data in the Sanjiang Lateral Collision Zone of SE Tibetan Plateau

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The Sanjiang lateral collision zone in the SE margin of the Tibetan plateau is a crucial area for the study of the collision between the Paleotethys orogenic belt and the oblique subduction of the Neotethys. In this study, we used data from three temporary seismic arrays and regional permanent stations to obtain shear wave velocity and azimuthal anisotropy for depths of 3 km to 50 km. Our results suggest that geometry of the low velocity zone along the Lijiang-Xiaojinhe fault (LXF), the fast velocity directions (FD) parallel to the LXF, and the nearly E-W oriented FDs in the Panzhihua region with high-velocity may indicate that the high-velocity blocks obstruct the southeastward migration of the Tibetan Plateau materials. The FDs at the northwestern end of the Red River fault (RRF) exhibit obvious segmented characteristics. This anisotropic pattern may reflect both the decoupling deformation of the upper and lower crust in the north and the coupling deformation in the south, as well as the strong influence of the RRF on anisotropy. The clockwise rotation of the crustal anisotropy in the western part of the study area may suggest that the deformation is related to the complicated geological tectonic and extensional cracks. The microcracks associated with regional compression may be responsible for the N-S trending crustal anisotropy in the east. In addition, the complex anisotropy in the LXF and RRF also highlights the important role of these faults in shaping crustal deformation [supported by NSFC Projects 42330311 & 41730212, National Key R&D Project of China 2017YFC1500304].

POSTER 48

Exploration of Anisotropy from Crystal to Whole-Earth Scales

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Evidence of seismic anisotropy is widespread within the Earth, including individual crystals, laboratory rock samples, borehole data, active-source seismic data, and global seismic data. The anisotropy of a material describes how wave speeds vary as a function of direction, and it is characterized by density and a 21-parameter symmetric 6 x 6 matrix that maps strain to stress. The space of 21-parameter elastic maps is vast and poses challenges for understanding and for practical applications based on laboratory or field data. Most seismologists assume a high-symmetry (low-parameter) version of Earth, either in the form of isotropy (2 parameters), vertical transverse isotropy (radial anisotropy: 5 parameters), or horizontal transverse isotropy (azimuthal anisotropy: 6 parameters). We offer a general approach to explore the space of elastic maps by starting with any given elastic map T having any type of symmetry, represented by Sigma: trivial, monoclinic, orthorhombic, tetragonal, transverse isotropic, isotropic, cubic, and trigonal. Using a combined minimization and projection procedure, we calculate the closest-Sigma maps to T, which results in 8 maps that can be visualized by a lattice of spheres representing the maps. The pathway from T to its closest-isotropic map can be obtained either by discretizing the direct path or by traversing a sequence of lattice nodes, such as trivial to monoclinic to orthorhombic to tetragonal to transverse isotropic to isotropic. We apply this approach to 21-parameter elastic maps derived from laboratory measurements of minerals, including dependencies on pressure and temperature. We also re-examine a global model of the D” region represented by 21-parameter elastic maps derived from geochemistry and rheology principles. The two primary advantages of this approach are 1) to provide visualization of elastic maps along specific pathways and 2) to offer distinct options for reducing the complexity of a given elastic map by obtaining a map that is closer to isotropic.

POSTER 49

3D Shear Wave Velocity and Azimuthal Anisotropy Model for the Crust and Upper Mantle in Alaska Extracted by the Joint Inversion of Wave Gradiometry Method and Ambient Noise Tomography Method

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The Wave Gradiometry Method(WGM) has emerged as a powerful multipurpose tool to extract strain and rotation tensor, identify phases, and most importantly to image the earth structure. The WGM measures the spatial gradients of the wavefield within a subarray to extract 4 major attributes: phase velocity, wave directionality, geometrical spreading and radiation pattern. These attributes can be further used to extract 3D shear wave velocity and 3D azimuthal anisotropy. The WGM method is combined with the ambient noise Tomography (ANT) to the USARRAY in Alaska to obtain a 3D shear wave velocity structure and azimuthal anisotropic model. Our results reveal complex anisotropic patterns related to subduction structures. The fast directions in the Aleutian fore-arc region show a depth-dependant pattern associated with overriding lithospheric plate, fore-arc mantle wedge, subducting plate, and sub-slab mantle in the fore-arc region, respectively.We also notice that there are different fast directions in the Pacific Plate and the Yakutat Plate, implying different sources of anisotropy for each. An annular anisotropic pattern is present behind the arc at the northeastern edge of the subducting plate, which could be induced by the toroidal asthenospheric flow at the plate margin. Furthermore, our results provide a new evidence for the existence of the subducting plate beneath the Wrangell Volcanic Field.

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POSTER 50

Imaging Lower Crustal Flow Using Harmonic Decomposition of Receiver Functions Beneath a Dense Seismic Profile in Eastern Massachusetts

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Ganderia and the Southeastern New England Avalon terrane are both terranes that rifted from Gondwana and accreted to North America in the early to mid-Paleozoic. Accretion of the Avalon terrane was accompanied by plutonism, deformation, and metamorphism including partial melting within the Nashoba terrane, the trailing edge of Ganderia, and may be interpreted as indicators for mid- to lower-crustal channel flow. Channel flow describes the flow of weak, partially molten material between more competent crust as a result of pressure gradients in the mid- to lower crustal levels. Such flow should typically result in seismic anisotropy due to the crystallographic preferred orientations of minerals and shape preferred orientations at various scales. Here, we present a new method designed to analyze the crustal anisotropic structure beneath the Nashoba terrane and provide insight into its capabilities in a first application to permanent stations in the area and currently collected data.

To investigate the hypothesis of crustal flow during the orogenic history of Southeastern New England, we deployed a dense profile of 6 broadband seismic stations crossing the Nashoba terrane. We analyze the harmonic variation of amplitudes in teleseismic P-Receiver Functions (RFs) to identify interfaces of isotropic and anisotropic contrasts within the crust. In the case of particularly prominent anisotropic features that have significantly larger amplitudes than other signals, it is feasible to derive quantitative constraints on the strength and orientation of the anisotropy. However, with growing complexity, a classical forward modelling or grid search approach becomes unfeasible.

These difficulties can be mitigated by applying Bayesian inversion, which infers values of model parameters from a probabilistic perspective. We use a Bayesian framework to invert for the anisotropic model that best fits the observed constant and harmonic terms. Applying a Bayesian inversion to the harmonically decomposed RFs has the potential to infer the anisotropic seismic model more faithfully, without attempting to fit unrelated signals and artifacts.

POSTER 51

Shear Wave Splitting Characteristics of Aligned Partial Melt Configurations in a Subduction Zone Back-Arc Setting

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Patterns of XKS shear-wave splitting (SWS), which depict the spatial distribution of fast orientation, ϕ, and delay time, δt, are commonly interpreted in terms of upper mantle deformation that causes lattice-preferred orientation (LPO) of anisotropic minerals such as olivine. However, shape-preferred orientation (SPO) of elastically distinct materials may influence SWS observations as well. Building on previous work (e.g., Hammond and Kendall, 2016), we have carried out global wavefield simulations using AxiSEM3D to understand the effects of vertically aligned melt discs (an endmember geometry) on anisotropy observations. We confirm earlier findings that the amount of splitting depends on aspect ratio, melt fraction, and thickness of the inclusion, and indicate the potential of this configuration to crucially influence the strength of observed SWS measurements in a setting where partial melt is present. We explore whether melt SPO along with LPO of olivine might be able to explain the enigmatic occurrence of exceptionally high δt in the High Lava Plains in the Cascadia subduction zone backarc. Here, we expand our modeling efforts to examine splitting due to the presence of dike-like partial melt inclusions, investigating spatial changes in the backazimuthal variation of SWS parameters. We carry out more advanced LPO/SPO models that e.g., invoke dehydration-related olivine fabric transitions in the matrix surrounding the partial melt, which we plan to integrate into generic subduction zone anisotropy models, including those whose geometry captures that of the Cascadia subduction zone.

POSTER 52

A Reformulation of the Browaeys and Chevrot Decomposition of Elastic Maps

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An elastic map T associates stress with strain in some material. A symmetry of T is a rotation of the material that leaves T unchanged, and the symmetry group of T consists of all such rotations. The symmetry class of T describes the symmetry group but without the orientation information. With an eye toward geophysical applications, Browaeys and Chevrot (2004) developed a theory which, for any elastic map T and for each of six symmetry classes Σ, computes the "Σ-percentage" of T. The theory also finds a "hexagonal approximation" — an approximation to T whose symmetry class is at least transverse isotropic. We reexamine their theory and recommend that the Σ-percentages be abandoned. We also recommend that the hexagonal approximations to T be replaced with the closest transverse isotropic maps to T.

POSTER 53

Refining Splitting Intensity Measurements of Shear Wave Splitting for Multi-Layer Anisotropy

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The presence of seismic anisotropy within the Earth's upper mantle is well-known and observed. Methods for measuring azimuthal anisotropy through shear wave splitting (Silver & Chan 1991, Vinnik et al. 1989) are proven to be effective, assuming a single layer of anisotropy with horizontal symmetry. However, these methods become less reliable when applied to regions of the Earth with more than one anisotropic layer. Results from these methods in the southwest Pacific imply non-orthogonal polarization directions, indicative of multi-layer anisotropy. The mentioned methodologies can produce multi-layer anisotropy measurements, but the resolution is highly dependent on azimuthal coverage and seismic data quality. Splitting Intensity (SI) is a robust method to measure azimuthal anisotropy from lower-quality data (Chevrot 2000), but it is mainly applied to single layer anisotropy.

Based on previously published theoretical expressions (Romanowicz & Yuan 2011), SI can be calculated from multiple layers of anisotropy. The focus of this study is to develop a robust measurement process for shear wave splitting in complex anisotropic media, incorporating the multi-layer expression of SI to solve for station-average anisotropic measurements. A double grid search method is applied to obtain splitting parameters from seismic data. Preliminary results of SI from stations inferred to have multi-layer anisotropy correlate with results presented with the theoretical expressions. Further development is required to refine the SI results obtained from this continually improving method. Results from this finer-constrained measurement process will be contributed as constraints for azimuthal anisotropy full waveform tomography of the southwest Pacific upper mantle and transition zone.

Applications and Discoveries in Cryoseismology Across Spatial and Temporal Scales

Oral Session • Thursday 2 May • 4:30 PM Pacific

Conveners: Rick Aster, Colorado State University (rick.aster@colostate.edu); John Cassidy, Natural Resources Canada, Geological Survey of Canada (john.cassidy@nrcan-rncan.gc.ca); Jan Dettmer, University of Calgary (jan.dettmer@ucalgary.ca); Jeremy M. Gosselin, University of Calgary (jeremy.gosselin@ucalgary.ca); Celeste Labedz, University of Calgary (celeste.labedz@ucalgary.ca); John-Morgan Manos, University of Washington (jmanos@uw.edu); Elisa McGhee, Colorado State University (elisa.mcghee@colostate.

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Integrated Geophysical and Temperature Sensing Techniques Towards Scalable Monitoring of Permafrost Variability in Utqiaġvik, AK

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Climate change is causing an increase in permafrost thaw, affecting both anthropogenically disturbed areas adjacent to infrastructure and undisturbed tundra regions. In this research, we use multiple geophysical methods—active and passive multichannel analysis of surface waves (MASW), electrical resistivity tomography (ERT), and ground temperature sensing—to study heterogeneity in permafrost's geophysical characteristics in Utqiaġvik, Alaska. To scale permafrost monitoring spatially and temporally, we deployed 2 km of distributed acoustic sensing (DAS) and distributed temperature sensing (DTS) cables that continually record passive seismic and temperature data for a three-year duration. MASW results from the active-source survey reveal a low-high-low shear wave velocities (*Vs*) pattern in most locations. A notable inverse correlation is observed between in-situ *Vs* and ground temperature. The *Vs* profiles and electrical resistivity profiles reveal cryostructures such as cryopeg and ice-rich zones in the permafrost layer. Corroboration of these geophysical observations with permafrost core samples' stratigraphy and salinity measurements further validates these findings. This combination of geophysical and temperature sensing methods, along with permafrost core sampling, confirms a robust approach to assessing permafrost's spatial variability in coastal environments. Continuous imaging of permafrost seismic structure through ambient noise DAS tomography, utilizing active-source survey *Vs* profiles as baseline models, may provide benchmarks for the rate of change in permafrost along the Arctic Ocean coast, thereby informing climate modeling efforts. Further, our results also indicate that civil infrastructure systems such as gravel roads and pile foundations affect permafrost by thickening the active layer, lowering the *Vs*, and reducing heterogeneity. We show how the resulting *Vs* profiles can be used to estimate critical parameters for designing buildings in permafrost regions and maintaining existing infrastructure in polar regions.

Observations From an Active Seismic Distributed Acoustic Sensing Survey, Combatant Col, British Columbia

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Active seismic surveys in glaciological settings can provide insights into glacier thickness, basal structure, and glacier-bed interface conditions. These surveys often require large investments in instrumentation, personnel, and camp infrastructure; however, distributed optical fiber sensing provides a stable, low maintenance platform for high spatio-temporal seismic sampling of the cryosphere. In conjunction with ice core drilling, opportunistic distributed acoustic sensing (DAS) deployments may be performed down remnant boreholes once ice cores are retrieved. Here, we present results of an active seismic survey conducted using Betsy Gun® seismic sources on a high alpine glacier in British Columbia. A Sintela Onyx DAS interrogator was used to sample both a borehole deployed cable and surface deployed cable. The borehole fiber extended ~218 m deep into the glacier ice and the surface cable extended ~300 m from the borehole. Seismic shots were placed in ~1 m deep boreholes drilled in wet surface snow along the surface fiber route and in boreholes spaced ~100 m radially away from the borehole fiber. In addition to active seismics, Combatant Col hosts many passive seismic events such as rockfall and avalanches originating from nearby Mt. Waddington and Mt. Combatant. Preliminary investigations reveal resonant borehole tube waves likely caused by nearby passive seismic sources. Rayleigh wave dispersion is also evident on surface trenched cable. These observations show promise for modeling glacier ice thickness and revealing glacier-bed interface characteristics currently elusive in this area.

Plucking Base Notes: Seismic Character of a Potential Glacial Quarrying Event at Saskatchewan Glacier, Canadian Rocky Mountains

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Glaciers are one of the most powerful geomorphic forces on Earth, carving landscapes through a combination of abrasion and quarrying. These rock fracturing processes produce seismic emissions, as observed in experimental conditions and predicted in numerical theory. Glacier seismicity also arises from profoundly diverse sources, which hinders our ability to substantiate causal relationships between field observations and glacier bed processes. Recent bed-proximal seismic observation of a subglacial asperity provided unparalleled insights on the seismic character of abrasion that supports numerical and experimental theory (Gräff et al., 2021). Similar empirical support has not been reported for quarrying.

Abundant and accurately locatable glacier-bed seismicity observed with a dense surface array at Saskatchewan Glacier in August 2019 provided new empirical support for hydrologically modulated transient slip mechanics (Stevens et al., accepted). This catalog also contains a burst of hundreds of bed-proximal events clustered on the headwall of an overdeepening as glacier slip accelerated on the morning of August 10th; a normally aseismic time within the diurnal seismic cycles observed during this month. The timing, position, and dynamic context of this seismic cluster is consistent with characteristics of subglacial quarrying experiments and relevant numerical theory (Cohen et al., 2006). Here we present detailed analysis of this potential quarrying event, refining the event catalog through manual reanalysis, double-difference relocation, and source parameter estimation to further motivate causal linkages to glacier quarrying theory.

Cohen, D. and 4 others, 2006, Role of transient water pressure in quarrying: A subglacial experiment using acoustic emissions. JGR-ES. doi: 10.1029/2006JF000439.

Gräff, D. and 5 others, 2021, Fine structure of microseismic glacial stick-slip. GRL. doi: 10.1029/2021GL096043.

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Ross Ice Shelf Lamb Wave Propagation and Permanent Displacement Induced by Whillans Ice Stream Slip Events

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Ice shelves are generally assumed to move slowly and steadily from their grounding lines to the ice front. Here we report the detection of ice-propagating extensional Lamb (plate) waves accompanied by pulses of permanent ice shelf displacement, observed by a network of co-located GNSS receivers and broadband seismographs deployed on the Ross Ice Shelf in 2014-2016. The extensional waves and ice shelf displacement are produced by the once or twice daily tidally triggered basal slip events of the Whillans Ice Stream (WIS), which flows into the ice shelf. The extensional waves are observed on broadband seismographs as two or three non-dispersive long-period (20 -100 s) pulses spanning 15-30 minutes, radiated at the three main sites of basal slip acceleration identified by previous studies of the WIS. The extensional wave initial particle motions are nearly horizontal and radial to the WIS, and are detected at distances of greater than 500 km. The propagation velocity of 2.8 km/s is intermediate between the shear and compressional ice velocities, with velocity and particle motions consistent with theoretical predictions for thin-plate extensional Lamb waves. Following the first extensional wave arrival, GNSS observations show that the entire ice shelf is displaced about 0.06 meters in a direction away from the WIS, with peak velocity that

is more than an order of magnitude above the normal flow rate. The observed maximum particle velocities of about 0.0002 m/s imply peak dynamic strains on the order of 10^{-7}, comparable to strains from earthquake surface waves that trigger ice quakes. These results demonstrate that stick-slip events in ice streams can produce elastic waves and short-term strain pulse that propagate across the entire downstream ice shelf.

Seismology at South Pole, Antarctica: History and Future Opportunities

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The U.S. government has operated a seismometer at South Pole, Antarctica (SPA) since the construction of Amundsen-Scott station in 1957. The current station (QSPA) has been highly utilized for the detection and location of global earthquakes and nuclear explosions, studies of swell activity and sea ice around Antarctica, and cryoseismology. However, long-period (> 40 s) noise levels compromise ambient ground motion observations on all three of the station's borehole broadband seismometers. These high noise levels arise from both instrument self-noise and susceptibility to magnetic field variations, ultimately compromising the ability to make unique normal mode and tidal loading observations at the rotation axis of Earth. To improve long-period seismic observations at the South Pole, the U.S. Geological Survey is collaborating with the IceCube Neutrino Observatory to install a Nanometrics Trillium 360 GSN seismometer at 2.4 km depth within the Antarctic icecap. This presentation will discuss progress toward developing the technology to emplace a sensor at such depths, including an overview of drilling technology used within IceCube. Additionally, opportunities to further advance the field of cryoseismology by leveraging the extensive infrastructure and physics experiments conducted out of Amundsen-Scott will be highlighted. Future opportunities include re-instrumenting QSPA, installing quasi-permanent broadband seismic arrays, and interrogating dark fiber (e.g., DAS) associated with this infrastructure.

Applications and Discoveries in Cryoseismology Across Spatial and Temporal Scales [Poster Session]

Poster Session • Thursday 2 May

Conveners: Rick Aster, Colorado State University (rick.aster@colostate.edu); John Cassidy, Natural Resources Canada, Geological Survey of Canada (john.cassidy@nrcan-rncan.gc.ca); Jan Dettmer, University of Calgary (jan.dettmer@ucalgary.ca); Jeremy M. Gosselin, University of Calgary (jeremy.gosselin@ucalgary.ca); Celeste Labedz, University of Calgary (celeste.labedz@ucalgary.ca); John-Morgan Manos, University of Washington (jmanos@uw.edu); Elisa McGhee, Colorado State University (elisa.mcghee@colostate.edu); Stephanie Olinger, Harvard University (stepholinger@fas.harvard.edu); Rachel Willis, Colorado School of Mines (rwillis1@mines.edu)

POSTER 182

Machine Learning for Icequake Detection and Location Across the Eastern Shear Margin of Thwaites Glacier, West Antarctica

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The dynamics and potential migration of the Eastern Shear Margin of Thwaites Glacier could play a critical role in the stability of the West Antarctic Ice Sheet and future sea-level rise projections. The current position of this boundary is inferred to be weakly controlled by basal properties and topography. Additionally, recent observations of a transition from frozen to thawed bed beneath this shear margin and evidence for a water system, could indicate a potential control on the strength of the bed and potentially allow future outward migration. Previous passive seismic studies of basal crevassing, stick-slip events, and their relationship with englacial and subglacial water have shed light on glacier basal conditions. To investigate the type and extent of these seismic events in addition to changes in basal conditions, we use a 2-year passive seismic dataset, from December 2019 to January 2022, from two 7-station arrays, TIME1 and TIME2, crossing Thwaites' Eastern Shear Margin. We follow an icequake detection, location, template-matching, and relocation routine using easyQuake, EQcorrscan, and hypoDD. Although results provide an icequake catalog for events around both seismic arrays, we focus on a cluster of 1757 events, located a few kilometers from the TIME1 array in an area of slow-moving ice. We interpret these icequake observations and implications for the stability of Thwaites' shear margin and the broader West Antarctic Ice Sheet.

POSTER 183

Probabilistic Multiphysics Inference for Permafrost Characterization and Earthquake Site Hazards Assessment

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Permafrost thaw negatively impacts ecosystems and infrastructure throughout northern regions, which are warming at greater than double the global average rate. Permafrost plays a crucial role for soil stiffness and shear strength, and its degradation is a source for increasing risks of natural hazards, including landslides, thaw subsidence, and earthquake-related hazards. The severities of these impacts remain poorly studied, and mitigation efforts require better subsurface characterization and monitoring of temporal permafrost changes, as well as improved constraints on permafrost mechanical (poro-elastic) properties. This work considers the potential of permafrost characterization with probabilistic multiphysics inference of non-invasive geophysical observations. Our analysis employs a probabilistic (Bayesian) framework for robust characterization of uncertainties in inferred permafrost properties. We demonstrate this analysis with synthetic audio-magnetotelluric, seismic surface-wave dispersion, and seismic horizontal-to-vertical ratio data under varying permafrost conditions. The complementary information contained in the different data types, and the probabilistic estimation of objective data weights, enables higher-resolution inference of shallow subsurface properties than can be achieved by independent inference from individual data types. This is particularly attractive for permafrost characterization and monitoring, which considers strong elastic and electrical resistive signatures. Finally, inferred shallow Earth structure under varying permafrost conditions are used to estimate parameters for typical seismic site hazard classification and assessment. Our initial results indicate climate-change likely has, and will, influence earthquake site hazards. Furthermore, our work represents an initial step towards improved permafrost characterization for seismic hazard assessment with robust uncertainty quantification while avoiding subjective inversion practices.

POSTER 184

Bayesian Surface Wave Dispersion Data Inversion of Glaciated Environments

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We present a probabilistic approach to the inversion of surface wave dispersion data from glacial environments for various material parameters. This is intended to (i) investigate the non-linearity of the problem and the non-uniqueness of the solution, and (ii) properly quantify uncertainties and trade-offs. The method is based on an approximation to a 1-D stratified model of the medium under investigation. We then apply this approach to seismic data from Distributed Acoustic Sensing (DAS) experiments deployed on the Vatnajökull ice sheet located on Grímsvötn volcano in Iceland, and the Northeast Greenland Ice Stream (NEGIS). We use a Bayesian inference approach, implemented with a Hamiltonian Monte Carlo (HMC) algorithm. Exploiting derivative information for efficient sampling of high-dimensional model spaces, HMC approximates the posterior probability density with a collection of sampled models. Applied specifically to multi-mode surface wave dispersion measurements, HMC yields an ensemble of models of 1-D anisotropic stratified media parameterised in terms of the P-wave velocities Vpv and Vph, the S-wave velocities Vsv and Vsh, the anisotropy parameter η, and density ρ. Besides estimating the properties of the medium, and in contrast to deterministic approaches, this method allows statistical studies to be carried out on the recovered models, such as exploiting the parameter statistical moments for uncertainty quantification, or assessing non-linearity by examining trade-offs between parameters.

POSTER 185

Unsupervised Detection and Characterization of Glaciogenic Noise Sources in Greenland During Winter

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Glaciers and ice sheets are seismologically rich environments, where ice fracturing, stick-slip basal motion, and subglacial fluid flow all generate distinct signals which can be used to characterize different glaciogenic processes. Recently it was found that meltwater produced during summer and stored in partially frozen surface lakes can be released in winter, resulting large scale ice-flow accelerations that potentially impact long-term ice dynamics and sea-level rise. To better understand these unique events and other poorly observed wintertime processes, we develop an unsupervised signal detection and classification workflow using UMAP and ST-DBSCAN algorithms to identify and characterize glaciogenic noise sources in Greenland. Here, we focus on multiple years of data from a single seismic station near the terminus of Jakobshavn Isbræ, the fastest-flowing outlet glacier in Greenland. We show the wintertime noisescape rapidly transitions from a multi-month quiescent period to that with frequent impulsive events and background noise changes. We use UMAP and ST-DBSCAN to sequence these changing events into different classes of signals which we interpret using a combination of polarization analysis, cross correlation, modeling, and supplementary datasets of ice dynamic and temperature changes. The results highlight both the benefits of using an unsupervised tool to parse glaciogenic signals which would likely go undetected elsewise, as well as the difficulty of using a single station to fully attribute them to specific glacier processes.

POSTER 186

Microseismicity Catalog of Icequakes Induced by Ocean Swell at the Ross Ice Shelf Ice-Front

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Ice shelves are a critical physical impediment to the flow of grounded ice toward the ocean, thereby mitigating subsequent impacts to sea level. Ocean wave interactions with ice shelves generate a continuous background wave field of high frequency Lamb, and other plate-guided waves that can trigger micro-icequakes (magnitude ~ -2.5), and calving. Three broadband seismographs deployed approximately 2 km from the ice front of the Ross Ice Shelf in west Antarctica between 2014-2017 (e.g., Bromirski et al., 2015) established that 8-30 s period ocean swell generates impulsive high-frequency seismicity. In some cases, these seismic impulses are associated with the multistage failure of near-front crevasses that culminate in calving (Aster et al., 2021). Ice shelf rifting, fracture, and flexure have also been interpreted from seismic events detected across the expanse of the ice shelf from the full array of 34 seismographs in this deployment (e.g., Baker et al., 2021). We are establishing a catalog of swell-induced short-period seismic events spanning the complete dataset at the three ice-front stations by analyzing swell (0.03–0.12 Hz) and high-frequency (0.5–5 Hz) band-pass filtered seismograms. Subevents from the dataset will be extracted through the stacking of transient event peak detections to produce matched filter templates. The templates will be processed with an efficient cross-correlation analysis (Senobari et al., 2019) to complete the catalog and characterize the subevent categories. The catalog will be leveraged to examine oceanic controlling mechanisms of cryo-seismic phenomena. Ocean parameters will include wave height and direction, swell (storm) origin, wave period, and sea ice state. Icefront icequakes are most frequent during the austral summer in the absence of sea ice which attenuates ocean swell (Chen et al., 2019). Antarctic sea ice minimum extent reached the lowest minimum in the 44-year record in February of 2023 (Purich & Doddridge, 2023), and seismic observations from this dataset will inform and benchmark the ice-ocean processes that influence stability at the ice shelf edge.

POSTER 187

Distributed Acoustic Sensing Reveals What's in Store (Glacier)

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The Greenland ice sheet is the largest contributor to present global mean sea level rise, and dynamics of Greenland glaciers therefore exert a primary influence on the extent of present and future sea level rise. Frictional, deformational, and hydrological processes near the ice sheet bed control the dynamics of many glaciers, yet our understanding of glacier dynamics relies predominantly on surface measurements, and observing glacier processes at depth remains a challenge. While borehole seismic deployments provide continuous recordings of elastic waves near the glacier bed at a high temporal resolution, the spatial extent of such deployments is often limited to a single point. Novel fiber optical techniques like distributed acoustic sensing (DAS) retain the high temporal resolution of traditional borehole seismic deployments while providing excellent spatial resolution throughout the entire thickness of the glacier. Here, we explore three days of continuous DAS data recorded between July 6 and July 9, 2019 at Store Glacier in West Greenland. To image the velocity structure of the ice, we compute ambient noise cross-correlations for the entire dataset. Correlation functions stacked over a duration of one hour reveal P-waves and S-waves that propagate from the near-surface at average velocities consistent with the results of an active source survey carried out using the same fiber deployment (Booth et al, 2020). We perform ambient noise cross correlation using data recorded by each channel to characterize spatiotemporal variation in glacier strain. Our results suggest that the broad region within a few kilometers of the borehole experiences diurnal periodicity in glacier strain with minimal depth variation, consistent with behavior predicted by a classic simplified model of glacier flow over a deformable bed (MacAyeal, 1989). However, our results also suggest that the region immediately local to the borehole experiences a more complicated strain regime that may be explained by bumpy bedrock topography or complex basal hydrology.

POSTER 188

Array-based Characterization of Seismicity from a Glacial Lake Outburst Flood

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As Earth's climate warms, it is increasingly important to monitor the dynamic and hydraulic conditions at glaciers, especially those that can generate catastrophic glacial lake outburst floods (GLOF). Gornergletscher is the second largest glacier in the Swiss Alps and for decades has hosted a GLOF event every summer, releasing millions of cubic meters of water on top of, through and underneath the ice in a matter of days [1]. We detect and characterize seismic tremor related to the GLOF event using a five-station Geophone array with an aperture of approximately 400 m installed over a five-week period in shallow boreholes in the glacier within 500 m of the lakefront. We calculate array coherency matrices as a function of frequency and time [2], then apply an unsupervised machine-learning algorithm, SpecUFEx [3], to reduce the array coherency matrices into low-dimensionality based on concurrent lake-level and GPS measurements. Some clusters coincide with the onset of the GLOF, suggesting that our technique could offer a means of detecting outburst floods to complement or replace other observation methods, i.e., *in situ* lake level measurements. One cluster captures a period of previously discovered harmonic tremor generated from stick-slip events located near the ice-bed interface [4], and other clusters appear to contain times of newly detected harmonic or quasi-harmonic tremor as well. We localize the newly detected tremor near the ice-bed interface, suggesting that stick-slip induced tremor may occur throughout the GLOF event, rather than just on a single day. By combining an array-based approach with unsupervised machine learning, we can characterize glacial tremor to better understand the dynamic behavior of Gornergletscher, especially as it pertains to catastrophic GLOF events.

Works Cited: [1] Huss et al., (2007). *Journal of Glaciology* [2] Seydoux et al., (2016a) *Geophysical Journal International* [3] Holtzman et al., (2018). *Science Advances* [4] Umlauft et al., (2021). *Geophysical Research Letters*

POSTER 189

Controlled-Source Seismic Imaging of Mcmurdo Ice Shelf Near Williams Airfield

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Understanding the structure and thickness of the McMurdo Ice Shelf and the ocean environment below is important from an operational as well as scientific perspective. The McMurdo Ice Shelf is part of the Ross Ice Shelf, and ice shelf mass loss has been observed due to warming ocean conditions in the Ross Sea. During December 2021, the Thwaites Interdisciplinary Margin Evolution (TIME) project team conducted a seismic survey along an 1100-m seismic line near William's Airfield on McMurdo Ice Shelf. We deployed twenty-four MagseisFairfield, Z-Land Generation 2, 5-Hz, 3-component seismic nodes at 50-m spacing for 30 days. Both passive and active seismic sources were captured, with a day of controlled seismic sources generated by a 12-lb sledgehammer at 23 locations with 50-m spacing, with 3 hammer strikes at each location to stack and enhance the signal. The hammer signal generated 80–100 Hz frequency observed in the spectrograms, which was used to develop four corner filtered shot gathers to observe wave propagations. We process the controlled-source refraction data to define a velocity model of the ice shelf and environment below using Python ObsPy tools. Corrected and filtered data were imported to Shearwater Reveal to visualize the seismic data and make observations about the data quality and wave propagation. The survey was also a methods test for the use of seismic nodes for ice shelf (and glacier) imaging with controlled sources, and we discuss lessons learned for future deployments.

POSTER 190

Unsupervised Clustering of Cryoseismic Events Recorded by Distributed Acoustic Sensing at Rhonegletscher, Switzerland

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Higher fidelity monitoring and better quantification of mountain glacier processes remain a key priority as climate change transforms glaciated regions into landscapes of rocks, debris, ice-debris complexes, and glacial lakes. Our capability to monitor these highly dynamic and hazardous conditions for local communities remains limited by a lack of data at high spatial and temporal resolution. Distributed Acoustic Sensing (DAS) provides a unique opportunity to capture detailed spatiotemporal variations within and around a glacier. We focus on a DAS experiment from Rhonegletscher (Switzerland), during which we recorded data continuously for one month in 2023 using a 9 km fiber-optic cable on the ice surface. This deployment extended from the accumulation zone to near the glacier terminus, providing a unique perspective on glacial processes across surface balance regimes. The data captured environmental noise (e.g., wind, precipitation events) and acoustic signals from a variety of glacial processes, including surface fracturing and basal icequakes. DAS monitoring results in large data volumes, rendering manual event picking and classification as well as real time data telemetry practically unfeasible. Instead, we used automated processing tools and unsupervised clustering for event detection and classification with the goal of generating a comprehensive, classified catalog of cryoseismicity in the Rhonegletscher. We generated a low-dimensional feature representation of the data from the automated processing tools and used this data as input for an unsupervised clustering algorithm. We compared the clusters' signal characteristics and spatiotemporal distribution with potential forcing mechanisms, including comparison with environmental data such as temperature and wind to assist in the identification or correlation of source processes. Our automated pipeline for DAS data analysis provides a new, high-resolution perspective on Rhonegletscher's response to short-term environment forcing and a pathway for leveraging the massive data volumes produced by DAS installations for real-time monitoring of alpine environments.

Assessing Seismic Hazard for Critical Facilities and Infrastructure—Insights and Challenges

Oral Session • Friday 3 May • 2:00 PM Pacific

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Challenges in Site-Specific Seismic Hazard Analyses for Mine Tailings Storage Facilities in South America

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The recent increased need for site-specific probabilistic seismic hazard analyses (PSHAs) of mine tailings storage facilities (TSFs) has been driven by recent failures worldwide that resulted in significant loss of life and environmental damage. As a result, the Global Industry Standard on Tailings Management was developed, setting guidelines for both the design of new TSFs and evaluations of existing TSFs, with seismic design criteria for high- to extreme-consequence structures being adopted for return periods of 2,475 to 10,000 years. These long return periods present challenges to mine owners as they often result in high design ground motions in seismically active regions such as those along the South America subduction zone. We have performed site-specific seismic hazard analyses for TSFs throughout South America (e.g., Colombia, Ecuador, Peru, Chile, and Argentina). One of the challenges in performing such analyses in these countries is that prior seismic hazard evaluations have often underestimated the hazard for several reasons. First, there has been an over-reliance on the historical seismicity record due to the belief that the historical record alone would accurately predict future hazard. Second, existing Quaternary fault databases are often incomplete, which commonly results in the discovery of previously unrecognized Quaternary sources or re-characterization of known faults. When local fault sources are incorporated, they commonly include narrow epistemic uncertainties that are poorly supported with available data. Third, hazard analyses in South America have not kept pace with rapidly evolving ground motion models (GMMs). The recently developed NGA-Subduction GMMs have presented major challenges because of the significant increase in hazard over previous models. Finally, there has been a lack of adequate characterization of site effects with GMMs and Vs30 being used when the site conditions would call for site response analyses, e.g., thin soil or weathered rock sites.

Landfill Design Ground Motion at the Paducah Gaseous Diffusion Plant (Central United States)

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The Paducah Gaseous Diffusion Plant, a Superfund site near Paducah, Kentucky, in the central United States, is a former uranium enrichment plant owned by the U.S. Department of Energy (DOE). Due to its proximity to the New Madrid Seismic Zone, ground motion hazard is a concern for the site's waste disposal facilities related to site cleanup, such as the landfill and the CERCLA disposal cell. Site effect is also a concern because the site sits on thick sediments (about 100 m) over hard Paleozoic bedrock. The Environmental Protection Agency regulation (Title 40) requires that the maximum expected horizontal acceleration with a 90 percent or greater probability that the acceleration will not be exceeded in 250 years, or the acceleration based on a site-specific seismic risk assessment, is considered for the landfill seismic design. The acceleration with a 90 percent or greater probability that the acceleration will not be exceeded in 250 years is equivalent to the acceleration with a 2 percent probability of exceedance in 50 years or 2,500-year return period. A probabilistic seismic hazard analysis (PSHA) conducted for the site in 1999 resulted in a peak horizontal ground acceleration (PGA) of 0.80g on top of rock and 0.51g on the surface with a 2,500-year return period. These high estimated accelerations made it difficult for the U.S. DOE to obtain a permit from the federal and state regulators to construct a landfill or CERCLA cell at the site. A deterministic seismic hazard analysis (DSHA) was conducted for the site in 2010 and resulted in a PGA of 0.36g on top of rock and 0.33g on the surface. The federal and state regulators accepted the PGA of 0.33g on the surface for seismic design of the landfill at the Paducah Gaseous Diffusion Plant in 2012. We will present a brief history of seismic hazard assessment for the Paducah Gaseous Diffusion Plant and discuss the strengths and weaknesses of PSHA and DSHA for developing design ground motions for critical facilities and infrastructure.

Characterizing Uncertainty in the Canadian National Seismic Hazard Model

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A major effort is underway for the critical review of the included epistemic uncertainty in the Canadian seismic hazard model and the influence on hazard products other than the mean. Within the Canadian engineering community, mean hazard is used for most designs and safety analyses, even for critical infrastructure and facilities. While site-specific models are required for most high-importance structures, the national model is often used as a screening tool or for comparison against site-specific results. Understanding the full distribution of epistemic uncertainty is warranted. At a minimum there needs to be a renewed focus on upper fractile (84th, 90th, 95th percentile) hazard, because the upper tail of the distribution is likely the tail that will most often challenge the engineered performance of a structure during a large earthquake. However, estimating upper fractile values brings additional model-building challenges. This presentation will focus on how uncertainty is currently included in the Canadian national seismic hazard model and on areas of research currently being explored to improve the characterization and communication of epistemic uncertainty within Canada's PSHA models.

Importance of Site-Specific Ground Motion Data for Critical Facilities

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For rigid structures of critical facilities situated on hard rock, accurate characterization of ground motions at high frequencies is critical. Empirical ground motion models (GMMs) typically lack enough observational data on hard rock sites, and predictions from the GMMs may carry substantial uncertainties. To adjust the seismic hazard for hard rock site condition, the current state-of-practice is to perform a V_S-kappa0 (kappa0 is the near-surface high frequency attenuation parameter) host-to-target correction to develop hard rock correction factors. However, in absence of site-specific ground motion (SSGM) data, the modeling parameters and their corresponding epistemic uncertainties are not well quantified, which leads to unreliable hard rock correction factors and hard rock adjusted seismic hazard results.

We have carried out an alternative approach to characterize the hard rock site response (HRSR) in probabilistic seismic hazard analysis (PSHA) using SSGM data. The approach relies on estimation of non-ergodic HRSR at a given site using SSGM recorded on broadband seismographs. Using non-ergodic site response, we effectively remove the site-to-site variability from PSHA while accounting for epistemic uncertainty of HRSRs which are well-quantified with sufficient recorded SSGM data. This approach can be implemented even for regions with low-to-moderate seismicity rate, where earthquakes with M > 3 recorded at distances > 50 km are common. Since 2020, we have instrumented multiple BC Hydro's critical dam facilities in British Columbia, Canada, to characterize the non-ergodic HRSR. Depending on the rate of seismicity and the level of noise at a given facility, we were able to collect sufficient SSGM data within 1-3 years. In addition, having multiple seismic stations at selected facilities has enabled us to explore the degree of topographic effects on HRSR. The non-ergodic HRSR can differ significantly from generic HRSR specifically at high frequencies, and the observed differences are likely due to factors that are not considered in typical ground response analysis (e.g., 2D, 3D effects).

Site-Response Assessment Using Empirical Techniques for Nuclear Sites in South-Eastern France: Comparisons With Ssr and Numerical Simulation Estimates.

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Site-specific Seismic Hazard Estimates is becoming the standard practice for critical facilities such as nuclear sites. This involves taking into account the specific characteristics and seismic response behaviour of the site under study as accurately as possible. To assess the seismic site response, Standard Spectral Ratio (SSR) or 1D (2D/3D) numerical modelling are usually used. Nevertheless, the SSR method requires choosing a reference site near the target one, and for ground motion numerical simulations, costly geotechnical and geophysical measurements are needed. Since several years, empirical approaches based on national/regional ground motion databases, such as empirical ground-motion models (GMMs) and Generalized Inversion Techniques (GITs), have proven that reliable site response could be obtained with respect to a given reference condition which does not have to be a real station located close to the target one. The aim of this work is to assess the reliability and robustness of site responses obtained using GITs and GMMs regressions techniques (site residual δS2S) for a sedimentary site located in a low to moderate seismic context (south-eastern France) where SSRs and transfer functions computed by numerical simulations (1D/2D/3D) are available. For comparisons, they are all computed with respect to the same reference station installed on outcropping rock close to the basin. Two types of generalized inversion techniques (Oth et al. 2011 and Grendas et al. 2022) and one ground motion model (Traversa et al. SSA abstract) have been used. They are based on the Epos-France database (Buscetti et al. In prep), consisting of earthquakes of M_l≥3 that have occurred in mainland France or surrounding countries. Finally, with the aim of assessing the minimum amount of data necessary to obtain reliable site responses using each technique, the original dataset has been decimated. The results will be presented in the perspective of providing a rough estimate of the minimum recording time required for seismic instruments to provide reliable site response at critical facilities.

Issues in the Selection of Design Values for Surface Fault Rupture for Critical Facilities Using Probabilistic Fault Displacement Hazard Analysis

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For most applications, the approach to fault displacement hazard is avoidance through use of setbacks from active faults; however, for some lifelines, an active fault must be crossed. In other cases, new faults are discovered at existing critical infrastructure that need to be addressed. Historically, deterministic approaches have been used to estimate design fault displacement, but probabilistic fault displacement hazard analysis (PFDHA) is being used more frequently. The PFDHA follows a similar approach as standard probabilistic seismic hazard analysis (PSHA) used for ground motion, but there are issues that affect PFDHA that are not common in PSHA. The first issue is the selection of the design fault displacement based on the hazard curve. Often, the

return period for the fault displacement is simply set at the same return period as the ground motion for the structure; however, the objective should be to have similar risk for fault displacement and ground motion, not similar hazard. Because the fault displacement hazard only includes events that rupture to the surface at the site, the hazard curves are flat at small displacements. If the recurrence interval for surface rupturing events at the site is not much larger than the selected return period, then the displacement at a given return period will be sensitive to the uncertainty in the activity rate. For example, an increase in the slip rate of a factor of 2 can lead to a factor of 6 increase in the displacement at the specified rerturn period. If a risk-targeted displacement is developed based on the same risk level used for buildings, the displacement can be a factor of 3 larger than the displacement for the 2500-yr return period. In many cases, simply using the displacement based on the mean hazard for a specified return period will not be appropriate for the design of critical infrastructure. GIven the sensitivity of the PFDHA results, alternative approaches to selecting the design displacement should be considered, such as using the median displacement from the distribution of displacements for events causing surface rupture at the site.

Exposure of Australia's Infrastructure to Ground Surface Rupture Hazard

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Australia has hosted at least 11 surface-rupturing earthquakes since 1960, with moment magnitudes (Mw) between 4.7 and 6.6. The Australian Neotectonic Features Database (NFD) hosts an inventory of over 400 Australian intraplate faults, fault-related folds, and other features that are demonstrated or suspected to relate to earthquakes large enough to deform the Earth's surface. Recent re-analyses of earthquake data have resulted in updated scaling relationships and slip distribution functions, for utility in probabilistic fault displacement hazard analyses. Geospatial comparisons of Australia's energy, resource, and transport infrastructure (e.g., dams, pipelines, transport) with historical and neotectonic ground surface rupture traces enables development of a proximity / overlap-based rating scheme for prioritising infrastructure mitigation / adaptation measures. This talk will present preliminary results from a suite of ongoing research programs on fault mapping, paleoseismology, and infrastructure exposure analyses at a variety of spatial scales across the continent.

Studies of Fragile Geologic Features in Central New England, USA, and Northeastern New Zealand

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We provide an overview of studies of fragile geological features (FGFs) in New England, USA, and New Zealand. The New England studies focus on FGFs in Massachusetts, New Hampshire, and western Maine. The FGFs are large erratic boulders that became delicately balanced during melting of the Laurentide ice sheet 21,000 to 15,000 years ago. Each FGF was photographed for development of a 3-dimensional model to quantify the fragility (shaking required to topple the FGF), and seismometers were briefly installed both on and away from the FGF to measure the response of the boulder to push tests and ambient noise. The age and fragility of the FGFs appear to show compatibility with the U.S. National Seismic Hazard Model (NSHM), likely due to the absence of large earthquakes (Mw>7) in the region since the FGF emplacement and short period motions from moderate earthquakes (5<Mw<7) being insufficient to topple the rocks. The New Zealand studies focus on FGFs in the east coast of the North Island, where the new NSHM shows major increases in hazard relative to earlier models. At the time of writing this abstract only reconnaissance efforts had been carried out, with studies of the fragility and age of specific FGFs planned for early 2024.

Fault-Displacement Models for Aggregate, Principal, and Distributed Displacements

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As part of this study, we present new fault displacement models (FDMs) for aggregate, principal, and distributed displacements based on the net component of the slip vector. The FDMs are developed based on the Fault Displacement Hazard Initiative Project Dataset comprised of 75 events with magnitude ranging from 4.9 to 8.0. The model for the aggregate displacement is formulated first in the wavenumber domain to incorporate seismology-based constraints for the extrapolation of the magnitude scaling of median displacements to large-magnitude events and then transformed to the space domain to facilitate its implementation. The space domain model is then empirically adjusted to account for small-to-moderate magnitude scaling, displacement tapering near the edges, and the effect of segmentation. Segments are used in the development of the original model to capture the slip variability better. For applications in which segments cannot be determined in advance, an FDM is provided, with the number, lengths, and locations of the segments included as part of the aleatory variability. The principal-displacement FDM is developed next as an adjustment to the aggregate-displacement FDM. The total distributed displacement is determined based on the aggregate to principal difference, and probabilistic models are developed to compute the number, location, and partition of total distributed slip into individual ruptures. A key feature of the new FDMs is the use of a power-normal distribution for the aleatory variability of aggregate and principal displacements, leading to narrower distributions of displacements for large magnitudes compared to existing FDMs. Furthermore, for large-magnitude earthquakes, the expected maximum displacements implied by the proposed model are consistent with the observed maximum displacements along strike, supporting the narrower shape of the upper tail of the power-normal distribution for large-magnitude events.

Looking for Kappa in the US and the UK Using Noise Modeling

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In this contribution we combine our experiences from two PSHA studies (using SSHAC protocol) performed for nuclear facilities: Idaho National Laboratory project in the US and Bradwell B project in the UK. We share and discuss the challenge of estimating high-frequency site attenuation, namely the spectral decay parameter kappa. The data quality assessment stage was crucial in identifying the usable data and their usable frequency band, especially at high frequencies. Several issues made the work particularly challenging in both cases, necessitating careful consideration of uncertainties: 1. All recordings came from distances larger than 100 km, significantly increasing epistemic uncertainties stemming from regional (path) attenuation and variability in crustal properties. 2. Most of the recordings were of small magnitude, so that the stress drop (corner frequency) uncertainty became a definitive factor in selecting the usable bandwidth and hence the appropriate estimation methods for kappa. 3. The uncertainties from the trade-off between site attenuation and site amplification were often considerable. 4. The datasets were small and of poor quality, with low signal strength, and many of the recordings were unusable according to typical signal-to-noise criteria. Such limitations were addressed by a signal-enhancing technique based on stochastic noise modeling. This models the noise that contaminates the earthquake signal and corrects the spectrum for it, rather than avoid it. Thus, the recorded data were rendered usable at much higher frequencies than traditionally possible, and in some cases heretofore unusable recordings were added, enhancing the datasets in quality and quantity.

Assessing Seismic Hazard for Critical Facilities and Infrastructure—Insights and Challenges [Poster Session]

Poster Session • Friday 3 May

Conveners: Céline Beauval, ISTerre, Université Grenoble Alpes (celine.beauval@univ-grenoble-alpes.fr); Glenn Biasi, U.S. Geological Survey (gbiasi@usgs.gov); Olga-

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POSTER 127

Implementation of Interconnected Fault Systems in PSHA: Testing Existing Algorithms in Different Tectonic Context

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Probabilistic Seismic Hazard studies aim at quantifying the recurrence of ground-motions, based on earthquake occurrence models and ground-motion models. Most source models built for PSHA integrate faults in a rigid way. Within a predefined fault, ruptures can occur on individual segments or on a combination of segments. Ruptures that would involve segments from different predefined faults are not included in the model. The source model thus most often includes only a subset of the future ruptures that may occur on the fault system. In the last decade several research groups have proposed algorithms for implementing faults in a more realistic way. The first and most well-known is the OpenSHA algorithm (Field et al. 2014; Milner and Field 2021), applied on the well-characterized fault system in California. Later on, the SHERIFS algorithm has been proposed (Chartier et al. 2017, 2019), it is simpler than OpenSHA and requires less input parameters. Both algorithms rely on the concept of interconnected fault systems, with rules established to defined which combinations of segments are possible, as well as different techniques to distribute the moment rate budget available in the system over the different earthquake ruptures. We analyze the potential of these algorithms over fault systems with varied levels of deformation: the Sumatran fault system (~15 mm/year), the Levant fault system (~4-5 mm/year), the Java Back-Arc Thurst Fault (~1-2 mm/year). We aim at understanding how the algorithms use the information available in the fault system (slip rate estimates, segmentation, paleoseismic earthquakes, historical earthquakes) to produce a set of ruptures with associated rates. We show that the way the scaling relationship is applied (either total length or total area) has a strong impact on the hazard results. We analyze critically the source models obtained, accounting for uncertainties, as well as the hazard levels obtained. Overall, the general trend is towards a decrease of hazard values with respect to a classical implementation of faults, but in some circumstances hazard values may also increase.

POSTER 128

Magnitude Dependency of Spectral Decay Parameter (Kappa) at Rock Stations from Event Dataset that is Restricted Only from Events that are Originated around Eastern Anatolian Fault (EAF)

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The decay of the high frequency ground motion amplitudes of Fourier spectrum, namely the spectral decay parameter, κ (kappa), is highly utilized and debated in the scientific community in the last decade due to its significant effect on earthquake hazard evaluations and results. A dataset with a good spread of magnitude variety in near site as well as far site recordings is needed to be able to check if this parameter is magnitude dependent or not. Due to paucity of data worldwide, especially hard rock sites, this dependency was not debated in full coverage, and the parameter is assumed to have the same decay tendency for high magnitude possible events with the evaluated κ values from low seismic records in the low seismic target regions. AFAD station spread around East Anatolian Fault has provided a decent dataset especially after the January 2020 Elazığ earthquake of M_w6.8, and the M_w7.7 and M_w7.6 Kahramanmaras earthquakes of February 2023. The results of these datasets are evaluated in terms of differences in different magnitude bins. Also, KOERI dataset provided a good insight on the magnitude dependency for the same region. Especially the results of AFAD Stations Stn4404 with V_{s30} 1380 m/s, Stn2302 and Stn2305 with V_{s30} 907 m/s, and Stn 2409 with V_{s30} 875 m/s will provide insight for low seismic, hard rock regions if only taking the low seismic data to arrive at zero epicentral spectral decay parameter, κ_0 could be reasonable or not. Future investigations to account for magnitude dependency and its relations will be the next generation debate in terms of κ and hazard evaluations.

POSTER 129

Monitoring and No-Money-Toring of Oil and Gas Production in Southern Italy

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Mother Nature does not mind if monitoring agreements are active, and sometimes earthquakes may occur at times, when seismic monitoring is not adequately covered by fundings. In this case the question rises, whether monitoring should be continued anyway, or it should be rather suspended, following the economic availability of a dedicated project. This is the inauspicious circumstance when *No-Money-toring* starts.

According to the governmental guidelines, in 2017, the role of the competent authority for the Monitoring of the Oil and Gas production in the Agri Valley (VA), has been assigned to INGV. The main concessionaire in the VA (South Italy) is the ENI oil-company, operating 25 productive wells located between the eastern side of the basin and the eastern ridge. With a production rate of around 90,000 oil barrels/day, the VA oil field is the largest on-shore oil field in Europe. Since the 1990s, hydrocarbons have been exploited from a high-productive reservoir, through production wells drilled down to a depth of 2-3 km below sea level. Since June 2006, wastewater associated with the oil production was re-injected, at around 3000m depth, into the CM2-well, an unproductive marginal section of the carbonate reservoir. Injection rates rarely reached peaks of 2800-3000 m^3/d (normal 2000 m^3/d), while the well-head pressure never exceeded 13-14 MPa. CM2 can be classified as a long-term, high-rate disposal well.

In the middle of the COVID-19 pandemic in April 2021, the two-year experimental period ended, and was extended for a further 12 months. Due to an unfavorable combination of individual administrative difficulties by the public administrations involved, financial funding was interrupted in April 2022. This led to a contractual and financial discontinuity for a period of more than 20 months. However, INGV decided to continue the monitoring activity; a decision that turned out to be useful, given the non-neglectable seismic activity, occurring during the year 2023. Our contribution will report on scientific and non-scientific aspects experienced during the Monitoring and *No-Money-toring* phase of the VA-project.

POSTER 130

Insights From Distinct Element Method Models on Fault Scarp Morphology in Thrust and Reverse Fault Earthquakes.

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We seek to better understand and forecast the near-surface coseismic deformation that occurs as a result of large magnitude thrust and reverse fault earthquakes using geomechanical models. We developed a distinct element method (DEM) model to evaluate the physical processes that control the pattern of ground surface ruptures on thrust and reverse faults. In prior work, we used 45 initial 2D DEM models to develop a classification system for fault scarp morphology (monoclinal, pressure ridge, and simple scarps) each of which can subsequently modified by hanging wall collapse. These relationships are supported by natural rupture patterns from recent and paleo-earthquakes across a range of geologic settings. In this next phase of our study, we tested a suite of 3,425 2D DEM experiments in dense, medium-dense, and loose sediment in a model 50 m wide with 3, 5, and 10 m of sediment depth. These models include homogeneous and heterogeneous sediment mechanics, a range of fault dips (20 – 70°), and displacements of up to 5 m. We used a machine learning model (based on computer vision) to take measurements of the DEM experiments every 5 cm of slip on the fault at depth. This resulted in ~250,000 measurements of the homogeneous DEM models, which enabled robust statistical relationships between model parameters (slip, fault dip, sediment strength, and sediment depth) with the observed surface deformation characteristics (scarp height, width, and dip as well as the tendency to form backthrusts and secondary fault splays). These relationships are supported by natural rupture patterns from recent and paleo-earthquakes across a range of geologic settings. In conjunction with these natural examples, our models provide a basis to more accurately forecast ground surface deformation characteristics that will result from future earthquakes based on limited information about the earthquake source and local sediment properties.

POSTER 131

Overcoming Factors That Limit the Predictive Power of Probabilistic Fault Displacement Hazard Models

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Fault displacement models provide surface slip probability distributions and are a key component of Probabilistic Fault Displacement Hazard Analyses (PFDHA). Relatively high residuals between predicted slip and slip observed in historical ruptures reflect large aleatory variability common across the models. We investigate variables that may modulate the amplitude of coseismic surface slip in order to refine slip predictions to match observations. Using new empirical models developed from the UCLA Fault Displacement Hazard Initiative global rupture database, we compare model residuals against variables thought to modulate surface slip, including depth to bedrock, topographic slope, relief, hypocentral and centroid distance, and number of fault strands.

Our initial findings show that the strongest source of discrepancy corresponds to portions of ruptures that violate the simple form of the predictive models, particularly where secondary faults are involved, reflecting the challenge of synthesizing slip observations in zones of complex geometry and multiple fault traces. This challenge is not easily overcome because models tend to have simple representations of slip distributions that do not capture real-world complexities. We propose that model predictions can be through careful selection of observational data that satisfy the premise of the model, that is, those which lie along the modelled fault trace(s). Conversely, quantifying fault complexity is a common objective warranting the inclusion of slip distributed off of a principal trace. For next generation fault displacement models, resolving accurate slip predictions for individual strands in areas of fault complexity may require careful filtering and selection of data on a case-by-case basis rather than through automated amalgamation approaches, though a hybrid method is possible. Robust interrogation of geological or geometric characteristics that modulate slip systematically at a global scale will first require refinement or filtering of the input observations to address cases that violate model assumptions.

POSTER 132

Time-Domain Seismic Response Retrieval from Ambient Noise Recorded by the Existing Seismometer of Dams Based on Interferometric Processing

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The seismometers installed at dams in Japan have recorded numerous seismic events, including significant earthquakes. These records are invaluable for analyzing the response of dams during seismic activities, providing insights into their behavior and allowing for the derivation of indices reflecting the dynamic properties of the structures. Applying the principles of seismic interferometry, we employed its methods to the seismic records of dams, estimating both the properties of seismic wave propagation and the dynamic characteristics of the structures.

In this presentation, we assess the applicability of seismic interferometry to the seismic records of dams, specifically its use with small vibration records obtained from existing dam seismometers. These records encompass data from minor earthquakes, where the maximum acceleration is less than 1 cm/s^2, as well as ambient noise expected to include waveforms of latent microtremors. Through waveform analysis spanning over 10 hours, we demonstrate the capability to extract time-domain response waveforms from the records of small vibrations resembling those obtained from seismic records of significant earthquakes (maximum acceleration exceeding 2 cm/s^2). Importantly, these results highlight the potential for interferometric processing to be consistently applied, not only to seismic events but also to seemingly trivial records, such as ambient noise. This aspect has traditionally been overlooked by the existing seismometers of dams are primarily designed to measure seismic waves with strong amplitudes. We will also present a case study involving recent significant earthquake events.

POSTER 133

Comparison of Methods to Produce Virtual Ruptures for Background Seismicity

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Virtual ruptures have become the standard of practice for modeling potential future earthquakes within source zones for probabilistic seismic hazard analyses (Bommer and Montaldo-Falero, 2020). The benefit of using virtual ruptures over point sources is the direct availability of distance metrics, such as rupture (R_{rup}) and Joyner-Boore (R_{JB}) distances, needed for ground motion models (GMM). Point sources provide only epicentral (R_{epi}) or hypocentral (R_{hyp}) distances, and therefore require a conversion (i.e. Scherbaum et al., 2004, EPRI, 2004, 2013, and Thompson and Worden, 2018) in most cases, which can result in an underestimation of hazard (Bommer and Akkar, 2012).

A significant challenge lies in the absence of standardized algorithms for producing virtual ruptures, with different code developers following different algorithms without any validated results as reference. The goal of this study is to start the validation and comparison process of two virtual rupture generator programs, similar to the study performed for seismic hazard programs (Hale et al., 2018). The two virtual rupture generators (VRG) within this study, referred to as VRG1 and VRG2, have different methods of placing, scaling, and assigning seismicity to the virtual ruptures. The two VRGs consist of one developed by Slate Geotechnical Consultants, Inc. and another developed by WSP Global Inc.

Multiple scenarios are run through the two VRGs and the resulting distance distributions are compared. Each scenario examines the impact of individual parameters, such as spatial distribution and rupture geometry, on the resulting distance metrics. A small number of scenario comparisons are discussed in depth as they illustrate differences in methodologies and results, as well as two scenarios that were used in a simple hazard analysis to show the sensitivity to differences in the VRGs.

POSTER 134

The Role of Epistemic Uncertainty Estimations in Seismic Safety Decision Making and Relation to Levels of Input Model Simplification

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Epistemic uncertainty and aleatory variability are key concepts in probabilistic seismic hazard analysis (PSHA). The classifiation into either epistemic or aleatory depends on the level of simplificatoin used in the seismic source characterization and in the ground-motion model. For a selected level of simplification, epistemic uncertainty is scientific uncertainty in the modeled earthquake effects while aleatory variability is the variability from unmodeled earthquake effects. Models with greater simplification will have larger aleatory variability and smaller epistemic uncertainty than models with less simplification. Although common PSHA practice is focused on the mean hazard, which is not affected by the partitioning of epistemic uncertainty and aleatory variability, the evaluation and quantification of the epistemic uncertainty is often required for seismic hazard studies for critical infrastructure projects. Therefore, the level of model simplification should be clearly defined in the PSHA to allow the users to be able to interpret what the epistemic uncertainty range represents. A common assumption is that the true hazard will lie within the epistemic uncertainty range; however, we show that this will generally not be the case for models with greater simplification and larger aleatory variability, such as ergodic GMMs. The most common use of epistemic uncertainty is to identify the key inputs that can be improved and reduced through additional data collection and improvement. Less discussed are the potential uses of epistemic uncertainty in engineering practice. Though regulations and codes typically specify that the mean hazard be used for determining the design ground motions, the performance of the structure can be evaluated to higher fractiles of the hazard. To help meet societal needs for earthquake resilience, the damage state of the structure can be considered in the development of emergency action plans to respond to the expected consequences if the ground motions for the higher fractiles are correct.

POSTER 135

Using 3D Seismic Simulations to Determine Structural Designs That Best Preserve Structural Integrity of Buildings in an Earthquake

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Many parts of the world experience highly destructive earthquakes several times within a century. Many cities that are at high risk of experiencing such an earthquake have increased in population. This underscores the need to address major structural vulnerabilities in existing and future construction in order to mitigate the destructive effects of seismic activity on those structures. However, many are hesitant to reinforce these structures due to cost constraints and determining the optimal structural reinforcement would require extensive testing. However, using real-world shake-table simulations on physical models to test the structural integrity of a building is very expensive. The costs associated with the construction of the model are extensive, often costing millions of dollars. It often takes months just to construct the model upon which the testing is done.

Virtual earthquake simulations dramatically reduce the time and cost required to test the physical effects of seismic activity of varying intensity on different types of structures, thus aiding in the discovery of novel structural engineering solutions that mitigate the destructive effects of seismic activity on those structures. By simulating in a 3D virtual physics simulator, one can efficiently determine the optimal structure to best preserve structural integrity of buildings and other structures without the cost of physical materials and shaketables.

Characteristics and Mechanics of Fault Zone Rupture Processes, from Micro to Macro Scales

Oral Session • Thursday 2 May • 8:00 AM Pacific

Conveners: Xiaowei Chen, Texas A&M University (xiaowei.chen@tamu.edu); Yifang Cheng, University of California, Berkeley (chengyif@berkeley.edu); Zhe Jia, University of California, San Diego (z5jia@ucsd.edu); Junle Jiang, University of Oklahoma (jiang@ou.edu)

Temporally-Varying Creep Behavior on the East Anatolian Fault and the End of the 2023 Pazarçik Rupture

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The 80 km-long Pütürge segment of the East Anatolian fault connects the end of the rupture zone of the February 2023 M7.8 Pazarçik earthquake in the SW to Lake Hazar in the NE. The NW half of the segment ruptured at depth in the January 2020 M6.7 Sivrice earthquake, but less is understood about the behavior of the SW half. Given the lack of a major structural barrier to the continuation of the Pazarçik rupture, we consider the possibility that frictional conditions—specifically a transition from stick-slip to aseismic creep—could explain why that rupture ended where it did.

To assess this hypothesis, we process InSAR data from ascending and descending tracks of the Sentinel-1 satellites that cover the Pütürge segment, from three time periods—before, between and after the two earthquakes—using the ISCE and MintPy software. We take short, fault-perpendicular profiles through the velocities and time series we produce to investigate possible creep behavior. We find that: 1) the Pütürge segment was creeping in the period 2014-2020, before the Sivrice earthquake, at rates that peak at ~6 mm/yr at its NE end, and decrease along-strike to effectively zero at its SW end; 2) the post-Sivrice earthquake deformation includes ~10 cm of surface creep between February and July 2020 along the Sivrice rupture zone, followed by a M~5.8 creep event on the fault immediately to the SW of that zone; and 3) the post-Pazarçik earthquake deformation (~10 cm of surface creep in 8 months) is concentrated along the SW-most section of the Pütürge segment, in the zone where there had been little creep before or after the Sivrice earthquake. This continuous and complex shallow creep along the Pütürge segment suggests that creep did play a role in ending the Pazarçik rupture, and also that the limited postseismic creep seen after that event is a result of the release of the majority of the stored elastic strain along the segment after the Sivrice earthquake.

Modeling Rupture Propagation Into Creeping Faults by Thermal Pressurization

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Different sections of faults, like the San Andreas (SAF), accommodate stress via stick-slip under velocity-weakening friction or through gradual creep in a velocity-strengthening regime. When a rupture reaches a region of slow slip, thermal pressurization of pore fluids can enable rapid weakening and dynamic failure of the creeping zone (Noda and Lapusta, Nature, 2013). We explore whether a theoretical M_w 7 earthquake, which propagates towards the creeping section, could generate enough thermal pressurization to rupture through the creeping section, building upon recent observations that the creeping section of the SAF may have experienced large seismic slip (Coffey et al., Geology, 2022). At the same time, the 2004 M_w 6 Parkfield earthquake did not significantly propagate into the creeping section. The highly simplified model of the simulated fault consists of locked and creeping segments, depth-averaged to consider only variations with its length and embedded within a 2-D linearly elastic isotropic medium. The fault is governed by a logarithmic rate-and-state friction law with thermal pressurization of pore fluids due to shear heating, with the diffusion of heat and fluids from the fault. We vary three thermal pressurization parameters (the coupling coefficient between temperature and pore pressure change, hydraulic diffusivity, and half-width of the actively shearing layer) and the effect of the off-fault inelasticity to find the combinations that lead to dynamic rupture through the creeping region when the event size is large enough. Our preliminary results indicate that there are indeed plausible parameter combinations for which M_w 6 events arrest, but M_w 7 events dynamically rupture the creeping segment. We will report on our current exploration of the fuller parameter space and ways of explaining the simulation results with theoretical considerations.

Across-Slab Propagation and Low Stress Drops of Deep Earthquakes in the Kuril Subduction Zone

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Deep earthquakes occur when subducting slabs dive into the mantle at depths of up to 700 km, where pressure is up to 100 times greater than in the crust. These high pressures and temperatures should prevent the occurrence of earthquakes, and it is still unclear how deep earthquakes start or propagate under these conditions. In our recently published study, we inverted seismic waveforms using a second-degree moments approach for the spatial dimensions, duration and stress drop of eight deep-focus earthquakes (Mw 6.7—7.7) in the Kuril subduction zone. We find stress drops of 1—10 MPa, and after adjusting for changes in rigidity with depth, we find that the spatial dimensions and durations of the deep earthquakes are similar to crustal earthquakes. We also measured values of the radiated efficiency (the ratio of radiated energy over available strain energy). For these earthquakes, radiated efficiency >1 is observed, suggesting that undershooting is prevalent in deep earthquakes, consistent with laboratory-derived weakening mechanisms. When we compared the earthquake spatial extents to thermal subduction models, we found these deep earthquakes were confined to the coolest part of the slab, with temperatures T<1000 °C, similar to shallow events. Hence, despite different triggering mechanisms, the same physics seems to control the rupture propagation of shallow and deep earthquakes.

Fault Zone Material Heterogeneities May Trigger Repeating Earthquakes in Kanto, Japan

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Fault zones feature small-scale material heterogeneities that strongly affect where earthquake ruptures initiate and terminate. In this presentation, we show that fault zones that repeatedly rupture during earthquakes in Kanto, Japan also exhibit anomalous material properties. The Kanto region in Japan is situated in a special tectonic setting where the Philippine Sea plate is "sandwiched" between the Okhotsk and Pacific plates, generating small to moderate-magnitude earthquakes that repeat within days to years along the plate interface between the Pacific plate and the Philippine Sea plate at 60-70 km. We apply a waveform cross-correlation approach to measure the in-situ Vp/Vs ratios of earthquake patches. We find anomalously low Vp/Vs ratios (~1.5) in these earthquake source regions, suggesting the fault zone rocks may have distinct mineral compositions, e.g., high concentration of alpha-quartz. We also estimate the stress drop of M>3.4 earthquakes using the spectral ratio method, leading to a median stress drop of 4.6 MPa. The typical stress drop values suggest the effective normal stress is much lower than the lithostatic pressure and the fault zone may also contain abundant fluid. Thus, a combination of different mineral compositions and richness in fluid can promote velocity-weakening behaviors and generate repeating earthquakes at 60-70 km. Our earthquake cycle simulations based on the frictional parameters of wet quartz can reproduce M~4 earthquakes that alternate between full and partial ruptures every 2-5 years, which are similar to the recurrence intervals of M~4 earthquakes at 60-70 km.

The Alto Tiberina Near Fault Observatory: A State of Art Monitoring Infrastructure for Studying Earthquakes Faults and Preparatory Phases

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Near Fault Observatories (NFO) are research infrastructures developed in the framework of the European Plate Observing System (EPOS), towards a pan-European organization for Solid Earth Sciences providing raw data and scientific products, collected by a suite of geophysical communities, based on the FAIR principles. S

NFOs consist of advanced networks of multi-parametric sensors continuously monitoring the chemical and physical processes related to the underlying Earth instabilities governing active faults evolution and the genesis of earthquakes. Such a methodological approach, currently applicable only at local scale, is based on extremely dense networks and less common instruments located at surface and within shallow boreholes within few kilometers from active faults where background activity is high and large earthquakes are expected.

The NFO community is composed by 6 permanent members plus 2 observers placed in different tectonic regimes. The Alto Tiberina fault (ATF) in the Northern Apennines of Italy is the target of the Alto Tiberina Near Fault Observatory (TABOO-NFO); a 60-km long low-angle normal fault (dip <20°) able to generate a M7 earthquake not present in the historical catalogues. Microseismicity is released at a consistently high rate on the ATF plane, including repeating earthquakes that together with a steep gradient in crustal velocities measured by GNSS and transient surface motion, lasting for few months and coinciding with seismic swarms, support the hypothesis that portions of the ATF are creeping aseismically.

Recent studies document that any given patch of a fault can creep, nucleate slow earthquakes and host large earthquakes (e.g., Iquique, Tohoku and Parkfield), encouraging a revolution in our way of thinking about how faults accommodate slip. However, the interaction between creep, slow and regular earthquakes is still poorly documented by observations.

TABOO is currently collecting unique data needed to address such questions with significant implications for seismic hazard and risk assessment globally.

Dynamic Rupture Simulations on the Alpine Fault, New Zealand: Investigating the Role of Fault Geometry on Rupture Size and Behavior Over Multiple Earthquake Cycles

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The right-lateral transpressional Alpine Fault is the primary plate boundary fault on the South Island of New Zealand. At a broad scale, its onshore surface trace between Milford Sound in the southwest, and the branching Marlborough Fault System in the northeast consists of two planar sections connected by a major geometrical boundary at Martyr River. This boundary is characterized by both a dip change of as much as 40° over an along-strike length of only ~5 km. Several previous studies suggest that changes in dip along a strike-slip fault can affect rupture dynamics. It is therefore possible that this geometrical feature affects conditional earthquake segmentation behavior on the Alpine Fault, as documented by the extensive paleoseismic record.

We use the 3D finite element method to simulate multiple cycles of dynamic ruptures on the southwestern ~320 km of the Alpine Fault. We embed the faults in a 1D velocity structure and impose heterogeneous initial tractions computed using seismologically estimated local principal stress orientations and magnitudes computed using a critically-stressed crust model. We simulate the coseismic period using dynamic rupture simulations, then account for the interseismic period by incrementing shear stress based on a set time between events. For each dynamic rupture simulation, we compare the modeled rupture lengths and surface slip values to geologic and paleoseismic studies to ensure that we are producing physically-plausible simulations consistent with observations. We find that the dip change at the segment boundary is not inherently a barrier to rupture within single events, but that stress changes associated with rupture through this boundary in one earthquake can sometimes lead to segmentation in the next one. Our results suggest that rupture hazard on the Alpine Fault may depend both on the slip distribution of and the timing since the previous large earthquake. This also implies that both fault geometry in and of itself and long-term stress patterns resulting from that geometry are important considerations for hazard assessment on other geometrically-complex faults.

Deformation Partitioning, Directivity Effects, and Stress-Drop of Seismicity Along the Main Marmara Fault Offshore Istanbul/Türkiye in the Light of an Overdue M7+ Earthquake

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The Marmara section of the North Anatolian Fault zone (NAFZ) in northwestern Türkiye is late in its seismic cycle and expected to produce a large M>7 earthquake in direct vicinity to the Istanbul metropolitan region. Monitoring the NAFZ below the Sea of Marmara is a challenge due to absence of near-fault islands except for its eastern section. High resolution seismic monitoring has been achieved through setting up the borehole-based GONAF (Geophysical Observatory at the North Anatolian Fault) infrastructure monitoring seismicity as well as slow deformation transients.

Analyzing the occurrence of repeating earthquakes as indicator for seismic creep we identify several repeater families below the eastern and – to a lesser extent- also below the central Sea of Marmara. We conclude on a systematic transition of deformation along the Main Marmara Fault from dominantly creeping in the west , an intermittent state of locked-creeping deformation at its central part, and the fully locked Princess Islands segment immediately south of Istanbul. Small, but statistically significant, spatial stress-drop variations are observed among some segments of the fault. Lower average stress-drop values are observed in zones surrounding earthquake repeaters, which may imply a weaker fault along the creeping region. Recent M>5 earthquakes along the Main Marmara Fault did not exhibit significant changes in the mean stress-drop, suggesting no reduction of fault stress level or fault strength due to the occurrence of these events. To improve rupture scenarios for the pending large Marmara earthquake we estimate the rupture directivities for 30 M>3.5 earthquakes along the Main Marmara Fault. We constrained earthquake moment tensors for these events providing evidence for their potential fault planes and observe a predominant eastward rupture direction for half of the events, most of them located along the western and central parts of the Main Marmara Fault. This suggest that about 50% of the analyzed events displayed a preferential orientation of energy release towards Istanbul, hence probably increasing the ground shaking in a major event.

Insight Into Depth Variations in Effective Stress and Fault Strength From Geodynamic-Seismic Cycle and Earthquake Dynamic Rupture Modeling

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The local stress regime and fault strength together exert first order control on fault mechanics and earthquake rupture dynamics. However, these characteristics remain elusive, especially at the level of detail desirable for initiating numerical simulations of large earthquakes on complex fault networks, which now are computationally possible. Linking between a geodynamic-seismic cycling model and a dynamic earthquake rupture model suggests that the effective stress field near a fault and the static and dynamic fault strength vary non-linearly with depth and are materially dependent. We present two model scenarios that contrast earthquakes resulting from (1) these heterogeneous initial conditions and (2) more commonly used, simpler initial conditions. Although the maximum fault strength is similar in both scenarios, the heterogeneous initial conditions in (1) result in larger fault slip, but lower average dynamic stress drop and lower rupture velocity. In addition, we observe that seismic waves traveling through complex materials around the fault in (1), as opposed to the homogeneous material in (2), influence earthquake rupture style and shallow slip accumulation. In both scenarios, the pore fluid pressure (Pf) increases linearly with depth. We further share how fault mechanics and earthquake dynamics are influenced by a simple change in the linear variation of Pf from sublithostatic to lithostatic, in which Pf is slightly less than, but constantly offset from, the lithostatic stress. If Pf follows a sublithostatic gradient, then pre-earthquake effective normal stress increases with depth. If Pf follows the lithostatic gradient, then normal stress is relatively constant with depth. As a result, a lithostatic Pf gradient moves peak slip and peak slip rate up-dip, and produces a more constant stress drop across the megathrust. These insights underscore the need to better understand initial earthquake conditions from a variety of sources, including collaborative modeling, in order to advance our understanding of earthquake initial conditions, fault strength and earthquake behavior.

Deep Slip Occurs Prior to Surface Creep Events on the San Andreas Fault

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Scientists have used creepmeters to observe the surface expression of creep events along the San Andreas Fault since the 1960s. These creep events represent episodic slip bursts that have a duration of 1–2 days with a small amount of steady background creep between events (e.g., Gittins & Hawthorne, 2022; Gladwin et al., 1994; Nason et al., 1974; Schulz, 1989). During a creep event, the fault typically slips a few millimeters over several hours to days, with events separated by a few weeks to months. At the surface, creep events accommodate >50% of slip along the San Andreas Fault (Gittins & Hawthorne, 2022), but the evolution of slip at depth is less well constrained because of a lack of depth resolution provided by the current creepmeter design.

To observe deeper—down to 10 km—we use strainmeters. This study investigates the deep slip associated with surface recordings of creep events. We analyze strain observations in the 10 hrs before and during creep events at the northern end of the Central San Andreas Fault. We identify 71 offsets in the strain time series created by short bursts of slip within longer creep events. Then, we perform a grid search to determine the location, depth, and magnitude of these slip bursts by modeling rectangular slip patches in a homogeneous elastic half-space. We find that these slip bursts occur up to 7 km from the recorded location of surface rupture associated with the longer creep event, as observed by creepmeters. 42–55% of the slip bursts are likely to occur below 4 km depth and have moments equivalent to Mw 3.2–4.1 earthquakes. Our observations suggest that creep events are not always simply shallow, triggered phenomena. They originate spontaneously from a range of locations, including depths that are comparable to the depths of nearby earthquakes. Creep events also show complex propagation histories, triggering several slip locations as they propagate horizontally. These strain offsets within creep events show a nucleation and propagation history that needs further exploration, perhaps with a more optimal instrument configuration and design.

Simulating the Formation and Evolution of Complex Fracture Patterns Arising From Shallow Strike-Slip Faulting With Finite and Discrete Element Analyses

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Shallow strike-slip faulting generates complex distributions of deformation that range from networks of en-echelon fractures and contractional and extensional structures to through-going shear zones expressed at Earth's surface. Distributed inelastic deformation accommodated by these features affects the amount of fault slip that reaches Earth's surface, thereby biasing slip estimates used for probabilistic seismic hazard and fault displacement hazard analyses. These well-documented fractures and shear structures have been studied in laboratory, field, and numerical analyses, but field interpretations are typically limited to 2D perspectives, and numerical investigations often cannot resolve discrete, localized shear structures.

In this investigation, we use 3D finite element method (FEM) and 3D discrete element method (DEM) models to examine how changes in shallow fault zone structure, material properties, and strike-slip loading conditions affect the predicted distributions of fault slip and strain. We use the unique advantages of FEM models (e.g., computational efficiency and straight-forward material parameterizations) and DEM models (e.g., improved resolving power in capturing discrete shear-zone structure development and evolution) to understand how material properties of the shallow crust, such as the internal angle of friction, cohesion, and dilatancy, affect the shallow fault zone fracture patterns in strike-slip faulting regimes. Our models suggest that DEM particle-packing densities and inferred material dilatancy strongly influence the complexity of shallow shear zones, where branching shear structures that develop within dilatant materials contrast with subvertical, planar structures that form in non-dilatant materials. In these models, the evolution of material dilatancy with increasing fault slip also influences the expression of fault zone deformation as fault slip continues to accrue. We compare our results with data-constrained field sites to understand how these models may inform surface displacement and deformation distribution predictions surrounding strike-slip faults.

Characteristics and Mechanics of Fault Zone Rupture Processes, from Micro to Macro Scales [Poster Session]

Poster Session • Thursday 2 May

Conveners: Xiaowei Chen, Texas A&M University (xiaowei.chen@tamu.edu); Yifang Cheng, University of California, Berkeley (chengyif@berkeley.edu); Zhe Jia, University of California, San Diego (z5jia@ucsd.edu); Junle Jiang, University of Oklahoma (jiang@ou.edu)

POSTER 74

Constraining 3D Fault Geometry With a Data-Driven Approach at the San Andreas—Calaveras Fault Junction

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Accurately characterizing three-dimensional (3D) fault geometry is crucial for understanding earthquake behavior and refining seismic hazard models. However, detailed subsurface fault structure is often unknown, particularly in complex fault networks. This study presents a data-driven approach to reconstruct 3D fault geometries by leveraging mapped surface traces, double-difference relocated earthquake hypocenters, and newly computed and improved focal mechanisms (Shelly et al., 2022; Skoumal et al., 2022). Our method integrates established machine learning techniques for event clustering to associate nearby events together and assigning events to mapped faults, offering improvements in resolving intricate fault networks.

Preliminary synthetic tests demonstrate that incorporating focal mechanism information significantly improves the accuracy of hypocenter clustering in anastomosing fault systems. Applying this methodology to the well-studied San Andreas-Calaveras fault junction reveals an unexpected finding that continuous quasi-linear trends of seismicity are erroneously subdivided by the clustering algorithm. We propose a refinement that combines adjacent clusters with similar orientations, resulting in a more accurate depiction of the fault network.

This research provides a low-user-input workflow for reconstructing multiple fault geometries at depth from readily available data. By analyzing the reconstructed fault network, we shed light on the complex structures involved in accommodating the partitioning of slip at San Andreas-Calaveras fault junction and highlight the potential differences in fault network morphology between locked and creeping sections of the San Andreas Fault. Our findings will contribute to a more comprehensive understanding of earthquake dynamics and improve constrains on fault connectivity for rupture forecasts.

POSTER 75

Unveiling Shallow Earthquake Ruptures in the Ryukyu Area: A Comprehensive Study Through Bp Imaging and Regional Cmt Catalog

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In the last few centuries, the absence of significant interplate or tsunamigenic earthquakes has led to ambiguous conclusions regarding the coupling rate in the Ryukyu subduction zone. Estimations of large slip-deficit rates from GPS data and the discovery of slow earthquakes suggest both strong and weak coupling rates. Despite these geophysical observations, the seismic database for small to large earthquakes remains incomplete due to the limited coverage of seismic networks. Discrepancies in focal depths between the JMA event catalog, GCMT, and NIED CMT solutions further challenge understanding seismogenic structures. To address this, our study aims to enhance the CMT catalog covering small to large earthquakes (M≥4) from 2000 to 2022. We include three broadband networks to ensure better azimuth coverage: BATS (Broadband Array in Taiwan for Seismology), F-net from NIED, and FJ-network (Fujian Earthquake Agency). The AutoBATS MT algorithm is adapted to facilitate the necessary epicenter scanning for CMT inversion. For the western Ryukyu area, our inversion results for larger earthquakes are overall consistent with the GCMT solutions. For earthquakes larger than 6.0, we also apply Multiple signal classification (MUSIC) back-projection imaging to determine the causative fault planes, rupture extends, and durations. The rupture properties of major earthquakes and the comprehensive regional CMT catalog may offer additional insights into future studies on coupling rates.

POSTER 76

Probing Transient Rheology and Spatial Heterogeneity of Faults Using Repeating Earthquakes and Deformation Data

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Fault zone rheology and heterogeneity have fundamental controls on earthquakes and fault behavior. Constraining these intrinsic fault properties requires high-resolution geophysical observations and faces enduring challenges due to a lack of in-situ measurements and validations. Here we use continuous seismic and geodetic observations following the 2004 Mw6.0 Parkfield earthquake of the San Andreas fault to image rapidly evolving transient faulting processes and thereby constrain fault zone rheology and heterogeneity. For seismic observables, we compare several characteristically repeating earthquake (CRE) catalogs to obtain refined event identification and estimate the in-situ fault slip history at depth assuming a model of single asperity surrounded by creep and a common scaling relation of recurrence interval and fault slip. For geodetic observables, we combine high-rate GNSS (Global Navigation Satellite System) and InSAR time series (Interferometric Synthetic Aperture Radar) displacement data. To optimize the disparate and yet complimentary spatiotemporal resolutions of GNSS and InSAR, we design a new two-step strategy to retain the GNSS-based high temporal resolution of finite-fault afterslip models while incrementally ingesting additional spatial constraints from less-frequently sampled, high-density InSAR deformation fields. We compare and reconcile the two independent approaches, based on the CRE scaling and geodetic finite-fault slip models, to estimate spatially- and temporally-varying postseismic fault slip history in the seismogenic crust. The derived or inferred fault slip histories are used to estimate the rheological laws and parameters for fault zones based on theoretical models. The along-dip and lateral variations of fault properties, along with discrepancies in seismic and geodetic estimates, help us further interpret the heterogeneous state of fault zones.

POSTER 77

Illuminating the Jericho Fault from A New Local Seismic Network

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The Jericho Fault is an active fault segment located north of the Dead Sea Lake. It is considered the source of significantly large earthquakes in the region, such as the 6.25 magnitude earthquake in 1927[AS1] and is classified as a locked fault. Although a significant amount of work has been reported on the Jericho Fault, several key questions remain unanswered. Firstly, can we provide direct seismological evidence of the fault from earthquakes? What is the fault width in seismogenic depths? Is the fault completely seismically quiet towards low magnitudes (i.e., below 1)? Answering these questions will improve seismic hazard estimates and provide information on micro-seismicity along locked faults.

From one year of data (06/22 – 06/23) we find 63 seismic events in the range of -0.54 < 0.84, that are below the detection threshold of the permanent regional network. We support the observation of a locked fault towards the microseismic range as most events lie off-fault. Additionally, microseismicity there does not follow a Gutenberg-Richter power-law distribution. Therefore, it questions the validity of using power-law distributions to estimate the maximum magnitude. The Jericho Fault releases significantly less seismic moment than the Anza gap (a seismically quiescent segment of the San Jacinto Fault), indicating a particularly quiet fault. The whole fault appears to be creeping from ~0-20 Km aseismically with tiny release of seismic energy, supporting observations from geodetic studies. More strain energy could be accumulating, and release as relatively large earthquakes compared to fault segments that release seismic moment more frequently. Secondly, we analyse trapped waves, which reveals information about the damaged section of the Jericho Fault zone. We observe trapped waves across our local array and to our knowledge this is the first direct seismological evidence from earthquakes of a coherent zone of damaged rock that trends northwards from the Dead Sea Lake.

POSTER 78

Fault Network Geometry's Control on Earthquake Rupture Behavior

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While fault slip behavior has been predominantly attributed to local fault plane properties such as frictional parameters and roughness, the role of larger scale fault geometry has remained relatively unexplored. Emerging observations highlight the importance of fault system geometry in the mechanics governing earthquake rupture processes. Drawing from compiled observations, we study how the geometrical complexities of fault networks impact various aspects of fault slip behavior, including how these complexities affect fault creep and earthquake source spectra. We quantify fault network complexity by measuring the degree of surface fault trace misalignment and the local variability of earthquake focal mechanisms. We investigate the relationships between metrics of fault complexity and surface creep rates, earthquake corner frequencies, and earthquake moment rate function complexity, demonstrating that complex fault networks suppress fault creep, lead to higher earthquake corner frequencies, and introduce complexities in the moment rate functions. We interpret these observations as a consequence of geometric locking, which inhibits fault creep, and the elastic loading and unloading of discrete fault structures, which leads to enhanced high-frequency seismic radiation. Our study is based on a dataset of diverse geophysical parameters gathered from California, supplemented by measurements from Japan, central Italy, and worldwide. The observations from independent sources, spanning different scales and geological regions, consistently support our hypothesis that complex fault systems contribute significantly to complex earthquake ruptures. Our findings demonstrate the potential for a new framework in which earthquake rupture behavior is governed primarily by fault network geometry.

POSTER 79

Posterior Exploration of Bayesian Kinematic Finite-Fault Earthquake Source Models

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The Bayesian inversion framework for earthquake source imaging yields an ensemble of posterior models, as opposed to conventional inversion methods that produce individual optimal solutions. Yet, using Bayesian posterior solutions for predicting stress and displacement fields, and their associated uncertainty has been under-explored. Here, we quantitatively characterize the uncertainty structure and predictive observables of kinematic finite-fault earthquake rupture models from published Bayesian inversions for several large megathrust earthquakes, including 2011 Mw9.0 Tohoku, 2014 Mw8.1 Iquique, 2015 Mw8.3 Illapel, 2016 Mw7.8 Pedernales, and 2015 Mw7.8 Gorkha. These events can be grouped into distinct types according to slip patterns: tsunamigenic (Tohoku, Illapel), no trench-breaking (Iquique, Pedernales, and Gorkha), and multi-patch (Illapel) rupture scenarios. Employing homogeneous and layered elastic structures, we compute and compare surface deformation and normal and shear stress on the fault plane for each event. In all cases, surface deformation manifests itself in a transitional way with uplift occurring closer to the trench and smaller subsidence effects in the down-dip direction. Compact large vertical seafloor deformation is prominent for events with tsunamigenic slip. Distributions of significant rupture observables are usually confined to the area directly above the prescribed fault geometries. Stress change appears to be event-dependent due to variable rupture patterns across events. We will leverage posterior model ensembles to rigorously evaluate error propagation in surface displacement and stress change, address how error varies as function of distance from the trench, and evaluate scale-dependent correlation between model parameters. Future work will include computing elastodynamic ground motion and stress changes during these events.

POSTER 80

Comparing Fault Zones that Host Induced and Tectonic Earthquakes in Oklahoma and California

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We have developed a new approach to detect and image fault zone structures through the azimuthal variation of earthquake spectra. The spatial distribution of earthquake clusters where the high-frequency amplification is observed could shed light on the characteristics of the fault damage zone. Our previous studies show that the Ridgecrest fault zone structure is more coherent along strike compared to that of the Parkfield region. Our results also demonstrate the fault zone structure can extend up to ~10 km given the observation of high-frequency energy from earthquake clusters. Our method has only been applied in tectonic regions thus far, but understanding the fault zone structure in induced seismicity regions is also important as it can provide pathways for fluid propagation. Hence, we plan to investigate induced earthquakes in Oklahoma and more tectonic earthquakes in Southern California. For example, possible candidates include the Fairview, Oklahoma region comprising near-vertical narrow strike-slip faults and the San Jacinto fault zone, which comprises three fault strands with different structure. We will use the stacked P-wave velocity spectra of M<3 earthquake clusters from broadband stations to identify any azimuthal variation in high-frequency energy. We aim to apply our method to search for fault damage zone structures in those regions in order to enhance our understanding of the co-evolution of fault zones and earthquake cycles.

POSTER 81

Systematic Measurements of Rupture Directivity for Small-to-Moderate Earthquakes in California

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Rupture directivity is an important but poorly characterized earthquake source property that can have a direct effect on the azimuthal distribution of ground motions and hence earthquake hazard. Directivity has been measured for many moderate-to-large earthquakes in California, but systematic measurements for smaller earthquakes are needed to obtain a more complete picture of the underlying rupture and fault mechanisms that control directivity and amplified ground motion. Developed by Ross & Ben-Zion (2016) and expanded by Calderoni et al. (2023), the directivity index is a measure of azimuthal difference in the spectral ratio between a target event and a nearby empirical Green's function (EGF) event, averaged over a frequency range spanning the target and EGF corner frequencies. Here, we generalize this approach by calculating the azimuthal distribution of the directivity index, which allows for inference of dominant rupture direction in cases where the rupture plane is unknown a priori. We apply this technique to assess spatiotemporal patterns in rupture directivity characteristics for small earthquakes throughout California that are well-recorded by recent network expansions in the state. We use synthetic tests to establish the quantitative relation between directivity index measurements and physical rupture properties, and also develop a system for ranking the quality of each EGF or combination of EGFs used in the measurements to improve the robustness of the results. Preliminary results show success for small-to-moderate strike-slip earthquakes in the San Jacinto Fault Zone, and we aim to expand that work to include M3+ events in throughout the state, as well as test the method on earthquakes in dip-slip regimes.

POSTER 82

Lithospheric Structure of the Hispaniola and Puerto Rico/Virgin Islands Microplates Using Teleseismic and Local Data

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The complex tectonics and high seismic activity of the Caribbean-North American plate boundary region is well documented. Hispaniola, in particular, has a history of devastating earthquakes with numerous aftershocks, but a better understanding of regional tectonics, as well as reliable estimates of seismic and tsunami hazards, await the development of a detailed 3D seismic velocity model and a comprehensive earthquake catalog with accurate locations. Moreover, the region experiences earthquakes to depths of ~200 km beneath eastern Hispaniola and the Mona Passage, the causes of which are not well understood. Various authors suggest that these earthquakes may result from the interactions between converging tectonic plates, or due to the subduction of the North American plate's slab edge beneath Puerto Rico, or from activity along a subduction transform edge propagator fault, but these hypotheses require further investigation.

To better constrain regional seismicity and advance our understanding of lithospheric structure in the region, this study leverages data recorded by local seismic networks to perform 3D seismic travel time tomography. Seismic stations have monitored the region comprehensively for the last decade, so the recorded data enable the development of a more detailed and accurate 3D model than has been possible previously. We measured ~5,609 teleseismic P-wave travel times from 189 earthquakes with magnitudes >5.5 recorded by 90 stations. Additionally, we have ~307,000 P (and S) arrivals from well-located local events (M>2.7). The model space is divided into two layers, crust and mantle, and is delimited by latitudes 15°S and 26°N and longitudes 58.75°E and 85°W. Nodes are spaced 14.5 km apart in depth and 25 km laterally in the crust and 20 km apart in depth and 40 km laterally in the mantle. The final 3D model is found with five iterations, in which raytracing is performed after each iteration until residuals change less than 5% between iterations.

POSTER 83

Investigation of Earthquake Nucleation Processes: A Case Study of the 2019 Ridgecrest Earthquake Sequence

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Understanding the nucleation processes of earthquakes is crucial in seismology. The 2019 Ridgecrest earthquake sequence, notable for its high seismicity rate, complex fault interactions, and the occurrence of the significant mainshock (Mw7.1) with abundant foreshocks, provides a unique case for studying earthquake nucleation processes. Despite previous analyses and modeling of seismic data, there remains considerable debate regarding the specific triggers and fault interactions that led to the 2019 Ridgecrest earthquakes, indicating a crucial need for further investigation. We aim to examine the near-source structure and faulting environment in the Ridgecrest region by studying 83,000 events spanning five years before and after the Ridgecrest mainshock with their corresponding first arrival times and waveform data. We will construct a high-precision earthquake relocation catalog based on the three-dimensional seismic velocity model and waveform cross-correlation data.

Furthermore, we plan to image the spatiotemporal evolution of the fault zone structures using a high-resolution in situ Vp/Vs method, offering potential new insights into the nucleation processes of the Ridgecrest earthquake. Our findings will shed light on the possible role of fluid dynamics and fault interactions in influencing the seismic behavior observed during the Ridgecrest earthquake sequence.

POSTER 84

New Zealand's South Westland Alpine Fault: What's Down There and How Does It Make Earthquakes Stop?

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Approximately half of past major Alpine Fault earthquakes have arrested close to the transition from the listric Central Segment to the sub-vertical South Westland Segment. Here, the fault undergoes notable changes in geometry, slip rate, kinematics, bounding lithology, resolved stress, seismogenic behaviour and frictional properties, all of which have the potential to influence throughgoing rupture behaviour. Unravelling which factors contribute to observed conditional rupture arrest here—and therefore assessing likely future rupture behaviour—requires a combination of detailed observations about the fault's physical state to inform realistic, physics-based earthquake rupture models.

Recent work to produce precise relocations of thousands of earthquakes and their focal mechanisms has illuminated the structure and microseismic behaviour of the segment boundary leading to improved quantification of the spatial variability in physical factors mentioned above. Here, we present these results and build on our observations to use those local earthquake phase-arrivals in 3D tomographic models of the segment boundary in unprecedented resolution. We present preliminary Vp, Vs and Vp/Vs models revealing large-scale changes in crustal structure across the segment boundary, high-velocity bodies associated with the Dun-Mountain ultramafic terrane and Livingstone Fault, and compare these with newly relocated seismicity to identify active structures. Our full suite of observations are then used to inform a series of 3D finite-element dynamic simulations of earthquakes along the fault. Iterative geometric and stress parameterisations allow us to assess the relative role different physical factors play in allowing ruptures to either propagate through, or terminate at the segment boundary. We find that successive on-fault stress changes from a series of earthquakes around the geometrical boundary can reproduce rupture arrest consistent with the paleoseismic record and surface slip values.

POSTER 85

Spatio-Temporal Slip Distributions of Deep Short-Term Slow Slip Events in the Nankai Subduction Zone Using Gnss, Tilt, and Strain Data

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Slow slip events (SSEs) have been repeatedly observed on the deep plate interface at ~30-40 km depth in the Nankai subduction zone, Japan. These SSEs have been monitored using three types of geodetic data: GNSS, tilt, and strain. GNSS has strength in their station density, whereas its sensitivity to crustal deformation is lower than tilt and strain. Tilt and strain has strength in their sensitivity to crustal deformation, but their station is much less than GNSS. In addition, tilt and strain has unique noise like Brownian motion, which makes us difficult to analyze those data. In this study, we develop the integrated inversion method using the three types of data for spatio-temporal slip distributions of deep SSEs in the Nankai subduction zone.

We first test the performance of the developed method using synthetic datasets. We calculated crustal deformation due to synthetic SSEs in the Shikoku region with three different magnitudes (Mw 5.7, 6.0, and 6.3). We also calculate synthetic observation noise (Gaussian noise for GNSS and Brownian noise for tilt and strain). The summed signals of these two synthetic values are considered as pseudo-observation, and we applied the developed method. We tested all possible combinations of data types and checked whether the assumed spatio-temporal slip distributions are well reproduced. We tested the resolution of the developed method using checkerboard test as well. We will also report preliminary results for real data application in the Shikoku region.

Cordilleran Strike-Slip Faults as Seismogenic and Seismological Features

Oral Session • Thursday 2 May • 4:30 PM Pacific

Conveners: Richard Lease, U.S. Geological Survey (rlease@usgs.gov); Sean Regan, University of Alaska Fairbanks (sregan5@alaska.edu); Sarah Roeske, University of California, Davis (smroeske@ucdavis.edu); Trevor S. Waldien, South Dakota School of Mines and Technology (trevor.waldien@sdsmt.edu)

Is the Rocky Mountain–Tintina Trench Tectonically Active?

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The Rocky Mountain–Tintina Trench (RMTT) is one of the most conspicuous topographic lineaments on Earth, stretching from Montana through the eastern Canadian Cordillera and into Alaska. It is the locus of major Eocene transtensional faulting and marks a step-change in lithospheric thickness, strength, and thermal properties. There is a moderate level of seismicity in the vicinity of the RMTT, and several historical earthquakes have caused shaking and minor damage. However, little is known about the paleoseismic record of the RMTT and the potential for larger and more damaging earthquakes along it. Improving this record is important for the safety of the ~135k people that live along the RMTT, as well as the dams, pipelines, highways, and rail corridors that cross it. Here we review high-resolution topographic data (drone and airborne lidar and ArcticDEM) along the Canadian portion of the RMTT and examine in detail several potentially fault-deformed Quaternary landforms. In the southern RMTT near the town of Fairmont Hot Springs (50.3°N), a Holocene alluvial fan surface is disrupted by a 4-m-high west-facing scarp. Electrical resistivity tomography reveals a listric normal fault beneath the scarp—kinematics that are at odds with contemporary compressive crustal stress patterns. Near the town of Mackenzie (55.1°N), seismic reflection surveys and outcrop observations are suggestive, but not conclusive, of fault-deformed glacial till. At the British Columbia - Yukon border (60°N) a subtle linear mound disrupts glaciofluvial outwash gravels, indicating Holocene strike-slip rupture. In northwestern Yukon, near Dawson City (64°N), a 120-km-long series of scarps and "mole-tracks" disrupts a ~3 Ma landscape, but a 200 ka glacial moraine overlying the fault is undeformed, suggesting that activity on this segment of the RMTT has waned in the mid-to-late Quaternary. These results are the first conclusive evidence of Quaternary surface-rupturing earthquakes along the RMTT and, in addition to the implications for seismic hazard, significantly change our understanding of the Cenozoic evolution of the Canadian Cordillera.

Evolution of Subsidiary Faults Associated With the Migration of the Mount Mckinley Restraining Bend, Denali Fault, Alaska

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The model of a migrating Mount McKinley restraining bend (MMRB) is established based on patterns of active faulting, topography, glaciers, and low-T thermochronology, but the connection between this migration and the patterns of local seismicity, and longer-term geomorphic markers is unclear. Previous analyses of Kantishna Cluster seismicity show that these earthquakes do not approximate discrete fault planes, yet correspond broadly with known active structures. We seek to derive a model of crustal deformation evolution associated with the MMRB that incorporates major regional geologic and geophysical phenomena. To constrain this model, we present new constraints on the rates and distribution of active faulting and combine this with the record of shallow seismicity and new geophysical observations. New results from terrestrial cosmogenic nuclide and luminescence dating of offset landforms, improved fault trace mapping and offset measurement from higher resolution topographic data, and new thermochronologic constraints refine our understanding of the extent, magnitude, and style of active faulting through the MMRB. We propose that the sub-clusters of low-magnitude seismicity with the Kantishna Cluster reflect individual 'process zones' of distributed fracturing and faulting associated with the development and propagation of faults outward from the migrating restraining bend. The geophysically-imaged sub-horizontal detachment beneath the Kantishna Hills occurs in a region exhibiting a longer record of distal deformation north of the MMRB as demonstrated by the uplift of the Kantishna Hills anticline. As cumulative uplift of the Kantishna Hills anticline decreases to the west, both the seismicity and the northern extent of active deformation abruptly step closer to the Denali fault. This concentration of deformation between the Hines Creek and Denali faults appears to reflect a shorter period of time interacting with the restraining bend and a lack of development of a deeper detachment to transfer strain into the foreland.

Residual Yakutat Microplate Velocity Drives Rapid Thrust Faulting North of the Central Denali Fault

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Plate convergence rates strongly influence seismicity and mountain building inboard of convergent margins, but the distribution and kinematics of structures accommodating far-field convergence can be elusive. In interior Alaska, Yakutat microplate convergence drives late Pleistocene–recent right-slip on the Denali Fault, but westward-decreasing slip rates leave substantial residual Yakutat motion unaccounted for. Here, we show that the Northern Foothills thrust slip accommodates a modern 4.4 mm/yr geodetic velocity gradient equivalent to ~78% of the total ~5.6 mm/yr residual Yakutat convergence along the central Denali Fault. Infrared-stimulated luminescence ages of strath terrace deposits (4–67 ka; 6 sites) quantify Totatlanika River bedrock incision across the 1947 M_w 7.1 thrust earthquake epicentral region. Incision rates increase northward abruptly from <1 mm/yr to 4.8–5.6 mm/yr across the range-front anticline overlying the blind thrust tip. Rapid 6.7 mm/yr slip on a steep thrust ramp modeled beneath the northern Alaska Range front accommodates the geodetic gradient, drives rock uplift at rates equivalent to measured incision rates, and implies that large earthquakes like the 1947 event may recur with 500–1400-yr frequency. Results illuminate focused seismogenic strain inboard of a complex convergent margin, and demonstrate that the pace of continental indentation in Alaska doubles prior expectations with direct implications for extant seismic hazard estimates.

Seismic Imaging of the Eastern Alaska Range Crustal Structure

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The Denali fault is an active right-lateral continental strike-slip fault that transects the North American Cordillera from northern British Columbia to the Bering Sea shelf. The structural evolution of the Denali fault as a major continental fault system that has accommodated hundreds of kilometers of displacement implies that the fault is a significant geophysical feature. However, the complex and diverse geology surrounding the fault, and variability in geologic and geophysical data resolution, cause the perceived geophysical signature of the fault to be spatially variable. Here, we explore the geologic evolution of the eastern Alaska Range and the central portion of the Denali fault by integrating new understanding of the geologic framework with new seismic images of the crustal structure. Our new seismic images utilize all available data (1999-2022) from both temporary and permanent broadband seismometers available from the IRIS DMC. These data include the recently deployed ICED array (Z5 network) that targeted the eastern Alaska Range and adjacent section of the Denali Fault that had previously been under-resolved by the TA and other temporary deployments. We combine new ambient noise based tomography inferring the shear wave velocities, P receiver functions to define the Moho topography, and a new machine learning based catalog of seismicity together to infer the structural heterogeneity of the crust around the Denali fault. Complimentary geophysical information from this section of the fault corroborates geologic observations indicating that the Denali fault is a primary lithospheric-scale boundary, with some sections that clearly indicate a step across the Moho.

The Crustal Magmatic Structure Beneath the Denali Volcanic Gap in Central Alaska Across the Denali Fault

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Within the active subduction system, the presence of the Denali Volcanic Gap (DVG), a ~400 km region separating active volcanism of the Aleutian Arc to the west and the Wrangell volcanoes to the east, remains enigmatic. It is unclear if the subduction system is producing and storing magmatic material at the bottom of the crust or if high stresses in the crust impede the transport of material in the mid-crust, thus stalling volcanic activity. To better understand the effects of tectonic forces in the south-central Alaska upper crust, we present a 270 km long and 15 km deep 2-D shear wave velocity model of south-central Alaska across the Denali fault. We use data from a linear temporary node deployment with more than 300 geophone stations and broadband stations available in the area. We use single beamforming/slant stacking to enhance the ambient noise cross-correlation signals and simultaneously measure location-dependent Rayleigh wave phase velocity and ellipticity or horizontal to vertical (H/V) amplitude ratios. We perform 1-D Markov chain Monte Carlo joint inversions of Rayleigh wave phase velocities and H/V ratios to calculate the shear wave velocity profile. Our main observations include a low-velocity zone below the Denali Volcanic Gap, the fold-and-thrust belt in the northern flank of the Alaska Range, and the Denali fault as a narrow localized low-velocity anomaly extending to at least 12 km depth. The low-velocity anomaly below the DVG could be associated with the accumulation of melt storage of subduction-related material in the mid-crust.

Cordilleran Strike-Slip Faults as Seismogenic and Seismological Features [Poster Session]

Poster Session • Thursday 2 May

Conveners: Richard Lease, U.S. Geological Survey (rlease@usgs.gov); Sean Regan, University of Alaska Fairbanks (sregan5@alaska.edu); Sarah Roeske, University of California, Davis (smroeske@ucdavis.edu); Trevor S. Waldien, South Dakota School of Mines and Technology (trevor.waldien@sdsmt.edu)

POSTER 86

Refining the Nature of Distributed and Localized Slip-Partitioning of the Totschunda-Fairweather to Denali Corridor Using Earthquake Relocations and Focal Mechanisms

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Southeastern Alaska and southwestern Yukon are at the plate boundary between the Pacific and North American plates and the Yakutat microplate. The region is undergoing complex active deformation due to the oblique collision of the Yakutat microplate with North America. Transpressional deformation is accommodated 300 km inboard from the plate boundary by large displacement, regional-scale faults, including the Fairweather, Denali, and Duke River fault systems. Monitoring in the region is limited due to the remote setting and year-round snow and glacial coverage. In the last decade, regional seismic networks have significantly expanded, leading to an increased density of stations largely attributed to the deployment of Transportable Array stations, many of which were converted to permanent stations in the Alaska regional network. In this study, we relocate more than 5,000 earthquakes between 2010 and 2021. These earthquake relocations show reduced uncertainty, particularly in depth, and allow us to show that brittle regime deforma-

tion occurs on a shallow fault network in the upper 10 km of the crust. The region has a shallow brittle-plastic transition consistent with elevated crustal temperatures across the Cordillera. We interpret and classify deformational kinematics across this corridor by combining earthquake relocations with regional focal mechanism solutions. The focal mechanism catalog includes 374 novel low-magnitude focal mechanism solutions. Our interpretive fault map includes the postulated Totschunda-Fairweather Connector fault, which helps to explain regional deformation. We identify new faults, such as the Kathleen Lake fault. Our interpretation includes a simplified conceptual model that describes the region characterized by transpression with distributed and localized slip partitioning. This study provides a current snapshot of active seismic deformation on a well-defined shallow network of faults occurring within this continually evolving oblique convergent tectonic regime.

POSTER 87

Revisiting the Enigmatic Magnitude-7 Denali Fault Earthquake of July 7, 1912

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The 2002 Mw 7.9 Denali fault earthquake ruptured 341 km within central Alaska. Its occurrence prompted a search for evidence of earlier earthquakes on the Denali fault, the most recent candidate being a Ms 7.2 earthquake on July 7, 1912. The enigma of the 1912 earthquake is twofold. First, the maximum reporting shaking intensity—documented by the Parker-Browne Denali mountaineering expedition—is ~250 km west of damaged trees documented by Carver et al. (2004), while empirical scaling suggests a rupture length of about 60-80 km for a magnitude 7.2 earthquake. We revisit the 1912 earthquake with two approaches: 1) probabilistic relocation of epicenter using globally recorded arrival times, and 2) compilation and reassessment of shaking intensity reports to estimate a macroseismic epicenter. Our preferred instrumental epicenter is west of the Parks Highway, in agreement with the maximum reported shaking by the Parker-Browne expedition. We also examine data choices that result in instrumental epicentral estimates that are toward the east and closer to the documented tree damage. We explore two possibilities for the 1912 earthquake, all of which assume the Denali fault as the host. The first scenario is that there was a single, exceptional earthquake having a long rupture and strong shaking, relative to its magnitude. The second scenario is that there were two earthquakes: a large one (M 7.2) in the west, near the Parks Highway, and a smaller one (M 6.5-7) in the east, near the Richardson Highway. The large event occurred on 1912-07-07 and produced the global arrival times and the strongest felt report near Denali, while the smaller event occurred minutes to months after the large event and was responsible for the tree damage reported by Carver. Further analysis of instrumental data, felt reports, and paleoseismic results may help discriminate among these scenarios.

Creating Actionable Earthquake Information Products

Oral Session • Wednesday 1 May • 8:00 AM Pacific

Conveners: Tiegan Hobbs, Geological Survey of Canada (thobbs@eoas.ubc.ca); Sabine Loos, University of Michigan (sloos@umich.edu); Marísa A. Macías, U.S. Geological Survey (mmacias@usgs.gov); Jessie K. Saunders, California Institute of Technology (jsaunder@caltech.edu); David Wald, U.S. Geological Survey (wald@usgs.gov)

Improving Rapid Earthquake Characterization for Tsunami Early Warning for Aotearoa New Zealand and the Southwest Pacific

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Aotearoa New Zealand, located in the Southwest Pacific Ocean, is vulnerable to tsunamis. The Rapid Characterization of Earthquakes and Tsunami (RCET) project, led by GNS Science (Geological and Nuclear Sciences), aims to improve rapid analysis of large local and regional earthquakes to determine their tsunamigenic potential and better capture the rupture process. To this end, we are focusing on refining a W-phase solution (automated moment tensor inversions) on a regional scale. Unlike simpler automated magnitude determinations routinely used to analyze earthquakes in Aotearoa New Zealand, the W-phase does not saturate with magnitude, making it better at quantifying Mw for the largest earthquakes. It also provides the centroid, rather than the hypocenterre of an earthquake, allowing better estimation of the spatial distribution of shaking impacts. For these reasons we are developing synthetic earthquake waveforms to refine W-phase inversions for Mw ~5+ earthquakes in New Zealand and Mw 6.5+ earthquakes in the southwest Pacific, including the Hikurangi-Kermadec subduction zone. The current tsunami early warning procedure calculates W-phase solutions within 20 minutes of earthquake origins with aim of reducing it to 5-10 minutes.

Using a large set of large magnitude events adapted to New Zealand and Hikurangi-Kermadec context, we refine our understanding of the limits regional W-phase inversion. We focus on the minimum magnitude we can accurately estimate, the minimal station coverage required and the complexity of the source that can be apprehended by the W-phase.

We simulate earthquake waveforms using a catalog of synthetic ruptures on the Hikurangi-Kermadec subduction zone. To generate the waveforms, we use SPECFEM3D Globe, a finite element method-based software that simulates wave propagation through a global velocity model of the Earth. These synthetic waveforms are then postprocessed and inverted to obtain a W-phase solution. Preliminary results define which minimum waveform resolution is required to observe a W-phase and that a simple centroid moment tensor source provides an adequate W-phase solution.

Site-Specific, Extended Shakemaps for Earthquake Engineering Applications

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The U.S. Geological Survey product that gives the estimated shaking intensity for earthquakes globally is called ShakeMap. It provides maps of estimated ground motion intensity metrics (IMs) in the minutes and hours following an earthquake. Providing this information as quickly as possible is critical for emergency responders and the public. In contrast, the response timeline for specialized use cases such as code compliance, damage analyses, fragility curve development, and examining triggering thresholds for ground failure is less compressed than for emergency responders, and more detailed information would be useful. Here, we describe recently developed tools to provide ShakeMap estimates of spectral acceleration in 22 periods (matching the current U.S. National Seismic Hazard Model periods) as well as orientation-independent components. We refer to ShakeMap products that include these extensions as “extended ShakeMaps.” The added level of complexity motivated us to also develop a user-friendly tool in Python called the “ShakeMap Sampling Tool” (SST) that gives all the estimated shaking metrics for a specific location (or list of locations). Additionally, we developed a web application where users can input locations of interest and view/download the SST results. Through this system, we can also provide composite ShakeMaps—maps of the maximum value of each IM across a sequence—which is especially useful for overall loss estimates. Composite ShakeMaps can also be used to provide a site-specific shaking history for analyzing repeated shaking to structures. The composite ShakeMap, combined with the extended IM products, facilitates forensics at building and infrastructure sites for which damage may be of concern, as described in the Disproportionate Damage Earthquake trigger specified in the International Existing Building Code and in developing ATC-145 “Guidelines for Post-Earthquake Assessment, Repair, and Retrofit of Buildings”.

Geonet’s Shaking Layer Tool: Understanding and Incorporating User Needs into Shaking Layers for Aotearoa, New Zealand

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Following a damaging earthquake, emergency managers are in great need for reliable shaking information to be able to make decisions and increase their situational awareness. Until now, these decisions in New Zealand needed to be made with incomplete geographical information, relying solely on observed data points from either strong-motion stations or felt reports. The New Zealand Shaking Layers project has been designed to fill in that gap: through the use of the software ShakeMap configured to satisfy New Zealand's characteristics, a tool is now available that provides shaking intensity maps for Peak Ground Acceleration, Peak Ground Velocity, Modified Mercalli intensity, and spectral acceleration at different periods. This project is a collaboration between GeoNet, New Zealand's geohazards data and monitoring programme, and the Rapid Characterisation of Earthquake and Tsunami (R-CET) science programme.

Alongside undertaking new physical science and software development, we used a combination of social science research methods and user testing to understand more about Shaking Layers's potential users. Here, we will present the results of a 2021-2022 public survey of over 1600 New Zealanders on their preferences for earthquake event information. Preliminary results show that 77% of participants stated that 'shaking intensity information' was either extremely or very important on a map after the earthquake scenario presented to them. Shaking intensity information would help them to determine if they should stay put or try and evacuate to safety and whether they should be concerned for family members. 'Earthquake size' (92%) and 'Epicenter' (86%) were the most useful types of information for those surveyed. Participants noted that this information allows for rapid decision making of tsunami threat in particular. Maps of expected landsliding and liquefaction were also extremely and very useful for the vast majority of participants. These results (in combination with techncial user feedback and persona development) provided clear guidance during the design process ensuring our product meets user needs.

Improved Rapid Source and Shaking Characterization Using Large Seismic Array Observations

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Rapid and accurate determination of finite source models and seismic intensity maps for damaging earthquakes are paramount for effective earthquake disaster mitigation and subsequent secondary hazard estimation. However, obtaining such estimates in the initial hours after a large event remains challenging, particularly for earthquakes with large source extents in regions with limited local seismic observations. In this study, we present improvements over our earlier strategy based on back-projection array technologies. Our approach involves estimating the source energy radiation utilizing multiple regional seismic array contributions, obtaining stable estimates of the fault geometry and subevent relative amplitudes. By combining Ground Motion Models and the estimated subevent distribution, we calculate Peak Ground Velocities (PGVs) directly by applying PGV-based site corrections using the USGS global Vs30 database. Alternatively, we can project the resulting subevents (high frequency radiators) onto fault geometries for use in estimating shaking with USGS ShakeMap. We evaluate our algorithm using representative earthquakes that occurred in recent years, including the 2024 Mw 7.5 Japan earthquakes.

Though we observe variations in our results obtained from different array geometries, the inferred fault planes approximate the finally determined rupture area well and the seismic intensity maps we produce exhibit a high degree of similarity with ShakeMaps constrained by strong motion and macroseismic data, where available. A noteworthy benefit of this approach is it does not rely on real-time local strong-motion observations. Ultimately, we intend to automate these algorithms, enabling the issuance of reliable seismic intensity maps shortly after damaging earthquakes. Such efforts could benefit post-earthquake decision-making and tsunami hazard evaluation.

Reference: Chen, W., Wang, D., Si, H., & Zhang, C. (2022). Rapid Estimation of Seismic Intensities Using a New Algorithm That Incorporates Array Technologies and Ground-Motion Prediction Equations (GMPEs). *BSSA*, *112*(3), 1647-1661.

A Growing Catalogue of Short-Period Earthquake Rupture Histories From Multi-Array Back-Projection

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For large earthquakes, the distribution of the high intensity zone depends to first order on the direction and length of rupture propagation. Furthermore, the speed of rupture propagation has a major influence through directivity effects. Of particular concern are rupture segments propagating at supershear speeds, which emit a shockwave-like pulse in the forward direction. Teleseismic back-projection imaging has emerged as a powerful tool for constraining the rupture propagation of large earthquakes with relatively little user input and capturing the high-frequency behavior of the fault, which is most relevant for impact, at least for most building types. However, its application often suffers from artifacts related to the receiver array geometry. We developed a teleseismic backprojection technique that can accommodate data from multiple arrays. Combined processing of P and pP waveforms may further improve the resolution. The method is suitable for defining arrays ad-hoc to achieve a good azimuthal distribution. We present a catalog of short-period rupture histories (0.5–2.0 Hz) for all earthquakes from 2010 to 2023 with Mw ≥ 7.5 and depth less than 200 km (62 events). The method provides automatic estimates of rupture length, directivity, speed, and aspect ratio, a proxy for rupture complexity. We obtained short-period rupture length scaling relations that are in good agreement with previously published relations based on total slip. Rupture speeds were consistently in the sub-Rayleigh regime for thrust and normal earthquakes, whereas a tenth of strike-slip events propagated at supershear speeds. Many rupture histories exhibited complex behaviors, e.g., rupture on conjugate faults, bilateral propagation, and dynamic triggering by a P wave. For megathrust earthquakes, ruptures encircling asperities were frequently observed, with down-dip, up-dip, and balanced patterns, with emissions up-dip of the main asperity more common than suggested by earlier publications. In the presentation, we will also consider the realtime potential of the algorithm.

Visual Communication of Aftershock Forecasts Driven by User Needs

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The U.S. Geological Survey releases aftershock forecasts following large (M5+) earthquakes in the U.S. and associated territories. Forecasts show the expected number (and range) of aftershocks in a specified area for various magnitude thresholds and time durations. Forecasts are released using a product template that contains tables and text. Visualizing these aftershock forecasts can more effectively communicate this information. In this research, we seek to identify which forecast visualizations (including maps) can serve a variety of user groups. In 2023, we held workshops with members of target user groups, including emergency managers, civil engineers, critical infrastructure operators, firefighters, public health officials, the media, and other science communicators. In these workshops, users performed small-group activities to elicit specific user needs on the dimensions of aftershock forecast information needed by their role (informational needs) and how this information would optimally be displayed (product needs). We conducted these workshops in the United States, Mexico and El Salvador to understand which forecast products may be effective across countries. Many users reported needing maps of shaking hazard to support their work. We find a greater variation in user needs across profession than country, and that user needs also vary with time. We identify common categories of use cases across the disparate professions and connect users' informational and product needs to these user archetypes. We

discuss practical implications for effective visual communication of aftershock forecasts and other natural hazards.

Tomorrow's Cities: An Interdisciplinary Decision Support Environment for Risk Sensitive Urban Planning and Design

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Understanding, modeling, quantifying, and managing future risks from natural hazards is becoming increasingly crucial as the climate changes, the human population grows, asset wealth accumulates, and societies become more urbanized and interconnected in many parts of the world. This is especially true in low-income contexts. The 2015-2030 Sendai Framework for Disaster Risk Reduction recognizes this need, emphasizing the importance of preparing for the disasters that our world may face tomorrow through strategies to minimize uncontrolled development/densification in hazardous areas. Assessing and communicating future natural hazard risk can support decision-making on urban development in planning and designing less-exposed and more resilient cities and regions. This presentation discusses these efforts, introducing the risk-based, pro-poor urban planning and design framework (and its implementing Decision Support Environment, DSE) developed within the Tomorrow's Cities project, the United Kingdom Research and Innovation (UKRI) Global Challenge Research Fund (GCRF) Urban Disaster Risk Hub. The Hub aims to support the delivery of the United Nations' Sustainable Development Goals and priorities 1 to 3 of the Sendai Framework for Disaster Risk Reduction. Specifically, the Tomorrow's Cities DSE integrates physics-based natural hazard modeling, dynamic exposure and vulnerability modeling of infrastructure systems and networks (physical and social), consideration of multi-hazard scenarios, and participatory approaches for identifying impact metrics tailored to the specific context and needs of marginalized communities. The presentation showcases the Tomorrow's Cities DSE implementation in Kathmandu, Nepal, where methodologies and guidelines for action-oriented, pro-poor, earthquake-risk-based decision-making are co-produced with local, national, and global stakeholders and research partners.

Exploring the Ethical Tensions and Communication Challenges of Publicly Available Global Aftershock Forecasting From Science Agencies

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Aftershock forecasting is an important tool that helps decision makers and various publics to understand what the future could look like in an earthquake sequence, after a large mainshock. The U.S. Geological Survey produces aftershock forecasts for various uses and audiences post-earthquake, assisting in decision making for those impacted. This information is available in several ways: domestically, an aftershock communication template is available to the public post Magnitude 5+ earthquakes; and, internationally, a product is shared with the Bureau for Humanitarian Assistance for events with PAGER alerts at the orange and red-level for fatalities. Given that the USGS already produces these, what is the ethical responsibility to make these international forecasts more available for public safety considerations? Further, by communicating these forecasts publicly beyond the United States borders, what are the considerations of scientific sovereignty of nations? What potential is there for miscommunication of forecasts in other nations, with diverse cultural and linguistic backgrounds? This presentation explores these ethical and social tensions, reporting on a group of listening sessions with scientific and response community members from around the world in 2022 and 2023. Further, we suggest some solutions to these issues as well as future pathways, including aftershock forecasting triggered by impact levels e.g. PAGER levels, rather than magnitude.

Development of Rapid Earthquake Damage Estimation System to Expedite Rescue Efforts in the Post-Disaster Phase

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In the first several hours following an earthquake, decision makers such as emergency managers have few fast options to gain situational awareness. They are often forced to rely upon calls to overloaded 911 lines, reports from first responders, reconnaissance along disrupted roadways by emergency personnel, or, after a day or two, aerial surveillance performed by the military. However, the first 24 to 48 hours are crucial for life-saving following a major earthquake. Situational awareness can be significantly improved using existing seismic risk modeling tools adapted for use with near-real-time seismic ground motion data typically available within tens of minutes. This work presents a new initiative to develop a Rapid Earthquake Damage Estimation (REDE) tool for earthquakes in Canada, similar to the United States Geological Survey's TwoPAGER. We explore best practices and determine the feasibility of using rapidly available seismic data from the upcoming Canadian Earthquake Early Warning network in the first-generation Canadian Seismic Risk Model (CanSRM1) framework to model the impacts on people, the built environment, and the economy from an earthquake within 10-20 minutes of a major event. In particular, we focus on results most relevant to life safety and early response: collapsed buildings, entrapment injuries, hospital demand surge, roadway debris which may block response, and immediate mass care needs like shelter requirements. It will help prioritize rescue and reconnaissance efforts, and can serve as a base of evidence for early resource allocation including federal requests for assistance. This tool is expected to be replaced within tens of hours by direct observations and aerial surveys as they become available. Information has been collected about how such a tool might be used by stakeholders: first responders, emergency managers and critical infrastructure operators. Based on the resulting prototype, a viable product is anticipated to be completed by late 2024.

Improving the Usability of Near-Real-Time Earthquake Information for Equity-Focused Decision-Making Through Earthquake Scenario Exercises

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Following an earthquake, near-real-time information provides valuable data on potential impacts like economic losses and fatalities to the public and decision-makers in the emergency management, humanitarian, finance, and other sectors. However, earthquake impact information is often designed without formal user input or a focus on socially vulnerable communities, resulting in information that is not necessarily suited for equity-focused disaster management decisions. In this research, we investigated user needs for equity-focused impact data. Following initial focus groups with a broad set of users from various sectors, we developed a mockup showing additional metrics of exposure and loss that highlight socially vulnerable populations in a way that addresses user needs. We then developed earthquake scenario exercises for a targeted group of users to gain feedback on the mockup through a usability testing workshop. Workshop participants included nine emergency managers from the Federal Emergency Management Agency (FEMA), the California Governor's Office of Emergency Services (CalOES), the American Red Cross, and Innovative Emergency Management. Following qualitative analysis, workshop results revealed that equity-focused impact metrics have the potential to influence more equity-focused emergency management decision-making, incorporating equity-focused decision-making into scenario exercises can influence equity-focused emergency management decision-making, and user-centered design can be beneficial in hazard impact product development. For near-real-time impact information at the USGS, we have identified the need for more accessible visualizations and language. More broadly, this research highlights how a user-centered and equity-focused design process can create meaningful interactions with stakeholders who can ultimately use products to support vulnerable populations after future earthquakes.

Creating Actionable Earthquake Information Products [Poster Session]

Poster Session • Wednesday 1 May

Conveners: Tiegan Hobbs, Geological Survey of Canada (thobbs@eoas.ubc.ca); Sabine Loos, University of Michigan (sloos@umich.edu); Marísa A. Macías, U.S. Geological Survey (mmacias@usgs.gov); Jessie K. Saunders, California Institute of Technology (jsaunder@caltech.edu); David Wald, U.S. Geological Survey (wald@usgs.gov)

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Post-Earthquake Liquefaction Mapping by Semi-Supervised Machine Learning Using Partially Labeled Imagery

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This study explores a new method to identify and map soil liquefaction areas from aerial images after earthquake events. Traditionally, liquefaction is recorded through field visits as geographic points, leading to incomplete data. Comprehensive mapping of affected areas is crucial for developing accurate prediction models. The research introduces a machine learning approach that leverages partially labeled data from expert visual assessments to detect and map unlabeled liquefaction areas. This method aims to increase mapping's spatial accuracy, and it was tested on aerial images from the 2011 Christchurch earthquake, using existing partial data as a reliable ground-truth source. First, the study compares a new semi-supervised learning technique (self-training classification) with traditional supervised learning. This approach is designed to overcome the challenges of limited and spatially incomplete labeled data. Second, it evaluates the effectiveness of various image features (color transformations, statistical indices, and texture components) in improving classification accuracy. Building footprints were also used to refine the results by excluding building roofs from the analysis. Additionally, the study employed the Fuzzy C-Means clustering algorithm to categorize liquefaction samples into two distinct classes (dry and wet). The final results showed that the semi-supervised method, especially when using selected high-ranked features, outperforms traditional methods and provides more complete spatial maps of liquefied areas.

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Investigating Different Methodologies for a Sar Coherence Change Detection Product

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The U.S. Geological Survey (USGS) provides rapid (within 30 minutes) estimates of earthquake-induced building damage and ground failure following significant events. These products are based solely on pre-event data and event-specific shaking estimates and do not include direct observations of damage or ground failure following an earthquake. To this end, the USGS is developing an intermediate-timeframe pipeline for post-earthquake products (within days to a week) that combines the current rapid estimation products with post-event observations with the goal of more accurately identifying the most affected areas. As a vital component of this pipeline, the USGS plans to generate an in-house Synthetic Aperture Radar (SAR) coherence-based Change Detection Map (CDM) using pre- and post-earthquake satellite observations to identify regions exhibiting surface property changes attributable to damage and ground failure. While NASA produces a similar product called the Damage Proxy Map (DPM), the USGS CDM is specifically being developed for integration into the USGS earthquake product pipeline. Here, we examine various methodologies to generate CDMs, with a focus on optimizing CDM robustness. We explore sample area dimension, the functional form of sampled coherence (e.g., boxcar versus Gaussian), and the combinations of SAR pairs (e.g., sequential-only versus multi-pairs). We generate CDMs using both Sentinel-1 (~30 m resolution) and Wide Ultrafine Radarsat-2 data (~10 m resolution), the latter of which has not yet been used to generate post-earthquake damage estimates. We compare our results against damage and landslide observations derived from high-resolution optical data (PlanetLab and WorldView, ~1-5 m resolution) from the 2023 Mw 6.8 Morocco earthquake. By exploring different CDM generation methodologies, we can constrain a CDM product's accuracy and spatial limitations in identifying building-specific damage and resolving decimeter-scale ground failure.

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New Earthquake Tsunami Preparedness Magazine for Northern California

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The Redwood Coast Tsunami Work Group released a new edition of "Living on Shaky Ground" on the anniversary of the December 20, 2022, *M* 6.4 Ferndale earthquake. This is the 7th edition and fourth major revision of the magazine first published in 1993 in response to the 1992 Cape Mendocino earthquakes. The magazine series is aimed towards residents and visitors of the predominantly rural part of California north of Santa Rosa and includes background on what causes earthquakes and tsunamis, what to expect, and how to prepare for them. From inception, the Shaky Ground magazines have focused on positive messaging and clearly outlining steps everyone can take to become more resilient. There were three goals in the 2023 edition: update earthquake and tsunami information, include sections on new technologies and programs, and make the magazine more readable, accessible, and inclusive. The timeline now includes the three significant earthquakes that have occurred in the region and adjacent offshore areas since the previous edition and a section on the Ferndale earthquake. Also added is a section on the tsunami hazards from the 2022 Tonga volcanic explosion. The new magazine features a page on what ShakeAlert is, what to expect, and how to react. It also includes expanded sections on children, the mobility challenged, and mitigation programs such as Brace and Bolt, and CERT teams. In response to the most frequently questions, pages have been added on earthquake basics including magnitude and aftershocks, and common misconceptions. To make the magazine more readable and attractive, the font size has been increased, four pages added, two thirds of the illustrations/photographs replaced, and people of diverse backgrounds featured. The intended audience is the general public, but the magazine also serves as a guidebook for regional outreach programs including CERT training and will become part of our on-line K-12 curriculum program. The magazine is currently available electronically at https://rctwg.humboldt.edu/home, a Spanish translation is in progress, and print versions will be available in early 2024.

POSTER 78

Integration of Seismic Monitoring and Involvement of Civil Protection Volunteers for an Effective Post-Earthquake Response

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After a significant seismic event, timely identification of severely affected areas is crucial to coordinate support actions for the population. INGV, in collaboration with OGS, theNational Institute of Oceanography and Applied Geophysics, has established a close partnership with Emilia Romagna's Regional Civil Protection Agency to develop an innovative real-time monitoring strategy. Since 2019, a network of civil protection volunteers has been implemented to monitor earthquake effects. Volunteers, previously trained through a cooperative learning process, respond to a targeted questionnaire, providing data on the perception of the event's impact on specific locations. This active learning approach directly involves volunteers in the process, facilitated by seismologists, promoting practical and lasting learning.

Thanks to the participation of volunteers already involved in risk communication projects, the project effectively connects with local communities. The project has a dual purpose: on the one hand, data collected by volunteers are transformed into macroseismic intensity and integrated into ShakeMap in real-time, improving its spatial coverage. On the other hand, the project acts as a social bond, strengthening the connection between the population and local authorities and monitoring entities. The success of this initiative has led to the expansion of the project to other Italian regions, with the future goal of

covering the entire national territory. The synergy between seismic monitoring and active community involvement proves to be a promising model for a rapid and inclusive response in post-seismic situations.

POSTER 79

Applying ShakeCast to Monitor Earthquake Hazards for Pipeline Infrastructure

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Earthquakes threaten buried pipelines through multiple modes of ground deformation, including liquefaction, coseismic landsliding, surface fault displacement, and ground shaking. The 2019 Pipelines and Hazardous Materials Administration "Mega Rule" (49 CFR § 192.613) requires natural gas transmission pipeline operators to inspect their pipelines within 72 hours of an extreme event that has the potential to impact pipelines via soil deformation, including earthquakes. Pipeline operators in the US are therefore in need of an earthquake monitoring system that can rapidly alert when a potentially damaging earthquake occurs in the vicinity of their pipeline asset.

BGC Engineering has integrated the USGS ShakeCast product into our geohazard management software, CambioTM, to aid operators in monitoring for earthquakes and to support post-event response. ShakeCast ingests ShakeMaps in near-real-time and compares shaking intensity against damage thresholds at locations of interest. The Cambio-ShakeCast module alerts operators with threshold exceedance related to potential damage to buried pipelines, either directly through transient pipe strain induced by seismic wave propagation, or indirectly from liquefaction, coseismic landsliding, or fault rupture. We monitor for threshold exceedance at points spaced at regular intervals along the pipeline and at mapped locations where the pipeline crosses terrain susceptible to liquefaction and coseismic landsliding, or known locations of active surface faults. Ground shaking thresholds were developed considering case histories of earthquake-induced pipeline damage, industry standards for seismic design and hazard assessments, and operator experiences. Recommended alert responses range from "information-only" to "prepare for immediate response" and are tailored to specific operator programs and the requirements of the Mega Rule. The integration of ShakeCast into Cambio addresses the pressing need from US pipeline operators for earthquake monitoring and creates an opportunity for continued innovation and as ShakeCast develops and we learn from operator experiences and responses.

POSTER 80

Making the Crowdsourced "Did You Feel It?" System More Accessible: A Global Analysis

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The U.S. Geological Survey's (USGS) 'Did You Feel It?' (DYFI) system is an internet tool that collects shaking intensity observations through crowdsourcing. It produces maps and provides supplementary data to ShakeMap, which offers near-real-time maps of ground motion resulting from significant earthquakes around the globe. However, barriers such as technology and language make DYFI an unequally accessible tool, which can lead to a limited scientific understanding of an earthquake's impact in certain regions. Here, we analyze users' global interaction with DYFI to evaluate its accessibility. We employ web analytics to quantify how users access DYFI and perform inference modeling to predict each country's response rate to DYFI. The panel dataset built for this model combines physical earthquake parameters from the USGS with socioeconomic variables from the World Bank and the Central Intelligence Agency for 151 countries from 2009 to 2020. Our web analytics show that users predominantly access DYFI through mobile devices. Additionally, results from the inference model reveal that socioeconomic parameters, including primary language spoken and GDP per capita, alongside physical earthquake parameters such as average shaking intensity, have a significant effect on a country's response rate to DYFI. As a result of these two forms of analysis, we establish a tiered ranking of countries to prioritize for improved DYFI awareness and accessibility. This ranking considers regions of the world lacking seismic station coverage that face barriers to DYFI access, such as language, technology, or other factors. Consequently, the USGS has prioritized the evaluation of DYFI's performance on mobile devices and has initiated the incorporation of additional languages into the DYFI system. Furthermore, our analyses suggest specific nations with low response rates could benefit from targeted outreach in conjunction with sister agency partners in each country.

POSTER 81

Global Structural Health Monitoring via MyShake: An Economical and Accessible Smartphone-Based Approach

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Structural Health Monitoring (SHM) is essential for the safety, reliability, and cost-effectiveness of structures over their lifespan. Traditional SHM methods rely on custom sensor deployments, requiring significant time, manpower, and resources. However, the ubiquity of smartphones with accelerometers presents a unique opportunity for widespread, affordable SHM. We showcase the MyShake smartphone app, developed at UC Berkeley and part of the Early Warning California initiative. This free app, downloaded globally over 2.9 million times, utilizes smartphone accelerometers to monitor civil infrastructure health through waveform recordings during significant shaking events.

MyShake leverages these smartphones to form a rapid-response network for monitoring civil structures. During events such as earthquakes and severe weather, stationary MyShake phones record and transmit seismic data. Since these phones are usually inside buildings, the data can reveal structural behavior. The app's ability to gather data enables us to assess the structural integrity of buildings where users are located.

Our controlled experiments validate this method, resulting in a database of modal frequencies from various buildings. Continuously monitoring these frequencies allows us to detect changes that may signal structural damage. Thus, MyShake offers a scalable, cost-effective solution for global SHM, enhancing civil structure safety and reliability. We also discuss scientific and technical challenges in large-scale operational deployment and suggest potential solutions.

POSTER 82

ShakeCast: Pivoting USGS Products to Respond to User Needs

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ShakeCast® is a U.S. Geological Survey (USGS) software application that automatically retrieves ShakeMap shaking estimates and performs analyses using fragility functions for buildings and lifelines, developed with support from external organizations interested in using ShakeMap for automatic decision-making. The ShakeCast system identifies which facilities or lifeline segments are most likely impacted by an earthquake—and thus which should be prioritized for inspection and response—and sends notifications to responsible parties in the minutes after an event. ShakeCast can improve critical lifeline situational awareness, inspection prioritization, and reduce response times after a significant earthquake by focusing inspection efforts on the most damage-susceptible facilities in severely shaken areas. Improvements to ShakeCast are done in conjunction with upgrades to the ShakeMap application. As a user-focused application, ShakeCast's initial specifications were developed working iteratively with the California Transportation Department (Caltrans). Caltrans became ShakeCast's primary early adopter and promoter among other agencies and utilities. Later, feedback and engagement with other critical lifeline and facility users guided technical innovations and product modifications. However, the practicalities of any automatic application, with operational complexities that are not necessarily user-friendly, can be technically challenging for some users. In this presentation, we focus on balancing robust and secure operational applications with the needs of critical users with a wide range of technical abilities and computational environments. We also provide an update to the technical specifications regarding the code base, dependencies, documentation, and deployment options. Lastly, we highlight recent ShakeCast case histories where critical infrastructure users employed the ShakeMap/ShakeCast combination in their decision-making.

POSTER 83

Guidelines on Using (Uncertain) Macroseismic Data in ShakeMap

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The U.S. Geological Survey (USGS) collects macroseismic intensity (MI) data from users worldwide through the "Did You Feel It?" (DYFI) system. DYFI is a primary MI source for USGS ShakeMap, which combines ground motion data with rupture parameters, site conditions, and ground motion models (GMMs) to estimate the spatial distribution of ground shaking. Despite their utility in ShakeMap, the potential for outliers and larger uncertainties makes it challenging to include crowdsourced intensity data operationally. We report here on developing guidelines for incorporating crowdsourced MI data into ShakeMap. We take advantage of our newly developed MI database to reassess the uncertainty of the MI assignment as a function of intensity and the number of responses (n_{resp}), demonstrating that higher intensities have more uncertainty. This is consistent with the known challenge of assigning higher, damaging intensity levels, even by experts. From an operational perspective, crowdsourced MIs are more consistent at lower intensities and can be readily used automatically. Higher intensities, particularly with few entries per locale, are more uncertain and require further downweighing with respect to other shaking estimates. We approach this problem with two strategies to quantify uncertainties: 1) We analyze MI residuals to understand trends with n_{resp}, MI, and the source of the MI data (e.g., DYFI, historical, or assigned), then assign MI uncertainties as a function of intensity by adding (heuristically) a constant such that the relative weight of the macroseismic data for a single response approaches that of the GMM contribution. 2) We simulate the rich MI databases using a Monte Carlo approach to ensure that the uncertainty assessments are consistent with the levels of variability observed in the data.

POSTER 84

Creating Earthquake Early Warning Post-Alert Information Products: Harnessing Existing Earthquake Information Tools to Depict Alerting Efficacy

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Here, we leverage existing post-earthquake information products to explore and develop graphical representations that depict earthquake early warning (EEW) alert performance, targeting components that will satisfy both technical and public audiences. Existing post-earthquake information products (including ShakeMap, "Did You Feel It?" [DYFI], and PAGER) offer proven examples of communicating the complexity of earthquake shaking and its impacts. Communicating the efficacy (accuracy and timeliness) of EEW alerts brings additional challenges, as quantifying and summarizing alert timeliness are not straightforward. For EEW systems like the ShakeAlert system for the West Coast of the United States, EEW alert information is updated as the earthquake progresses and alerts are issued via multiple platforms using various alert thresholds, so no single map can readily communicate EEW alert efficacy. We thus need to reconcile comprehensive reporting against agreeable visualizations. By considering ShakeMap shaking estimates—constrained by DYFI-reported intensities and station observations—as a baseline for ground-truth experiences, we quantify how many potential recipients there were of timely versus late and missed alerts with respect to the actual shaking experienced. The maps and other visualizations we propose could be a first step toward communicating objective and quantifiable alerting successes while putting the alerting challenges into a spatial perspective. Coupled with reports of users' alerting experiences, reactions, and perceived utility (Goltz et al., this meeting), we can examine EEW alerting efficacy quantitatively and qualitatively. By leveraging existing, familiar technologies and data already produced—augmented with depictions of warning timeliness—post-event EEW information follow-up products we put forward could be both intuitive and informative, helping people connect what just happened regarding EEW alerts with the shaking they felt from the earthquake.

POSTER 85

A Framework for Implementing a New Intensity Metric for USGS's Shakemap: Cumulative Absolute Velocity (CAV)

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The U.S. Geological Survey's (USGS) ShakeMap has been providing rapid, global estimates of earthquake shaking characteristics for decades. USGS has provided ground shaking characteristics as maps of intensity measures (IM) such as peak ground velocity, peak ground acceleration, spectral acceleration (at three periods), and macroseismic intensity. These products have been effectively used by emergency managers, loss modelers, engineers concerned about post-event structural performance, and even for insurance products. However, more advanced IMs offer important benefits for characterizing the ground shaking intensity by accounting for energy and duration of shaking, which have the potential to be useful for applications that include assessing the potential for failure involving landslides, liquefaction, and critical infrastructure. These metrics include cumulative absolute velocity (CAV), Arias intensity, significant duration, and permanent static displacement. We present a framework for implementing CAV in ShakeMap. There are numerous models to estimate CAV, because they were developed for specific regions and tectonic environments. We start by developing a database of recorded CAV values for a specific region along with predicted CAV values from ground motion models (GMMs). We use OpenQuake to predict CAV values with GMMs, but since many GMMs of CAV are not currently available in OpenQuake, we must contribute them. Since the USGS produces ShakeMaps on a global scale, it is imperative that we test and expand the suitability of the models for all possible regions and tectonic environments, which can then be done for other IMs. We expect our work to improve hazard assessment of landslides, liquefaction, and infrastructure, and advance earthquake science and operations.

Cryptic Faults: Advances in Characterizing Low Strain Rate and Environmentally Obscured Faults

Oral Session • Wednesday 1 May • 8:00 AM Pacific

Conveners: Theron Finley, University of Victoria (tfinley@uvic.ca); Tiegan Hobbs, Geological Survey of Canada (tiegan.hobbs@NRCan-RNCan.gc.ca); Barrett Salisbury, Alaska Division of Geological & Geophysical Surveys (barrett.salisbury@alaska.gov); Lydia Staisch, U.S. Geological Survey (lstaisch@usgs.gov)

An Ongoing Search for Active Faults in Major Seismic Zones of Québec, Eastern Canada

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Southern Québec lies in an intracratonic setting that has experienced historical damaging earthquakes (e.g. 1732 M5.8 Montréal, 1663 M7 Charlevoix, 1935 M6.2 Témiscamingue). Despite the fact that approximately half of Québec's population lives within one of the identified seismic zones, no studies to date have identified surface-rupturing faults. The lack of paleoseismic datasets and specific earthquake source scenarios impedes hazard estimates and risk preparedness, and is due in part to the province's very young geomorphic surface. Since the last glacial maximum at ~21 ka, marine and lacustrine deposition dominated until a few thousand years ago, removing much of the Quaternary record of fault activity.

The study aims to develop a systematic criteria for fault scarp identification in this low-relief, deglaciated landscape, by adapting criteria used in the Fennoscandian Peninsula. We manually searched 2016 lidar-derived digital elevation models (DEMs) within three populated seismic zones to identify potential post-glacial surface-rupturing faults. We present the first

geomorphic map of possible post-glacial fault scarps in Québec. One scarp was investigated with geophysical surveys, and we excavated the first paleoseismic trench in Québec, which did not find evidence of Quaternary faulting. This study paved the way for paleoseismic studies in the province and created a network of geoscientists/governmental agencies aware of, and invested in, paleoseismic studies. We hope our study can be used to optimize future paleoseismic research in the province of Québec and similar intracratonic deglaciated landscapes.

Timescales of Surface Faulting Preservation in Stable Continental Regions From Landscape Evolution Modeling and the Geomorphic and Historical Record

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Large surface-rupturing intraplate earthquakes in stable continental regions are infrequent, with recurrence intervals of thousands to hundreds of thousands of years. The landscape preservation of surface ruptures is controlled by many factors, including earthquake depth, magnitude, and recurrence interval, climate, anthropogenic modification, and pre-existing topography or geomorphology. As such, recurrence intervals—and therefore seismic hazard—may be biased or inaccurate from the landscape record alone. In this study, we take a two-pronged approach to better understand how surface ruptures of primarily dip-slip events may be preserved in the landscape. First, we use a 2D scarp diffusion model to explore how different parameters influence the creation and erosion of fault scarps. These parameters include the magnitude of surface rupture vertical offset (likely related to depth and magnitude of faulting), climate (using diffusion rate as a proxy for precipitation), erodibility (related to underlying surface material), and recurrence interval of similar magnitude events. Second, we compile information on historical surface ruptures in intraplate settings in a variety of climates, including the central and eastern North America, Australia, Europe, Mongolia, India, and West Africa. We then use data from the compilation to assign parameter value ranges for the models. We use vertical offsets of 30 to 300 cm, recurrence intervals of 500 yr to 20 kyr, diffusion rates of 0.001 to 0.01 m^2/yr, and erodibility values from 0.001 to 0.006 yr^{-1} on both flat and sloping surfaces with cm- and m-scale roughness. We find that recurrence interval and erodibility strongly influence the timescales of scarp preservation in the landscape, whereas vertical offset and climate have less influence. We compare the timescales of scarp preservation in the landscape evolution modeling results with observations from the historical and paleoseismic record. This study highlights the factors influencing scarp preservation in intraplate settings and implications for calculating the seismic hazard of a region based on the landscape record.

The 2018 Kaktovik, Alaska Earthquakes and Their Context: Insights From Seismotectonics, Insar Geodesy, and Static Stress Changes

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On August 12, 2018, a M_w=6.4 earthquake struck in the northeast Brooks Range southwest of Kaktovik, Alaska, followed by a M_w=6.0 event to the east six hours later and a multi-year-long aftershock sequence. Although they fortunately caused no injuries or damage, the Kaktovik earthquakes are notable for at least five reasons: 1) they occurred just south of the petroleum-rich 1002 Area of the Arctic National Wildlife Refuge; 2) they dwarf the previous largest earthquakes recorded in Arctic Alaska (M=5.3-5.4); 3) they occurred ~1,000 km from the southern Alaska convergent margin in a presumably low-strain-rate region; 4) their strike-slip character contrasts with their geologic setting in a fold-and-thrust belt; and 5) the USArray Transportable Array and the Sentinel-1A satellite pair allow them to be studied in high temporal and spatial resolution. We first examine the seismotectonic context and evolution of the Kaktovik sequence by assembling an integrated earthquake catalogue for northeast Alaska from eight sources. The catalogue reveals a history of seismicity in the northeast Brooks Range (including many strike-slip events), as well as a possible uptick in seismicity rate around the eventual epicenter of the second large (M_w=6.0) Kaktovik earthquake in the half-hour or so preceding it. To assess how the Kaktovik earthquakes fit into their seismotectonic context, and how they might modulate future seismicity through stress transfer, we use Interferometric Synthetic Aperture Radar (InSAR) to build slip models of the earthquakes. The InSAR displacements can be fit well by slip on a planar rupture based on the focal mechanism of the Mw=6.4 event and a lineation observed in the ascending-track interferogram, or a nonplanar rupture built from features of the descending-track interferogram. Using these two slip models, we calculate that the Kaktovik sequence slightly increased the Coulomb stress ~50 km to the south at the site of a subsequent Mw=5.3 earthquake in July 2019, and also increased Coulomb stress on faults to the north and/or northwest towards the coast.

Deciphering Low-Rate Faulting on the Landscape Above the Marsh Creek Anticline in Arctic Alaska

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In regions of rapid contractional deformation (≥1 mm/a), rivers adjust to earthquake-induced differential rock uplift by steepening, narrowing, and/or incising terraces. Such landscape signatures constrain the location and millennial tempo of active faulting but may be subdued or absent where tectonic rates are low. Hence, understanding how rivers interact with low-rate tectonic deformation is key to characterizing long-term seismic potential where strong earthquakes are infrequent but nonetheless destructive. For example, ~1000 km north of the 53 mm/a Yakutat-North America collision at Alaska's southern margin, the northeastern Brooks Range hosts low geodetic velocities (<1 mm/a) but strong historic earthquakes (≤M_w 6.4). There, we are conducting a geomorphic study of a composite structure long thought to take up much of the contemporary tectonic budget and termed the Marsh Creek anticline.

Topographic profiles reveal a north-dipping limb with ~100 m of relief, implying monoclinal surface folding above a north-dipping blind thrust fault imaged in seismic reflection data. The Katakturuk River and Marsh Creek drain the Brooks Range upstream of the fold and traverse the structure's topographic crest on the Arctic Coastal Plain, where both rivers cut ≤60 m into weak Paleogene strata and bend ≤3 km west, leaving three inner bend fill terrace levels ≤16 m above the channel. Absent downstream changes in channel slope or width, we hypothesize that episodic differential uplift across the Marsh Creek structure reduces river gradients upstream of the fold, driving aggradation of coarse bedload from upstream and forcing the channel to erode westward and vertically into friable Paleogene strata, thus producing river bends and progressively abandoning fill terraces. We collected cosmogenic ^{10}Be samples to constrain erosion rates upstream of the fold and, in concert with ^{14}C and luminescence dating, bracket timing of terrace abandonment and incision rates. Results will test our hypothesis that the observed landscape records sediment production upstream of the fold that outpaces earthquake-induced incision.

Utilising UAV Lidar to Investigate Potential Late Quaternary Surface Ruptures Along the San Juan Fault on Vancouver Island, BC

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Identifying active crustal faults within the northern Cascadia forearc is challenging due to low rates of recorded seismicity, late Quaternary glacial scouring, and dense vegetation that often obscures fault-related geomorphology. However, recent research has identified surface ruptures along the Leech River, Beaufort Range, and XEOLXELEK-Elk Lake faults on southern Vancouver Island, which each pose a considerable risk to the >500,000 people that live in this area. We investigate the San Juan Fault (SJF), another putative active fault within this region. The SJF is an 80 km long, E-W striking, terrane-bounding fault, which displays a conspicuous topographic lineament similar to the known-active Leech River fault located ~10 km to the south. Originally a collisional suture between the Wrangellia and Pacific Rim terranes, it is last known to have accommodated left-lateral slip during the Eocene driven by accretion of the outboard Crescent-Siletz terrane. The position of the SJF in the forearc of the active Cascadia subduction, its favourable orientation relative to the regional stress field, and its strong topographic signature have led some to hypothesise that it is seismically active, but no convincing evidence has been found yet. We utilise both airborne lidar and uncrewed aerial vehicle (UAV) lidar to map the surface trace of the SJF. The UAV lidar is capable of collecting much higher density point clouds (2-3X that of conventional airborne lidar) and thus produce sub-meter resolution bare earth models, allowing for identification of fine-scaled features. A scarp-like feature is evident in the lidar data, but it is unclear whether it records Quaternary surface rupture or differential erosion during glaciation, a challenge commonly faced by tectonic geomorphologists working in previously glaciated terrain. We look for evidence of late Quaternary reactivation along the eastern half of the SJF (offsets to glacial landforms and river channels, and scarp morphology) and consider sites where paleoseismic studies could confirm a tectonic origin.

Late Pleistocene and Protohistoric Earthquakes on Forelimb Thrusts Within the Seattle Fault Zone: Implications for Independent Hanging Wall Deformation Rates

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The Seattle fault zone (SFZ) preserves a long-term deformation record of north-directed reverse faulting, although the majority of paleoseismic studies show evidence for multiple Holocene ruptures on ancillary bedding plane backthrusts within the hanging wall fold of the main fault. These paleoseismic studies elucidate the complex nature of hanging wall deformation within the SFZ and motivate our approach for evaluating fault-related folds for seismic hazard. In this study, we focus on two recently identified <2 km-long fault scarps located ~30 km apart along the SFZ that, unlike the previously studied south-facing scarps of the north-dipping backthrusts, are north-facing and spatially correlative with the main blind fault traces of the SFZ. Through geomorphic mapping, paleoseismic trenching, Bayesian analyses of ^{14}C ages, and dendrochronology, we show that these north-facing scarps are underlain by south-dipping thrusts that yield evidence of three earthquakes. The oldest earthquake identified within the trenches across each scarp temporally overlap during the late Pleistocene but are likely separate events, while the youngest is constrained to the late Holocene on the western-most scarp and is possibly Historic. To understand the structural significance of these faults relative to the main blind fault(s) and backthrusts, we combine ground-based magnetic transects, oriented perpendicular to the fault scarps on Bainbridge Island, with measured bedrock sections. Our analysis reveals that the high-resolution magnetic signals reflect the lithologic variability in the underlying Tertiary bedrock. The main fault location is apparent from broad changes in the magnetic data, but the fault scarps lack a distinct and coherent signal between the two transects, suggesting that the north-facing fault scarp is also a fold-associated fault. Our results further emphasize the independent rupture of the fold-associated faults, which also display shorter recurrence intervals than the main fault(s) of the SFZ. This study highlights the cryptic nature of assessing thrust and reverse fault systems for seismic hazard analysis

Recurrence of Large Upper-Plate Earthquakes in the Salish Lowland, Washington State, USA

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Our paleoearthquake database consists of 32 earthquakes over the last 15,000 years on ten fault zones in the Salish lowland (Elk Lake fault, Boulder Creek fault, Bellingham coastal faults, Darrington-Devil's Mountain-Leech River fault zone, North Olympics fault zone, Southern Whidbey Island fault zone, Seattle fault zone, Canyon River-Saddle Mountain fault zone, Tacoma fault zone, and Olympia fault zone). We take the OxCal modeled probability distributions for each earthquake age and calculate Highest Density Intervals (HDIs) for each earthquake. Subsequent Monte Carlo sampling used the HDIs to calculate the order of earthquakes and recurrence intervals. Recurrence calculations used earthquake pairs determined by the ordering analysis to sample recurrence intervals from the HDIs. The result is a large sample of recurrence intervals from the ordered earthquake pairs, from which we draw summary values, including average recurrence interval (ARI). The Seattle fault zone is the most active fault in the region (nine events) and has the smallest ARI (1400±260 years); the largest earthquake of this sequence is the 923CE earthquake. The next most active are the North Olympics fault zone (four, possibly five events, ARI=2285±1195 years), and the Darrington-Devils Mountain-Leech River fault zone (four events, ARI=3355±675). The ARI across the region for all 32 events is 820±534 years.

Earthquakes ages have less error after 4000 years BP but dating quality declines for earlier events. This may be a function of preservation (not as much material to sample) and possibly sample quality (delicate plant fossils vs. charcoal). We observe that overall earthquake rate apparently increases after 4000 years BP (10 events before, 22 events after). This may reflect preservation, but all of the fault zones have terrestrial stratigraphic records that extend to the late glacial, suggesting the post-glacial stratigraphic record along each fault zone is complete. Paleoseismic recurrence broadly agrees with recurrence calculated using geodetic data, while recurrence estimated from seismic catalogs is shorter.

Towards Improved Understanding of Regional Tectonics and Faulting at the Mendocino Triple Junction from Geomorphic Investigation

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Hazard associated with the transition from the dextral San Andreas Fault system to the Cascadia subduction zone in the Mendocino triple junction (MTJ) region is complex and in need of ongoing research using up-to-date methods. This area has high rates of seismicity and is characterized by an enigmatic network of faults having some combination of compressional and dextral motion that has been difficult to constrain, perhaps complemented by diffuse shearing and folding. The densely vegetated mountains, river valleys, and coast appear to record strikingly variable patterns of tectonic uplift, subsidence, and fluvial and coastal erosion that cause ongoing drainage divide shifts, unusual stream channel longitudinal profiles, and variable amounts of topographic development. These patterns have also been indicated by geodetic surveys following historic earthquakes. The geomorphic characteristics can be interrogated to understand the regional tectonics, which can in turn be used, in combination with analysis of recently released lidar topographic data, to identify locations of active faulting. We are currently working to generate a suite of catchment erosion rates from cosmogenic isotope inventories within and adjacent to the Mattole and Eel Rivers. We are mapping and dating uplifted fluvial terraces along the Mattole and Eel Rivers, and marine terraces from along the MTJ coast. This is complemented by generation of quantitative landscape metrics including channel steepness index and chi. We are also mapping active fault traces and expanding collaborative work on known high-potential paleoseismic sites. Our long-term objectives include better understanding of the connections between, and geometry of, the San Andreas, Maacama, and Bartlett Springs Faults and the southern Cascadia onshore fault network, better understanding of the linkages between tectonics, stream capture, and critical anadromous fish habitat, and better understanding of how topographic development and fault activity are related, with an eye towards improving hazard models.

Geophysical Validation of Tidally Calibrated Strains From the Novel Alto Tiberina Near Fault Observatory Strainmeter Array (TABOO-NFO-STAR)

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Six borehole tensor strainmeters, installed between Fall 2021 to Spring 2022, comprise a strainmeter array along the Alto Tiberina fault system (STAR), Italy. The array provides an opportunity to investigate deformation from seismic and aseismic slip on hazardous high- and low-angle normal faults. Prior to use in tectonic applications, the strainmeters require in-situ calibration

and correction for non-tectonic signals. We tidally calibrate the instruments and test the results against environmental signals and signals from coseismic deformation associated with polarized compressional body waves and static offsets originating from local to teleseismic distances. Calibrated analyses demonstrate that the STAR sites deviate from typical assumptions of isotropic, homogeneous conditions, with four of the six strainmeters (TSM3-6) exhibiting negative areal coupling that complicates analysis of surface loads. For coseismic deformation, the results show interstation precision and accuracy to nanostrain levels. Potential complications for interpreting deformation at TSM3 may arise from dynamically triggered near-borehole fracture slip and fluid flow, but apparently only in response to high strain rates, while low strain rates remain consistent with our expectations. Although use of the tidal calibrations seems valid for TSM1, 2, 3, 5, and 6, future improvement may be possible as longer, stable timeseries become available, with particular attention to TSM4. Overall, the present analyses demonstrate expanded geodetic capability for detecting nanostrain deformation in the Alto Tiberina Near Fault Observatory, which other observatories have shown would be needed to detect slow, transient slip, and both coseismic and dynamic strain from local to teleseismic earthquakes.

The Parguera Fault: Quaternary Reactivation of a Fault in Southwest Puerto Rico

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Puerto Rico is located in a seismically active oblique plate boundary and has experienced historical moderate to large earthquakes. However, the location and kinematics of active faults on Puerto Rico remain mostly unclear. Here, we present evidence of a previously unrecognized east-west-trending normal fault in southwest Puerto Rico, which we name the Parguera fault. At the northwestern edge of seismicity from the 2019-ongoing southwest Puerto Rico seismic sequence, near the coastal town of La Parguera, we mapped a set of east-west oriented scarps that cross multiple generations of alluvial fans. Our mapping consists of both remote, sub-meter resolution lidar-derived topographic interpretations and field observations. We also apply optically stimulated luminescence (OSL) geochronology and subsurface datasets (ground penetrating radar and aeromagnetic data).

The scarps mapped on the lidar-derived topography are discontinuous, cross elevation contours, and extend at least 12 km laterally, with up to a 2 m, primarily down-to-the-south vertical offset of geomorphic surfaces. In some places, the scarp coincides with a pre-existing unnamed bedrock fault that separates Cretaceous basalts and Parguera limestone or juxtaposes different Cretaceous basalt units. The scarp location is also consistent with discontinuities in subsurface data, supporting the presence of a fault at depth, where aeromagnetic data highlight discontinuities in the underlying basement rocks coincident with the mapped scarps. Based on field observations, the faulted alluvial fans may be correlative with previously mapped Holocene-age fans along the southern flank of the Lajas Valley, just a few km to the north, which we hope to confirm with pending OSL ages. We interpret that the scarps across possible Holocene-age fans, supported by subsurface data, indicate the presence of a previously unrecognized Quaternary-active normal fault that may represent reactivation of an older bedrock fault. Evaluation of this feature will serve to improve our understanding of the seismic hazards and tectonic history of Puerto Rico.

Cryptic Faults: Advances in Characterizing Low Strain Rate and Environmentally Obscured Faults [Poster Session]

Poster Session • Wednesday 1 May

Conveners: Theron Finley, University of Victoria (tfinley@uvic.ca); Tiegan Hobbs, Geological Survey of Canada (tiegan.hobbs@NRCan-RNCan.gc.ca); Barrett Salisbury, Alaska Division of Geological & Geophysical Surveys (barrett.salisbury@alaska.gov); Lydia Staisch, U.S. Geological Survey (lstaisch@usgs.gov)

POSTER 86

Seismic Imaging and Structure of the West Napa Fault Near Calistoga, California

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The 24 August 2014 Mw 6.0 South Napa, California, earthquake caused extensive structural damage in the City of Napa, California. The causative fault, the West Napa Fault (WNF), continues northward from the City of Napa to Saint Helena, California, and post-earthquake investigations suggest an additional fault section extending past Calistoga. We evaluated the structure and geometry of the WNF near Calistoga, California by conducting an active-source, high-resolution (2-m shot and receiver spacing) seismic imaging survey across the suspected trace of the fault. We deployed two parallel seismic arrays using 3-component nodal seismometers and recorded P- and S-waves generated from vertical sledgehammer impacts on a steel plate and horizontal sledgehammer impacts to an aluminum block, respectively. We used refraction tomography to develop 2-D V_P, V_S, V_P/V_S, and Poisson's ratio models, and Multichannel Analysis of Surface Waves (MASW) to develop additional V_S(Rayleigh- and Love-wave) models. The $V_P$model for the southern array shows a low-velocity zone with velocities between 1900 and 2200 m/s near the suspected trace of the fault. We observe an increase in depth of the 1500 m/s $V_P$contour (top of groundwater) coincident with the near-surface location of the low-velocity zone, which suggests the fault acts as a barrier to groundwater flow. Our $V_S$tomographic model for the southern array shows lower V_S west of the suspected location of the fault. Based on our refraction tomography and surface-wave models, we interpret a steeply west-dipping main fault and possibly a minor splay approximately 40 m to the east of the near-surface trace.

POSTER 87

Geologic and Geomorphic Evidence for Possible Reactivation Along the Dry Creek Fault Zone and Hoadley Fault, Cryptic Faults in the Northern Sacramento Valley and Surrounding Areas

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Observations along the Dry Creek fault zone (DCFZ) and Hoadley fault (HF) suggest that there are cryptic, Quaternary faults present throughout the northern Sacramento Valley and into the southern Klamath Mountains. Bedrock mapping along the DCFZ identifies distributed folds, fractures, and faults in pre-Tertiary bedrock across a deformation zone approximately 3 km wide and 12 km long located north of Redding, CA. Extended, interconnected surface lineaments may be 38 km total length. Surficial geomorphic mapping does not identify discrete surface displacements in late Quaternary erosional surfaces and fluvial terraces along the DCFZ. Instead, a broad deformation zone in bedrock is oriented sub-parallel to Inks Creek fold belt structures. A fault strand on the northwestern margin of the zone generally coincides with the alignment of several Quaternary surface back edges that form a diffuse, irregular escarpment. On the south side of the deformation zone, a heavily weathered, unlithified sedimentary deposit identified on an intermediate terrace in the Sacramento River sequence appears to be in fault contact with Paleozoic bedrock. The deposit appears to predate the terrace and its age is uncertain. Absent some topographic expression, deformation in other Tertiary to Quaternary deposits or surfaces indicates deformation probably predates the terrace sequence, which is younger than ~0.8 Ma.

Southwest of Whiskeytown Reservoir, a subtle northwest-striking, irregular, and discontinuous escarpment crosses Quaternary fan surfaces in the Boulder Creek drainage along the northern strand of the Hoadley fault in the southern Klamath Mountains. The escarpment is subparallel to ridgelines, bedrock foliations, and is mapped as a normal fault. There is up to ~10 m of vertical separation along the escarpment and is consistent with a normal sense of motion. Nearby exposures did not have clear evidence of faulting in boulder-rich fan deposits. Together, these observations point to late Cenozoic re-activation of multiple faults at different orientations in the relatively low-strain setting of north-central California.

POSTER 88

Constraints on Late-Quaternary Fault Displacement and Tectonic Hazards in the Sacramento–San Joaquin Delta, Northern California, From Shallow Sediment Cores Across the Pittsburg–Kirby Hills Fault System

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Seismic sources and their associated hazards within the Sacramento-San Joaquin Delta region of north-central California ("the Delta") are poorly characterized, due to slow slip rates that combine to accommodate no more than ~5 mm/yr of plate-boundary-parallel slip and that do not keep pace with the fluvial and tidal processes that dominate the geomorphology of the region. Local topographic highs in the western Delta suggest that some structures accommodate vertical displacement, but the age and rate of this deformation is not known. Tidal marshes preserve stratigraphy that can be used to constrain fault offsets and timing across active structures, providing insights to refine our understanding of Quaternary fault activity within the Delta.

The ~100-m-high Kirby Hills are at the core of a positive flower structure within the north-south trending Pittsburg–Kirby Hills Fault System (PKHFS), and are surrounded on three sides by tidal slough. The PKHFS originated in the Late Cretaceous as an extensional system associated with the Rio Vista forearc basin. In the modern tectonic regime, apparent reverse displacement of Eocene bedrock across the PKHFS suggests the possibility of active uplift or transpression across the structure, but the modern kinematics and rates of deformation on the PKHFS are not well constrained.

Shallow (<6 m depth) subsurface stratigraphy from 15 hand-auger cores in the Montezuma Slough tidal marsh, along strike of the PKHFS to the south of the Kirby Hills, provides insights into Quaternary deformation across the PKHFS. A peaty deposit overlies the PKHFS in the northern part of the marsh. This layer is thinner within the PKHFS (~1-2 m) than outside it (~3+ m), consistent with relative uplift within the fault zone and suggesting that the positive flower structure that forms the Kirby Hills is producing vertical displacement in the late Quaternary. Radiocarbon ages of subsurface peat samples within the fault zone are older than peat ages at comparable depths elsewhere in the Delta, suggesting relative uplift within the PKHFS during the Holocene.

POSTER 89

Characterization of Slip Rates Across the Buffalo Valley, Buena Vista Valley, and Southern Shoshone Faults, Central Nevada

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The Buffalo Valley, Buena Vista Valley, and southern Shoshone faults are active range front normal faults that accommodate extension within the slowly deforming Basin and Range province in central Nevada. The faults are included as crustal sources in the 2023 update of the USGS National Hazard model, but with an absence of any earthquake recurrence data. Observations from lidar hillshades and field transects indicate the presence of progressively displaced alluvial fans along each fault. Here we present surficial geologic maps and vertical displacement estimates for the three faults. Additionally, we present descriptions of soil pits from displaced surfaces along the Buffalo Valley fault. Deformation along the Buena Vista and southern Shoshone faults is primarily concentrated along a singular fault strand. Vertical displacements from three alluvial fan surfaces along the Buena Vista fault include 1.5 m, 4 m, and 15 m. Along the southern Shoshone fault, alluvial surfaces are displaced 2.2 m and 10 m. Deformation along the Buffalo Valley fault is distributed across several parallel strands. Cumulative displacement across the oldest surface (three traces) is about 16 m and late Pleistocene fans are displaced between 1.75 and 4.2 m. A possible displacement of 0.75 m is recorded in a latest Pleistocene fan. Soils developed into late Pleistocene surfaces along the Buffalo Valley fault are characterized by thick (>1 m) textural B-horizons associated with stage III+ carbonate development suggesting the surfaces are greater than 100 ka. In progress ^{10}Be surface exposure dates from surficial boulders and ^{10}Be depth profile analyses from the soil pits will place age constraints on displaced deposits, and be used to estimate fault slip rates. These data will allow development of earthquake recurrence estimates for refinement of seismic hazard models, and for assessment of blind geothermal systems in the region.

POSTER 90

Late Pleistocene Kinematics of the Great Southern Puerto Rico Fault Zone, Puerto Rico

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At the Northern Caribbean Plate Boundary Zone, geodetic data show differential motion between the Puerto Rico-Virgin Islands (PRVI) microplate and neighboring Hispaniola. The precise location of this microplate boundary is unclear over geologic timescales. This differential motion may be accommodated through distributed deformation on multiple faults located throughout southwestern Puerto Rico, with lateral motion and/or shortening predicted by various tectonic models. Recently, several onshore faults in southern Puerto Rico were recognized as Quaternary-active. However, the kinematics of these faults—particularly any lateral component—remain largely unconstrained. This is due in part to extensive erosional and anthropogenic landscape modification, steep relief, and frequent landsliding, limiting the preservation of geomorphic features that could serve as recorders of fault motion. Here we constrain the kinematics of the Great Southern Puerto Rico fault zone (GSPRFZ), an onshore fault considered for inclusion in the upcoming 2025 USGS National Seismic Hazard Model update for Puerto Rico and the U.S. Virgin Islands. Integrating <1-m lidar-derived topography, historical air photos, and field mapping, we identify a series of ~50–1200-m-long fault scarps and lineaments that trend northwest-southeast and extend for ~25 km across the southern coastal plain. Fault scarps are primarily south-facing, cut across topography, and displace Quaternary deposits and landforms. We document multiple offset geomorphic markers, including channel thalwegs and interfluves formed in deposits previously mapped as Quaternary piedmont alluvial plain. We observe both vertical (south-side-down) and right- lateral m-scale displacements, which indicate that the GSPRFZ may accommodate right-lateral oblique motion in the late Pleistocene, consistent with northeast motion of PRVI away from Hispaniola. Additional studies are needed to determine the kinematics of other onshore Puerto Rico faults and better understand how these faults may be accommodating deformation at the PRVI-Hispaniola microplate boundary.

POSTER 91

A Comprehensive Search for Evidence of Active Faulting in the Southern Coast Mountains of British Columbia, Canada: Progress and Preliminary Results

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The southern Coast Mountains of British Columbia are situated in the inner northern forearc of the Cascadia Subduction Zone. They are traditionally viewed as the static backstop for the northward moving Oregon coast block. While many faults have been mapped in the Coast Mountains, conclusive evidence of Holocene displacement has not been observed. The recent discoveries of surface ruptures along the Leech River, Beaufort Range, and XEOLXELEK-Elk Lake faults on neighboring Vancouver Island underscore the importance of reexamining the faults in the southern Coast Mountains, which could pose a significant hazard to densely populated areas including Metro Vancouver. However, this effort is challenged by glaciated, mountainous geomorphology, and dense vegetation.

We collated digital elevation models of varying coverages and scales, from 1-arc-second satellite data to meter-scale lidar data. Particular attention was paid to locations of previously mapped faults and seismicity. We identified escarpments related to regional-scale lineaments at Bowen Island, Alouette Lake, Coquitlam Mountain, and Nahatlatch Lake, in addition to known fault systems such as the Fraser River Fault. We conducted field surveys in 2022 and 2023 to collect ground observations where the linear features appear to intersect Holocene sediments. In some areas, we deployed a UAV lidar scanner to obtain ultra-high resolution topographic data. At one site in the Britannia Shear Zone, we observed a 20-cm offset in the soil profile on opposite sides of a fault exposure, but the UAV lidar did not reveal a scarp extending from the outcrop. In addition to vegetation cover and glacial erosion, we have been challenged by unpredictable weather, difficult access to remote sites, and a lack of sufficiently fine-grained Holocene sedimentary deposits to potentially record sub-meter-scale displacements. Future plans include helicopter-based lidar surveys of remote areas and sub-bottom profiling in lakes that may better preserve offsets in Holocene stratigraphy. The results of this project will be incorporated into Canada's national seismic hazard and risk models.

POSTER 92

Investigating Holocene-Active Faulting in the Strait of Georgia, British Columbia Through Archived Seismic Reflection Data

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Previous evidence of Holocene-active faulting in the central Strait of Georgia has been observed through limited interpretations of seismic reflection, bathymetric relief, and seismicity datasets. However, in part due to a dearth of attention and historic unavailability of subsurface data, our understanding of such active faulting in the region is incomplete. This has resulted in piecemeal knowledge of the presence, spatial extent, and seismogenic capacity of faults in the region, despite their potential hazard to critical infrastructure near the city of Vancouver, British Columbia. Thick deposits of Holocene muds, a result of rapid sedimentation in the Fraser River Delta, limit the usefulness of 3.5 kHz sub-bottom profiling techniques and may rapidly infill surface fault expressions, complicating interpretation. Furthermore, modern permitting requirements associated with minimizing submarine noise make obtaining the necessary deeper seismic reflection data challenging.

The Geological Survey of Canada (GSC) has a vast archive of paper seismic reflection records in the Strait of Georgia, collected in the 1980s-2000s, which have been recently scanned and digitized. This presents a new opportunity to examine the subsurface in an area with high potential seismic risk and partially identified evidence of active faulting. This study utilizes the GSC's archived data to look for evidence of Holocene faulting in the central Strait of Georgia. We aim to present preliminary structures identified through this investigation and tie these findings with other recent work to characterize potentially active faults in the region surrounding Vancouver. Our work highlights the importance of leveraging existing subsurface datasets to fill knowledge gaps and inform hazard assessments.

POSTER 93

Steps Toward Linking the Kaltag and Tintina Faults in Interior Alaska

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Alaska tectonics are driven by subduction of the Pacific Plate beneath the North American Plate at the state's southern border, causing N–S compression and shearing of southern Alaska to the west. Transpression and rotation occur over 700 km north of the subduction trench in Interior Alaska, where the Kaltag–Tintina fault system, a north-convex right-lateral strike-slip arch, spans the entire state. The Tintina fault is a westward extension of a major tectonic strike valley in Canada, and both it and the Kaltag fault are characterized by linear scarps, slope breaks, swales, and right-lateral offset streams. Slip rate estimates for the system range from 0.01 to <0.5 mm/yr, suggesting interseismic periods of thousands to tens of thousands of years and contributing to poor preservation of past activity and large uncertainty in seismic potential. Despite geomorphic expression, diffuse seismicity, and several recent M4–5 events, documented Quaternary activity along the two faults is sparse and the link between the two faults near the Yukon River Bridge—economically crucial infrastructure—is poorly understood. Ongoing work with new statewide high-resolution imagery and elevation datasets suggests that the W–NW striking Tintina fault system bends to the W–SW around Mt. Schwatka. West of Mt. Schwatka, DGGS collected high-resolution lidar that confirms disappearance of young deformation into the linear Rogers and Isom creek valleys near the Yukon River. However, farther W–SW along strike in the southern Ray Mountains, lidar elevation models reveal ~25 km of youthful surface rupture, the western end of which represents a ~35 km left step at the mapped end of the Kaltag fault at Tanana. These newly discovered faults suggest a M6.5 paleoearthquake ~50 km SW of the Yukon River Bridge. Though the first attempt at traditional paleoseismic trenching was inconclusive, lidar and field mapping illustrate the variability in geomorphic preservation of fault activity over short distances and highlight the difficulty in properly characterizing seismic hazard for low strain rate faults in forested, high-latitude terrain.

POSTER 94

A Detailed Earthquake Catalog for Interior Alaska Fault Zones

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We use network-matched filtering (NMF) and relative earthquake relocation techniques to derive a detailed catalog of earthquake locations for the Minto Flats fault zone (MFFZ) in interior Alaska between September 2014 and December 2019. The MFFZ is a left-lateral strike-slip fault system situated between the right-lateral Denali and Kaltag faults. It produced a magnitude-6 earthquake in 1995 and has potential for a magnitude-7 earthquake. We systematically test parameters for the NMF and earthquake relocation routines and perform a qualitative check on the final catalog in order to reduce false detections that would skew relocations. Our results provide the most complete catalog for the MFFZ and include deeper events, clusters of shallow seismicity and a complex, and segmented fault structure not observed in the original regional catalog. We are also able to determine the fault orientation of the northwest cluster of seismicity containing the 2014 Mw 5.0 event as well as identify a previously unstudied third strand segment in the southwest region of the fault zone.

POSTER 95

Spatial Patterns of Tectonic Deformation at the Mendocino Triple Junction Inferred From River Terraces and Landscape Morphology

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At the Mendocino triple junction (MTJ), the Cascadia subduction zone, San Andreas Fault system, and Mendocino Fault meet in a complex deformation zone. In the immediate MTJ area, from roughly Ferndale to Shelter Cove, CA, previous investigation of the fault networks was primarily through bedrock mapping, with little differentiation between inactive and active faults, and few constraints on Quaternary deformation rates. Quantification of crustal deformation is limited to coastal uplift rates derived from emergent Holocene and Pleistocene marine terraces, and stream metrics and erosion rates from small coastal drainages within ~5 km of the coast. In this steep and densely vegetated environment, recognizing spatial variation of inland Quaternary crustal deformation rates could help identify the presence and location of active faults where there is little direct surface expression. We use lidar to map fluvial terraces and other geomorphic surfaces along river valleys in the MTJ area up to 30 km inland. Longitudinal profiles, height above river, and morphological characteristics are used to correlate terrace surfaces along the rivers. In the Mattole watershed, terraces with different vertical spacings occur along channel reaches having different gradients separated by distinct knickzones. These patterns may indicate spatially variable uplift rates. Complementary analysis of landscape morphology including hillslope steepness and relief, and river metrics such as channel steepness index expands the spatial extent of inferred deformation beyond the terraced river valleys. These analyses must consider apparent drainage area reduction due to drainage divide migration and stream capture, which itself provides additional insight into the landscape response

to tectonic forcing. Spatial variation in apparent uplift rates indicate possible location and kinematics of crustal faults related to the San Andreas Fault and Cascadia subduction zone which are objectives for future study.

Detecting, Characterizing and Monitoring Mass Movements

Oral Session • Thursday 2 May • 8:00 AM Pacific

Conveners: Kate Allstadt, U.S. Geological Survey (kallstadt@usgs.gov); Clément Hibert, University of Strasbourg (hibert@unistra.fr); Ezgi Karasozen, University of Alaska Fairbanks/Alaska Earthquake Center (ekarasozen@alaska.edu); Liam Toney, U.S. Geological Survey (ltoney@usgs.gov)

Infrasound Array Analysis of Rapid Mass Movements in Mountain Regions

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Rapid gravity-driven mass movements (RGMMs), such as rock-falls, snow avalanches, glacier break-off events, debris flows, lahars and pyroclastic density currents are among the most hazardous phenomena occurring in mountain environments. In the last decades remote monitoring solutions for RGMMs have been implemented using acoustic signals radiated by these rapidly moving flows. In particular, infrasound observations, which entail sound below 20 Hz, has been shown to provide a valuable, low-cost, low-latency, and relatively straightforward complement to in situ measurements. Here we present a review of recent infrasound observations comparing various types of RGMMs highlighting the capabilities and limitations of infrasound array monitoring techniques for both research and monitoring applications. We showcase processing strategies for using low-cost infrasound arrays, with apertures of a few tens of meters, to locate and track moving sources and extract information about their source mechanisms using infrasound energetics. This research provides comparative case studies of diverse flow phenomena using infrasound arrays situated several kilometers from respective flow paths.

The Mount Rainier Lahar Detection System: Risk Mitigation for an Unlikely, but Potentially Catastrophic, Event

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Mount Rainier (Washington, USA) last erupted ~1,000 years ago and has experienced tens of eruptions over the last 10,000 years. Of all the hazards associated with Mount Rainier, large lahars pose the greatest risk to communities downstream of the volcano—more than 90,000 people live in areas that could be impacted by a future large lahar. Large lahars have reached as far as the Puget Lowlands (> ~50km) at least 11 times over the last 6,000 years. All but one was associated with an eruption; the exception is the ~1507 A.D. landslide-initiated Electron Mudflow, for which no evidence of an associated eruption has been found. Recent studies show that the western flank of Mount Rainier could produce future non-eruptive landslides and associated large lahars down the Puyallup and/or Tahoma Creek drainages, potentially reaching nearby small towns within 5-10 minutes and larger communities within 60 minutes.

The Mount Rainier Lahar Detection System is part of a risk-mitigation strategy pursued by a group of local, State, and Federal agencies since 1998. It consists of several components: 1) a real-time network of tens of seismometers, infrasound arrays, tripwires, webcams, and other instruments located on the flanks of the volcano and along vulnerable drainages operated and upgraded periodically by the U.S. Geological Survey (USGS) Cascades Volcano Observatory (CVO) and the Pacific Northwest Seismic Network; 2) an automated detection system, designed and maintained by CVO, that triggers alarms in two separate county- and State-run 24/7 emergency operations centers; and 3) a set of protocols and inter-agency agreements among CVO, Pierce County (Washington) Department of Emergency Management, and the Washington State Emergency Management Division that delineate each agency's detection, alerting, and/or warning responsibilities, protocols that are reviewed and tested periodically. CVO's protocols have required establishing a rotation of scientists who carry a duty phone to provide partners with a 24/7 point of contact, and who are expected to respond within 1-2 minutes to automated alerts from the detection system.

Characterization of a Debris Flow at Mount Rainier via Seismoacoustics and a Novel Usage of a Laser Rangefinder

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Mass movements such as debris flows and lahars can occur at volcanoes with or without associated unrest and have the potential to impact life and infrastructure for tens of kilometers downstream with little warning. Many have low-amplitude emergent onsets and moving source locations, making their initial detection and characterization difficult. Small debris flows can occur at volcanoes due to heavy rainfall or snow- and ice-melt in the summer. Recordings from such events can be used to develop and test novel monitoring techniques as well as detection and characterization algorithms in the absence of larger, but less frequent, lahars.

Here we present recordings of a small debris flow at Mount Rainier (Washington, USA) that occurred on August 15, 2023, in the Tahoma Creek drainage. Mount Rainier has had at least 11 large lahars over the last 6,000 years, including one occurring without evidence of eruptive activity. In response to this hazard, the USGS and partner agencies operate the Rainier Lahar Detection System (RLDS) that was recently upgraded and densified. The current network consists of broadband seismometers, infrasound arrays, tripwires, and webcams concentrated along multiple potentially hazardous drainages. The 2023 debris flow was recorded by this network and by a suite of temporary campaign geophysical equipment. Among these instruments was a laser rangefinder recording at 1 Hz, co-located with a seismometer and infrasound sensor directly adjacent to the channel. The intent was to test its utility in detecting lahars as a potential replacement for tripwires currently in use to provide confirmation of a lahar. The laser rangefinder and co-located instruments clearly recorded the flow, in addition to the 10 broadband seismometers and 4 infrasound arrays in the permanent network, as the flow moved down the drainage. The 2023 debris flow produced recordings that have allowed us to calibrate and evaluate RLDS algorithms and served as a successful test for new geophysical equipment that may be useful for detection of lahars at Mount Rainier and elsewhere.

Identification of Lahar Signals: A Supervised Learning Model Applied to Monitoring Data of Volcan De Fuego, Guatemala

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The rise in popularity of machine learning models has provided improved tools for identifying and classifying seismic signals of different natures. Here, we showcase a novel approach that uses a supervised K-nearest neighbor model to detect tremor signals associated with rain-triggered lahars at Volcan de Fuego, Guatemala. For this, we used a set of three permanent and five temporary broadband seismometers installed between ~10–350 m from the thalweg of two active lahar channels around Fuego. The recorded signals display durations between 0.5–6 hours, high signal-to-noise ratios, and overall high-frequency activity with lower frequencies active during denser, high-energy flow portions. We established a binary classifier trained with features that describe the seismic record in the time and frequency domains, split into 10-minute overlapping windows. The best features for this method were chosen based on the model's performance. They included measures of the signal's amplitude, frequency content, and statistical functions of the prior, such as kurtosis, skewness, and entropy. A training set of 5 confirmed lahars

and equally long background noise was enough to achieve greater than 90% precision at stations with a comparatively low sampling rate (50 sps). Cross-validation shows that two of our datasets with higher sampling rates (200 sps) require a higher number of neighbors to achieve similar precision results: n<10 at 50 sps vs. n>50 at 200 sps. A post-processing step converts the resulting discrete sample predictions into prediction intervals and discriminates false positive results. This model detected 161 of 172 observed lahars during the 2018-2022 period at the longest-running seismic station in one of Volcan de Fuego's active channels. While these detections did not always match the total duration of observed lahars, they still correctly classified ~95% of the signal portion attributed to lahar activity during this period. We highlight the potential of our method for real-time monitoring applications, providing a valuable tool for the timely identification of lahar signals.

Lahar Early Warning at Volcano Santiaguito: A Classical and a Deep Learning Approach

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The Santiaguito Volcanic Complex is located in Guatemala's Western Volcanic Highlands, along the westernmost section of the Central American Volcanic Arc. Santiaguito presents multiple hazards (including explosions, local earthquakes, lahars, mudflows, and pyroclastic flows) to the local population, which numbers 1.6 million people within 30 km^2 around the volcano. Lahars are flows of a mixture of a large amount of water and pyroclastic debris (that can include gases) which can rapidly initiate and reach speeds of tens of meters per second down wide barrancas (canyons) making them highly destructive. Lahar occurrence strongly correlates with rainfall at the volcano and they are commonplace in the long rainy season. They pose a great hazard to local inhabitants who regularly cross the channels as they live and work on farms on or near the flanks of the barrancas. INSIVUMEH, the national seismic and volcano monitoring agency, has recently built a network of 10 seismic stations that can monitor these flows in collaboration with external agencies. We used the open seismic data from 2022 and 2023 to consolidate a Lahar catalogue, having a total of 43 Lahars. We then use the Lahar data (91 waveforms) from 2022 to train a Siamese Neural Network that uses 5-minute single-station waveforms to produce a Deep Learning Lahar detection. We use the same data to develop a classical Lahar detector that uses ratios between two different short-term/long-term average amplitude (STA/LTA) characteristic functions implemented in SeisComP. We then test both approaches on continuous data from 2023 and compare them. We demonstrate the advantages and disadvantages of both approaches and show that both could be combined for optimal Lahar Early Warning. We show how the classical method, implemented through SeisComP, is being used to operate an early warning messaging system. We expect that the developed tools can be portable to other volcanic areas and even other flow types. Furthermore, we demonstrate the usefulness of Siamese Neural Networks for the development of Deep Learning models when a small number of training data is available.

Towards Building a Machine Learning Based Automatic Detection System for Surface Events in the Pacific Northwest

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Systematic monitoring of mass movements, such as landslides, avalanches, rockfalls, and debris flows, is vital for mitigating risks in places where such events threaten to impact people or infrastructure. The Pacific Northwest Seismic Network (PNSN) detects a subset of surface events as a byproduct of the routine detection and location workflow for tectonic and volcanic earthquakes.

In this study, we explore a vast range of feature space and model architecture designs for event classification. We found that the random forest algorithm along with a specific set of features is the best model for its generalization over the PNW data sets. We trained our model on a curated set of waveforms from Ni et al. (2023) for earthquakes and other seismic sources recorded by the PNSN over the past 20 years and developed a workflow that can be deployed on continuous data. We then used our model to automatically detect and characterize events at Mount Rainier, identifying surface events in a month of continuous data from three seismic stations. The model successfully identified all surface events manually picked by PNSN analysts for the study period with a high classification probability exceeding 0.9. Additionally, it detected approximately ten times more surface events with a high probability of 0.8, with a subsequent manual review revealing their resemblance to waveforms of verified surface events or volcanic events. In one attempt to validate our new detections, we computed maximum cross-correlation coefficients of detected event waveforms with ground-truthed surface events in the Earthscope Exotic Seismic Event Catalog for the Mount Rainier region and found that many of the detected surface event waveforms exhibited high correlation coefficient values exceeding 0.9. We also report their approximate location using phase picking of the onset of the emergent waveforms and use a grid-search method for determining locations using a uniform velocity model. Ongoing efforts to generate better training catalogs and to verify new detections involve incorporating additional stations, DAS, eyewitness accounts, and infrasound data.

Source Characterization of Surface Events in the Pacific Northwest

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The Pacific Northwest (PNW) is subject to various geohazards due to its active tectonics, volcanism, and surface processes. The Pacific Northwest Seismic Network (PNSN) monitors seismic activity in the PNW with a mandate to characterize tectonic earthquakes. Volcanoes are relatively well monitored by the PNSN in terms of determining source origin time, location, and magnitude for volcano-tectonic earthquakes. However, many other event types are labeled by seismic analysts as "surface events," which are informally understood as being mass flows of snow or rock avalanches, rockfall, landslides, and debris flows but are not characterized further by analysts.

We collect seismograms from ~ 8000 events with 5-10 seismic stations located on six PNW volcanoes; Mounts Hood, Rainier, St. Helens, Baker, and Adams, with the goal to further characterize these surface events. We use an ensemble deep-learning phase picker to pick the onset of the waveform, which helps determine where the emergent signal starts. We then calculate the signal-to-noise ratio (SNR) and only pick traces with sufficiently high SNR. We also pick the time of the peak amplitude in the envelope function to track the centroid time of the event. We locate event onsets and centroids using a simple grid-search algorithm. We estimate a potential direction of motion (flow) and velocity using 1) Doppler effects measured from the seismogram's spectral content and 2) the difference between the centroid and event onset times and locations. We analyze these directions and velocities relative to high-resolution digital elevation models and discuss the potential and limitations of this method as a prototype for detecting debris flow or lahar in the Cascades.

Dissecting Seismic Signals to Estimate Landslide Volume

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Determining the size of a landslide based solely on the seismic signal it produces could be a useful tool for rapid event characterization, response, and early-warning systems. In this study, we work towards establishing a general relationship between the seismic signal and the physical properties of large, rapid landslides that are detected by regional seismic networks. To do this, we analyze the seismic signals for known landslide events and determine which combination of seismic parameters best predict landslide characteristics of interest, primarily volume.

We analyze events from the Exotic Seismic Events Catalog (ESEC), a published catalog including information on the seismic detection and physical properties (e.g., volume, runout distance, and drop height) of 290 seismogenic landslides. This collection spans several continents, which provides us with a diverse dataset to work with. We focus on large (>105 m3) mass movements with fall, slide, and avalanche movement types because they are seismically detectable at regional scales and generate observable long-period (>20 s) signals that we can invert to obtain the force history of the landslide's bulk motions. We analyze parameters in the high-frequency range (1-5 Hz) to represent the portion of seismic energy produced by smaller-scale processes, such as disrupted flow and granular interactions. We also include characteristics of the force histories inverted from the long-period signals which represent the bulk movement of the failure mass. We find that envelope rise time, envelope area, and maximum force scale logarithmically with volume, whereas peak frequency and maximum

amplitude have a less-defined relationship. Using this information, we perform a multivariate linear regression to develop an empirical relationship between these parameters and independently estimated volumes (usually via remote sensing), as reported in the ESEC. We find that a combination of envelope rise time, envelope area, and maximum force, derived solely from seismic analysis, provide a reasonable estimate of landslide volume with well-defined uncertainties.

Radial Backprojection Imaging of Recent Mass Movements in Alaska

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Backprojection imaging has shown utility for locating seismic events using waveform data, without requiring timing information from clear phase arrivals. Processes imaged with backprojection include earthquake rupture, volcanic tremor, and surficial mass movements. Here we develop a novel backprojection method using the radial horizontal component, instead of the conventional technique utilizing the vertical component, and apply it to recent mass movements in Alaska. Use of the radial horizontal component is designed to image the source region with Rayleigh waves, which are efficiently generated by surficial seismic sources. Although radial backprojection offers many advantages to vertical backprojection, including improved signal-to-noise ratio (SNR) of the image and the ability to image the source location with only two stations, its application requires additional details in order to quantitatively interpret the normalized amplitude of the backprojection image. For vertical backprojection, a normalized amplitude between 0 and 1 indicates either perfectly destructive (0) or perfectly constructive (1) stacking of the vertical waveforms at different stations. In contrast, a normalized amplitude of 1 for radial component backprojection indicates perfectly constructive stacking of signals exhibiting exclusively radial particle motion (i.e., no transverse component). We apply this novel radial backprojection method to a glacial calving event at Barry Arm on December 15, 2022, a landslide on the Kenai Peninsula near Seward on September 15, 2022, and a large ice-rock avalanche at Iliamna volcano on June 21, 2019. These case studies demonstrate the ability of radial backprojection to locate a source with as few as two stations and the improved SNR of the radial backprojection image compared to vertical backprojection. We also discuss the similarities and differences between radial backprojection and the method known as radial semblance developed by Kawakatsu et al. (2000; JVGR) and Almendros and Chouet (2003; BSSA).

Enhancing Real-Time Landslide Detection for Improved Tsunamigenic Landslides in Alaska

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In response to the increasing prevalence of mass movements, such as landslides, coupled with the urgent need for early warning systems, this study presents significant advancements in refining real-time landslide detection. Currently, we run a real-time landslide detector based on long-period seismic data within the dynamic landscape of southern Alaska. Over the past year, we have compiled a diverse dataset encompassing landslides (0.2 - 10 M m3), as well as regional (M 3-5) and teleseismic seismic events that triggered false detections.

In this study, we refine detection techniques by combining historical landslides, which benefit from well-studied properties, with a diverse set of landslides detected in real time during the 2023 season. We employ a range of waveform similarity measures, explore different signal processing criteria, and assess various detection thresholds to derive sets of statistics aimed at enhancing detection performance. Our primary objective is to substantially improve accuracy and reliability in the early detection of landslides, with a particular focus on tsunamigenic events. The ultimate goal of this research is to provide a robust and efficient solution for early detection of tsunamigenic landslides, contributing to improved warning systems and mitigation strategies in coastal regions.

Seismic Collapse Mechanisms of Large (M~4) Rock and Ice Avalanches in Southeast Alaska

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Mass movement events such as landslides and rock and ice avalanches are traditionally analyzed at seismological observatories as single forces that model mass trajectories unfolding in space and time. These events may also be analyzed as point sources with moment tensors, though this approach may not always apply for complex events with tortuous runout trajectories, multiple simultaneous detachments, slow slip, and emergent signals. Despite their complexity, these events may also produce a more coherent long-period signal which in the far field may be analyzed with moment tensors. When applicable, moment tensor analysis of landslides provides a way to routinely and quickly characterize mass movement events which can aid in providing prompt response and warning. In the present study we examine a dataset of seismic events in Alaska identified as icequakes or avalanches by the Alaska Earthquake Center and estimate the source mechanisms (moment tensors) of five events from the recorded waveform data. These five events occurred in the Southeast Alaska between 2005-2016 and were massive rock and ice avalanches with reported volumes on the order of 30-60 million m3, weighing between 20-100 billion kg. Due to the large size, these events were observed at seismic stations located thousands of kilometers away. Some events occurred during deployment of the USArray network in Alaska and Canada which allowed us to examine datasets containing hundreds of stations. The best fitting solutions produce synthetics seismograms that agree with long-period observational data. We analyze the moment tensors in terms of their source-types, which reveal negative isotropic (collapse or dilatational) parameters, and we discuss these and other gravitational mass movements from mining sites. We also discuss work towards operational implementation for routine analysis of similar events.

The Seismic Puzzles of the 2022 Chaos Canyon Landslide in Rocky Mountain National Park

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On 28 June 2022, ~2 million m^3 of ice-rich debris mobilized from the southeast flank of Hallett Peak in Rocky Mountain National Park, sliding about 245 m in ~2 minutes, and narrowly missing a group of climbers downslope in Chaos Canyon. The size and energy of this event was evident in eyewitness videos and reflected in the ground vibrations it generated, recorded up to 70 km away. Using eyewitness accounts, field and remote sensing techniques, historic climate data, and seismic evidence, we pieced together a detailed timeline of this landslide stretching back decades to when the slope started moving as air temperatures warmed. In this talk, we focus on June 28, and on the seismic aspects of the landslide event.

We first describe how we used the seismic signals and eyewitness accounts to piece together a complex sequence of events starting with a gradual build-up in rock fall activity and culminating in three energetic sliding episodes. We also discuss a seismic "red herring": a M1.4 earthquake-like signal ~1 min prior to the main sliding event that initially appeared to be coming from the landslide, but that later evidence, including a repeating earthquake analysis, revealed to be a blast from reservoir construction 36 km east of the park. Videos show some sliding was already underway when the blast occurred making it unlikely that it triggered the slide, but the weak shaking it induced at the landslide (~0.001% g) could have influenced slide behavior. Finally, we investigated why the main event did not generate observable long-period seismic signals related to bulk mass accelerations that are typical of large, rapid landslides by modeling the event using the SHALTOP numerical landslide model. We found that this landslide was actually slower and less mobile than most landslides of similar size, resulting in long-period signals that were too low amplitude to be observable. In summary, we combined diverse evidence and techniques to understand this event, and the seismic signals were valuable in helping unravel this unusual landslide sequence.

New Insights on the Åknes Rockslide (Norway) Using Borehole Microseismic Data

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The Åknes rockslide, located in Western Norway, is one of the most thoroughly instrumented rockslides in the world. Since the 2000s, it has been equipped with various instruments measuring its displacement (extensometers, GPS, lasers,…). Measured movements are in the order of 1 to 3 cm/yr.

As part of the monitoring system, eight geophones were installed at the surface around the backscarp of the slide in 2005. Although the data are only recorded in triggered mode, the large amount of data collected over the years has proven useful to characterize different types of events related to the slide movements.

More recently, a borehole was instrumented with eight geophones continuously recording at 1000 Hz down to a depth of 50 m, crossing two sliding planes. There, seismic events characterized by a very high frequency content and a short duration can be detected. These events are likely located very close to the borehole. In particular, periods of intense seismic activity could be identified. The detailed analysis of the waveforms during such periods reveals series of repeating events interrupted by quiescence phases that could be interpreted as creeping on different patches of the shear zone. At least one of these periods could be correlated with an increase in the water pressure at the depth of the corresponding shear zone.

How Do Slow-moving Landslides Maintain Steady Motion?

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Slow-moving landslides predominantly manifest steady motion, in striking contrast to rapid runaway landslides that accelerate and fail catastrophically. However, we do not fully understand how slow-moving landslides arrest and stabilize their motion. Better understanding of the underlying mechanisms potentially holds the key to illuminate their slow-to-fast motion transition and also offers insights on frictional faulting processes. To approach this problem, we deployed dense instrumentation on the slow-moving (~1.5 cm/d) Slumgullion landside in Colorado from 2022 to 2023. The sensors encompass four surface creepmeters along its southern edge, four embedded strainmeters on the slide, and six GPS receivers and 150 nodal seismometers covering the middle section. These sensors record data at one-minute or higher rates. We complemented the field measurements with high-resolution TerraSAR-X and PAZ SAR repeat acquisitions.

From the 2.5-μm-precision creepmeter and strainmeter data, we observed coupled slip and strain events that migrate along the slide on a ten-day timescale, appearing as accelerations or decelerations in slip rate and axial strain with wavelengths of ~100 m. From creepmeters along the southern edge, we have also observed slip signatures of episodic acceleration-deceleration in duration of minutes and magnitude of sub-millimeters. These distinct slip patterns seemingly resemble fault creep that consists of a relatively sharp acceleration followed by gradual slowdown. The observed motion propagation and high-rate creep signals suggest possible changes in landslide shear strength, which may be related to pore-pressure feedback and/or rate-dependent material strength. We are actively processing the collected GPS, SAR, and nodal seismic data to extend our observations form the marginal transform to interior parts of the slide. These additional data may allow distinguishing the frictional properties and strength of the basal and lateral landslide boundaries. Findings from this work are anticipated to shed light on the mechanism of slow-to-fast slip in landslides and tectonic faults.

Big Tsunamis in Little Lakes

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The past decade has seen a spate of dramatic tsunamis, largely going unnoticed, triggered by landslides into small water bodies. This presentation will explore examples since 2016 in British Columbia and Alaska, including those listed below:

Location	Date	Landslide volume (Mm^3)	Maximum runup (m)
Cowee Creek	30 Dec 2016	0.5	?
Elliot Creek	28 Nov 2020	18	> 100
Brabazon Range	~12 Aug 2021	~10	~30
Upper Pederson Lagoon	15 Apr 2022	~1	~7
Ecstall River	1 Sep 2022	5+	?

Some of these events resulted from landslides that produced distinctive seismic signals, but in only some of these cases was this seismic signal automatically characterized as a landslide. These went unnoticed until later, when their dramatic impacts were discovered by locals or through examining satellite imagery. Comparing the events reveals patterns that could inform mitigation strategies, including assessment, targeted seismic monitoring, and probabilistic hazard mapping. Fortunately, these recent events have had only minimal human impact. However, there are several sites with dramatic signs of slope instability above lakes fringed with human infrastructure and popular with visitors. It's critical that we improve assessment, planning, and monitoring related to these hazards before we have the benefit of tragic hindsight.

Detecting, Characterizing and Monitoring Mass Movements [Poster Session]

Poster Session • Thursday 2 May

Conveners: Kate Allstadt, U.S. Geological Survey (kallstadt@usgs.gov); Clément Hibert, University of Strasbourg (hibert@unistra.fr); Ezgi Karasozen, University of Alaska Fairbanks/Alaska Earthquake Center (ekarasozen@alaska.edu); Liam Toney, U.S. Geological Survey (ltoney@usgs.gov)

POSTER 55

The MVO Rockfall Location System 24 Years On: Reimplementation, and Re-Analysis of Pyroclastic Flow Trajectories

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Montserrat, West Indies. On March 20th, 2000, heavy rainfall induced 4 hours of progressively intensifying lahars and pyroclastic flows, reaching the ocean in most directions. Most of Montserrat's population lived close to the Belham Valley, which was greatly impacted. Having recently re-joined MVO after a 3.5 year absence, this event gave new impetus to an idea that I had originally had in July 1996 from observing the bar graphs of the RSAM system: could we devise a real-time system for the location of pyroclastic flows, based on the distribution of amplitudes across the seismic network? Within 24 hours, I had a near-real-time "rockfall location system" running, featuring a crude shrinking grid search, and sending alarms by SMS. By databasing the estimated trajectories, "heatmaps" of rockfall activity could be plotted between pairs of dates/times, to reveal which parts of the dome were growing/collapsing, giving us a sort of seismic-X-ray vision to peer through the persistent cloud that shrouded the lava dome. However, given the fast-paced nature of a volcanic crisis, a systematic evaluation of performance did not occur and, unfortunately, this software and the corresponding database was lost in June 2003, when I departed MVO. We have re-created this system as an ObsPy-based package, and hundreds of event trajectories are being recomputed. In this presentation, we will assess system performance, and see what lessons can be learned about the Montserrat eruption.

POSTER 56

Using Infrasound to Detect Snow Avalanches and Inform Forecasts in Alaska

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Slab avalanches occur when an unstable mass of consolidated snow breaks away from a mountain slope. These events can damage key infrastructure such as roads, railways, and powerlines. It is expected that climate change will lead to increased avalanche activity. Avalanche forecasts, which are key to mitigating hazards, partially rely on visual observations, which cannot be made during low visibility. Infrasound observations, which work in all visibility conditions, have proven useful in the detection and characterization of avalanches in Utah and Canada. However, there is limited research using infrasound to detect and characterize avalanches in maritime snowpacks (those located near coastlines). Specific to Alaska, a need exists to effectively discriminate between earthquakes and avalanches. We deployed an infrasound network in Tutl'uh (Turnagain Arm), Alaska, USA to capture natural and triggered avalanches. This presentation will detail the deployment and discuss plans for data analysis.

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POSTER 57

Deep Transfer Learning Framework for Regional Landslide Mapping Using Post-Event Imagery

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Landslides, often occurring in mountainous regions and triggered by earthquakes or heavy rainfall, are a major natural disaster. Traditionally, identifying landslides involves manually analyzing optical remote sensing imagery, a process that is both slow and labor-intensive. This study proposes an automatic landslide detection method using advanced deep learning techniques. Previous research in this area has focused on using RGB channels from both before and after the event, along with other data sources like digital elevation models, for change detection. However, the effectiveness of deep learning in this context depends heavily on the availability of high-quality, large datasets, which can be a challenge in the immediate aftermath of a landslide. This study specifically explores the transferability of a deep learning model trained on data from the 2016 Kumamoto Earthquakes. It tests the model's effectiveness in detecting landslides caused by different events: the 2018 Hokkaido earthquake and the 2017 Asakura Rainfall, both in Japan. These events were chosen for their regional similarities, including terrain, vegetation, urban areas, geology, and landcover. The proposed deep convolutional neural network model uses a ResNet50-based DeepLabV3+ framework, which facilitates automated landslide feature extraction from post-event images. This approach does not require fine-tuning for each specific event or the development of unique training data sets. The model demonstrated high accuracy in identifying landslides from the 2016 Kumamoto Earthquakes and performed well in the two unseen events. The impacts of different tile sizes, number of tiles, imagery resolution, and data augmentation techniques are investigated to provide instructions on best practices.

POSTER 58

Quantifying Seismic Properties of a River Channel at Mount Rainier for Use in Debris-Flow Monitoring and Analysis

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One of several challenges in interpreting properties of surface processes, such as debris flows, from seismic waves is developing accurate Green's functions for the environments through which the waves propagate. The waves generated from these processes are primarily recorded at local sensors, and the heterogeneous quality of the surface environment greatly affects the waves over relatively short distances. In particular, the high-frequency energy that is primarily generated by many surface processes is highly attenuated by near surface materials. Our research focuses on understanding some common seismic properties of channel material in the Tahoma Creek drainage at Mount Rainier, USA, to accurately analyze the seismic waves from seasonal debris flows in the drainage, the most recent of which occurred on 15 August 2023. To investigate the seismic properties of the channel material, we deployed 9 nodal seismometers on 9 August 2022 in a ~70 m linear array perpendicular to Tahoma Creek. We used a hammer to create seismic impulses adjacent to the active channel to calculate surface wave velocities and Q, the quality factor for attenuation, for 10 Hz frequency bands between 20 Hz and 55 Hz. The 20 Hz to 55 Hz band encompasses both the majority of energy generated by our hammer blows and contained in our empirical Green's functions for the channel. The 2023 debris flow waveforms that were recorded on additional, nearby temporary stations also primarily contained energy between ~20 Hz and 40 Hz. As the channel is mostly composed of loose gravel, sand, and silt, we find that the surface wave velocities and values for Q are very low and typically decrease with increasing frequency. The surface wave velocities are less than 200 m/s and the values for Q are less than 40 for all frequency bands. We will use the results to correct the amplitudes of the empirical Green's functions that we created for the region and extend the Green's functions to the active channel. These results will be crucial for interpreting the seismic signals from debris flows at near-field stations and for modeling debris flows in the drainage.

POSTER 59

Investigating Seismic Signals From the Barry Arm Landslide

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Barry Arm is a glacier carved fjord located in Prince William Sound, AK. The slopes are steep and unstable and have the potential for catastrophic failure and to cause landslide-driven tsunamis - a significant hazard for nearby coastal communities.

With the threat of major slope failure looming overhead, identifying and interpreting seismic signals seen on the Barry Arm Landslide is important to rapid warning of tsunamis. We analyze seismic signals in this region beginning in the summer of 2020 to better understand slope mechanisms and possible precursor signals that may assist with warning time. Local glaciers and frequent earthquakes in the area add to the complexity of the problem.

Utilizing two seismic stations, one positioned atop the slide and the other situated about 3 km away - across the fjord, we identify different styles of seismic signals associated with the Barry Arm Landslide. These signals differ from each other in terms of their shape, duration, amplitude and frequency. We are able to distinguish these signals from glacier noise by waveform style, comparing amplitudes on different sides of the fjord, and by infrasound back-azimuth. Our seismic station situation is unique as we have two local stations that provide detailed insight into the activities occurring in the area.

We use detection algorithms (like STA/LTA) to develop time histories of each event type. These time histories can be compared to other environmental factors including precipitation, temperature, and deformation of the slope. By comparing seismicity with movement of the slope (identified though ground-based radar and remote sensing observations) and possible triggering factors our goal is to identify seismic signals that may indicate deep-seated movement of the slope that can be potentially associated with catastrophic failure. This study contributes to effective risk mitigation and the protection of coastal communities.

POSTER 60

Seismology Versus Infrasound: Which Monitoring Technique Is Better for Detecting Advancing Lahars?

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Recent studies have reported on remote detection of small secondary lahars using infrasound (low frequency acoustic) arrays at Fuego Volcano (Guatemala). They demonstrated that the frequent small secondary lahars generate a unique infrasound signature that is detectable when the lahar is more than 5 km away from the recording site. At Fuego's Ceniza drainage these early warning detections precede the arrival of the actual lahar by as much as 20 to 30 minutes. This precursor can be enough time to provide an early notification and complement subsequent alerts triggered by AFM systems (geophone seismology), which are particularly effective when situated adjacent to a drainage. AFMs, using relatively high frequency seismic sensing, is a much more established tool for monitoring lahar activity. In this work we evaluate the advantages and disadvantages of infrasound versus seismic monitoring the small secondary lahars at Fuego.

We use a dataset of dozens of lahars from 2022 during which a seismo-acoustic installation was situated adjacent to Ceniza at 14 km flow distance from the volcano. We observe that AFM monitoring has some distinct advantages, over infrasound, including a fundamentally less-noise signal associated with the passing of the flow. Infrasound monitoring at Fuego, in particular, is complicated by multiple other sources of signal and noise, such as from volcanic vent activity, thunderstorms, aircraft, and wind. An advantage to infrasound, however, is that it appears to be uniquely sensitive to more distant sources. While high frequency seismic ground vibrations appear to attenuate relatively rapidly, such that the lahars are not seismically detectable further than a few kilometers, arrays of (as few as two) infrasound sensors appear capable of detecting more distant sources using modified beam forming tech-

niques where the direction of incident infrasound is constrained by knowledge of the volcano's drainages. With knowledge of the lahar's flow path infrasound can be used to reliably detect many (but not all) of the lahar signals up to tens of minutes before they arrive at the monitoring site.

POSTER 61

Repeated Seismicity Conditions Paraglacial Valleys for Slope Failure in Prince William Sound, Alaska

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Paraglacial valley rock slopes in Prince William Sound, Alaska are located within a highly active seismic region and are susceptible to damage from earthquake shaking in conjunction with cycles of glaciation. We hypothesize that because ice is rigid at high co-seismic strain rates, glaciers buttress adjacent ice-contact rock slopes during earthquakes reducing seismic damage, and that as glaciers retreat, the portion of the rock slope susceptible to seismic damage increases. Repeated earthquakes over time thus help condition ice-free areas of paraglacial valleys for slope failure. We use numerical modeling to assess rock mass damage generated by seismic loading at times of different glacier elevations from the Last Glacial Maximum to present. Our models are based on in-situ conditions at Serpentine Glacier Valley, which contains several large, active landslides. Results show the evolution of spatially distributed rock slope damage generated by individual earthquakes, and how a history of repeated seismicity in Serpentine Valley generates rock mass damage conditioning areas of the slope for failure during present-day ice retreat. Glaciers buttress adjacent rock slopes during earthquakes reducing damage in areas of ice contact, while slopes above the glacier incur greater co-seismic fracturing. Over time, earthquake induced damage is maximized in areas that are most often ice free, as well as at slope breaks and crests susceptible to topographic amplification.

POSTER 62

Optimizing Landslide Detection and Validation Through Sentinel-1 Radar Imagery: Case Studies of Hokkaido and Hiroshima in Japan

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Satellite-based (optical and radar) imaging techniques are frequently employed for landslide detection with short time intervals, especially for emergency response, risk assessment, and hazard mitigation. While radar imagery overcomes many limitations associated with optical imagery, it is still constrained by various noise and distortions, potentially resulting in the underestimation of significant landslides and an increased prevalence of smaller landslides. The primary objective of this study is to develop a methodology that can enhance the detection accuracy of different-sized landslides using radar imagery. We utilize multi-temporal imagery from the C-band Sentinel-1 satellites, which are freely available on the Google Earth Engine platform, to analyze the rainfall-triggered landslides in Hiroshima and earthquake-induced landslides in Hokkaido, Japan, across different time frames. We investigate the change in the backscattering intensity coefficient of radar images with VV (vertical transmit-vertical receive) polarization and test the effectiveness of speckle filtering and range-doppler terrain correction using the SNAP software. We explore different cutoffs of the backscattering intensity coefficient, which increase the performance of the area under the ROC curve, to determine the threshold that best captures significant changes associated with landslide events. We choose the same threshold for distinguishing landslide and non-landslide areas in the backscattering intensity maps with and without speckle filtering. For validation, we quantitatively compare our satellite-based detection results with the high-resolution optical-based landslide inventories in terms of the spatial overlap, sizes, and scaling properties of landslides. The results indicate that filtering Sentinel-1 images enables more robust detection of larger landslides and simultaneously reduces false negatives for smaller landslides. These additional processing steps hold promise for more accurate and efficient landslide monitoring at various spatial scales and potentially over time.

POSTER 63

Landslide Susceptibility Assessment Using Earthquake Ground Motion for Different Return Periods in Rasuwa District, Central Nepal

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This study in Rasuwa district focuses on characterizing co-seismic landslide-prone areas by integrating peak ground acceleration (PGA) data expected for various earthquake return periods into a composite map that combines seismic hazard and landslide susceptibility mapping (LSM). Probabilistic seismic hazard assessment (PSHA) is employed to generate seismic hazard maps, depicting PGA for 50%, 10%, 5%, and 2% probability of exceedance (PE) over 50 years. Notably, hazard levels increase from the northern to southern parts of the study area, with the highest PGAs recorded at 0.19g, 0.35g, 0.45g, and 0.55g, respectively. Simultaneously, logistic regression (LR) is utilized for LSM, analyzing 890 co-seismic landslides with 23 different conditioning factors (CF). Standardization of continuous and categorical CF variables is conducted for the coefficients of each factor map. The relative relief emerges as the most significant predictor among the various factors, and the LSM results are classified into five susceptibility indexes. High susceptibility areas concentrate along both banks of the Trishuli River, the main drainage system in the southern part of the study area.

Validation of the LSM model is carried out using the area under the ROC curve and statistical inferences method, demonstrating good agreement with previous landslide occurrences. Composite maps reveal an increase in susceptible areas from 50% to 2% PE in 50 years, with high and very high susceptibility indexes increasing sequentially with rising PGA. The integration of seismic hazard maps and LSM offers a comprehensive understanding of co-seismic landslide-prone zones over different timeframes, providing valuable insights for development planning. These results hold practical implications for formulating and revising building code provisions, implementing slope improvement measures, guiding generalized land use planning, and informing subsequent management strategies.

POSTER 64

[Un]supervised Clustering of [Non-]Earthquake Signals Commonly Recorded on Regional Seismic Networks

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It is well known that surficial mass movements (SMMs), such as landslides and rock falls, have seismic signatures distinct from other routinely-recorded seismic sources like earthquakes and explosions. However, overlaps between the characteristics of these signals can still make it difficult to discriminate between source types during operational seismic monitoring. This ambiguity motivates the development of automated techniques for seismic signal classification. Furthermore, seismic differentiation within the broad class of SMMs has additional scientific and rapid response value. Examination of SMM seismic waveforms highlights a particularly strong contrast between the signals produced by primarily vertical processes — i.e., "falls" — versus processes that have a non-negligible horizontal component — e.g., landslides and avalanches, or "slides" in our abbreviated terminology.

Here, we present a machine learning (ML) classification scheme for differentiating between seismic signals generated by falls versus slides. We additionally include shallow earthquakes and blasts because these are most similar to SMM signals and are commonly recorded on regional seismic networks. These classes, therefore, are the most useful for automated classification. We neglect debris flows in this study because of their much longer durations and low amplitudes. Our signals derive from waveform picks in the Exotic Seismic Events Catalog, a diverse collection of non-earthquake seismogenic surface events, and the ANSS Comprehensive Earthquake Catalog. We use a shallow, feature-based approach to classification using statistical metrics extracted from waveforms. Feature importance metrics provide insight into the ML methods we use, which leverage both unsupervised techniques (to assess the diversity of seismic signals in our training dataset via clustering) and supervised techniques (to train and evaluate a classifier). We picture our classification workflow as one modular element of a larger non-earthquake assessment workflow that includes detection and location as preliminary (or concurrent) steps.

POSTER 65

Seismically-Derived Ground Tilt From Rainfall-Triggered Lahars at Volcán De Fuego, Guatemala

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Broadband seismometers deployed for lahar detection may also respond to load-induced ground rotation near the lahar channel. We analyzed tilt signals on two permanent and four temporary broadband stations deployed along two active secondary lahar channels on the flanks of Volcán de Fuego, Guatemala over parts of three years. These rainfall-triggered lahars occur mainly between May and October and have durations from 30 minutes to 6 hours. Seismic stations were located at distances from 10 to 350 m from the channels and have corner frequencies at 60 or 120 seconds. These deployments were designed for lahar detection at relatively high frequencies at which lahars are most energetic. The seismograms exhibit clear signals below the instrument corners that suggest the lahar masses produce rotation at the stations. We began with a catalog of lahars for years 2021-2023. For each lahar, tilt was derived using a standard approach for signals below the instrument corner: integrating the raw signal; applying a low-pass filter below the instrument corner; and multiplying by a scale factor. The derived tilt signals are fairly complex and vary between stations within a single drainage for a given lahar event. Typical signals have a relatively sharp onset followed by multiple pulses within a single lahar event which are generally consistent with the timing of later flow surges as indicated by the high-frequency seismicity. The tilt particle motions are not necessarily perpendicular to the channel and are often elliptical. Finite-difference modeling using a UAS-derived high-resolution DEM suggests topographic effects produce mismatches between back-azimuth and particle motion direction of 10-25°. In a small number of cases, we combine time-lapse camera images with the lahar records to estimate the lahar masses. This study builds on earlier work that demonstrates the utility of broadband seismometers as tiltmeters in a variety of natural settings.

POSTER 66

The September 16, 2023 Greenland Event: Mysterious Days-Long Monochromatic Very Long-Period Signal Triggered by a Landslide

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Peculiar, energetic seismic signals were generated close to the Dickson Fjord, a remote area of East Greenland on September 16, 2023, followed by a large tsunami, which impacted the northern shore of Ella Island. Using high-resolution Planet Labs Dove mini-satellite imagery we identify that a landslide occurred on the Southern side of the Dickson Fjord on the same day. Seismic signals were recorded at regional to teleseismic distances. Besides a first strong transient signal in the range of 0.02-0.06 Hz, which we attribute to the landslide, a very long (~50 hours), low-frequency, monochromatic (~0.01 Hz) signal was observed at teleseismic distances. We modeled full waveform broadband seismic data to invert for the seismic sources for both types of signals using moment tensor and single force models. The first transient signal is well reproduced at regional distances by single and double source models, which are consistent with the landslide process. The long lasting oscillating signal is modeled at teleseismic distances by a damped dipole oscillator, which reproduces the pattern of Love and Rayleigh waves observed at different azimuths. By combining different data and source models with the Fjord system geometry, we are able to reconstruct the complex source process.

Earth's Structure from the Crust to the Core

Oral Session • Wednesday 1 May • 8:00 AM Pacific

Conveners: Keith Koper, University of Utah (kkoper@gmail.com); Jeroen Ritsema, University of Michigan (jritsema@umich.edu); Vera Schulte-Pelkum, University of Colorado (vera.schulte-pelkum@colorado.edu)

A High-Resolution Body Wave Tomography Super-Virtual Interferometry of the Rio Grande Rift

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The Rio Grande rift stretches from southern Colorado through New Mexico into Mexico and it separates the eastern Great Plains from the southern Colorado Plateau. To explore the relationship between the rift, the adjacent Basin and Range Province, and the Colorado Plateau, we used seismic recordings of earthquakes from the La Ristra seismic deployment to model seismic P velocities in the uppermost mantle beneath this region via Super-virtual Refraction Interferometry. This technique improves the accuracy of Pn measurements by increasing its signal-to-noise Ratio via the Super-virtual Green's Function. We use data from over 50 earthquakes, mostly along the Gulf of Alaska's convergent plate boundary. This technique is useful for Moho modeling and understanding the structure of the Rio Grande rift. It enhances the amplitude of the Pn phase for seismograms recorded at distant stations, from small-magnitude earthquakes, and/or in the presence of seismic attenuation due to, for example, partial melt.

Specifically, we used vertical component broadband seismograms from 58 different stations to create super-virtual refraction studies. The process involves two primary steps to obtain the refracted Pn phases. We first estimate the classical refraction by computing cross-coherence between seismograms observed in two seismic stations. We then stack the virtual Green's Functions for a number of earthquakes that occurred in the Pacific Ocean, which are mostly colinear with the La Ristra seismic array. In the second step we convolve the seismogram of the closest station of a given station pair with the stacked virtual Green's function. The output is stacked over seismograms for all recorded earthquakes and then used for Pn refraction tomography to model Pn velocities beneath the La Ristra seismic deployment.

The Poisson's Raio Surrounding the Subduction Megathrust

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Hydrologic and lithologic variations along the plate interface in subduction zones control the strength and slip behavior of megathrust faults. Many models of plate interface fault slip behavior invoke high pore-fluid pressure to explain the variability in rupture behavior. High pore-fluid pressure can explain apparently high Poisson's ratio (> 0.33, $Vp/Vs > 2$) within a low-velocity zone (LVZ) along the plate interface, often inferred from studies of the scattered *P*-to-*S* seismic wavefield. We further investigate this region with array-based deconvolution which allows for identification of the receiver-side, surface-reflected and back-scattered *P*-to-*P* wavefield, and which has finer resolution than the upgoing *P*-to-*S* scattered wavefield. Using the timing of surface-reflected *P*-to-*S* and *P*-to-*P* scattered phases in both the Alaska and Cascadia subduction zones, inversions for LVZ properties result in $Vp/Vs < 2$. Using both array-based and time-domain deconvolved teleseismic waveforms, we show that Vp/Vs estimates that depend on the upgoing *P*-to-*S* scattered phases might be biased toward high Vp/Vs (> 2.2) owing to their lower volume resolution and the inherent frequency limitations in extracting these signals from *P* coda. These results indicate that anomalously high Vp/Vs found while including the upgoing (direct) *P*-to-*S* scattered mode may instead be an artifact of using band-limited signals or scattered-phase interference. These findings remove the observational requirement for a thick region of high pore-fluid pressure and allow for alternative hypotheses to explain the suite of fault slip behavior along the subduction zone plate interface.

Improving the Salt Lake Basin Velocity Model Using Multi-Year Nodal Geophone Arrays

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An accurate high-resolution velocity model is critical for evaluating the ground shaking hazard from moderate to large local earthquakes. The current community velocity model (CVM) for the Salt Lake Basin in Utah was constructed mostly based on legacy gravity measurements, supplemented by sparsely distributed well logs and legacy active-source seismic profiles. Since 2018, the seismic data coverage of the Basin has substantially improved with the addition of data from three nodal geophone experiments: a 2018 32-node linear array across the East Bench fault of the Salt Lake City segment of the Wasatch fault zone, a 2020 217-node Magna earthquake (M_w 5.7) aftershock array, and a 2023 38-node multi-month distributed array deployed to investigate hydro-geophysical signals. In this presentation, we will summarize our recent effort to improve the Salt Lake Basin CVM by adding new constraints derived from the nodal data. Specifically, we will show that the first positive peak of receiver functions in the Salt Lake Basin is sensitive to the P-to-S conversion at the base of the semi-consolidated sediment layer, which rapidly changes depth across the East Bench fault. Moreover, good correlations exist between the delay time of the first receiver function peak, Rayleigh wave ellipticity, and the local gravity anomaly, demonstrating the potential of jointly inverting the three datasets to refine the 3D basin model. We have determined a preliminary model by jointly inverting receiver function waveforms and Rayleigh wave ellipticities plus phase velocities. The results indicate a greater thickness of unconsolidated and semi-consolidated sediments, compared to the existing CVM, between the East Bench fault and the West Valley fault zone. This area underlies the most densely populated parts of Salt Lake City. Our new velocity model will contribute to improved earthquake hazard assessments by enabling more accurate numerical ground motion simulations for realistic earthquake scenarios.

Seismic Structure of Northern Alaska From Ambient Noise Adjoint Tomography

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Northern Alaska is a remote, arctic region roughly 1000 km from the nearest plate boundary at the Alaska-Aleutian subduction zone. Physiographically, the region is dominated by the east-west trending Brooks Range and the adjacent Colville Basin and North Slope region. Seismically, northern Alaska is characterized by diffuse bands of seismicity, distributed crustal deformation, and moderate-sized earthquakes (M<6). In this work, we take advantage of years of high-quality seismic data from the EarthScope Transportable Array to undertake a seismic imaging study of northern Alaska. Our goal is to generate a 3D, high-resolution velocity model of structure below the region, in order to improve our understanding of the regional tectonics. To accomplish this, we use adjoint tomography, a seismic imaging method which seeks to minimize differences between seismic data and synthetically-generated waveforms from numerical simulations of wave propagation. We use the empirical Green's function (EGF) dataset of C. Liu et al. (2022), which is derived from ambient seismic noise and provides excellent data coverage of the region. Preliminary results demonstrate that our inversion is sensitive to crust and upper mantle structure, and it is able to resolve lateral velocity variations which show similarities to known geologic and tectonic features. Current efforts aim to invert the EGF dataset for a target period band of 8–50s. We present ongoing work from this project, including an updated, anisotropic velocity model, and key tectonic interpretations.

Using Local and Regional Travel Time Data From the ISC to Estimate Lithospheric Velocity Structure

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While a great deal of seismic data is openly available, there are still some regions not well-covered by stations with open waveform data. In many of these cases, however, arrival data from stations is contributed to the International Seismological Centre (ISC). In the absence of waveform data, how effectively can we utilize available ISC data to determine velocity structure? We have developed a method of using simplified ray paths to model regional phases, and use this method to model Pn, Pb, Pg, Sn, Sb, and Sg phases from crustal events in East Asia. The travel times are then used to tomographically invert for P-wave and S-wave velocities in the crust and upper mantle, as well as corresponding source terms, which can accommodate errors in origin time and depth, and site terms, which can accomodate local station conditions (e.g., Vs30). We start with the simplest parameterization (layer over a half-space) and then introduce additional complexity (e.g., variable Moho thickness, additional crustal layers) to gauge its effect on our model. Preliminary results show some success in retrieving the expected variations in crust and mantle velocities from the seismo-tectonic structure, but a higher-order parameterization might be needed to capture the overall complexity of the region. We can test the predictive nature of the models with the observed travel times from ground-truth (GT) events not used in the development of the model. If proven to be effective, we can readily apply the method to other regions where waveform data may be limited.

Intraplate Volcanism in Northeast China Controlled by the Underlying Heterogeneous Lithospheric Structures

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The origin and mantle dynamics of the Quaternary intraplate sodic and potassic volcanism in northeast China have long been intensely debated. Here we present a high-resolution three-dimensional crust and upper mantle S-wave velocity model of northeast China by combining ambient noise and earthquake two-plane wave tomography based on unprecedented regional dense seismic arrays. Our seismic images highlight a strong correlation between the basalt geochemistry and upper mantle seismic velocity structure: sodic volcanoes are all characterized by prominent low seismic velocities in the uppermost mantle, while potassic volcanoes still possess a normal but thin upper mantle “lid” depicted by high seismic velocities. Linking our tomographic images with previous petrological and geochemical study results, we propose that the heterogeneous lithospheric structures beneath northeast China control the style of mantle dynamics in producing the Quaternary sodic and potassic intraplate volcanism. The very young Wudalianchi and Nuominhe potassic volcanism is likely caused by the interaction between the asthenospheric low-degree melts and the overlying subcontinental lithospheric mantle, whereas the more widespread Quaternary sodic volcanism is directly sourced from the upwelling asthenosphere as a result of localized lithospheric thinning and destruction.

Seismic Evidence for a Melt-Rich Lithosphere-Asthenosphere Boundary Along the Base of Young Slab at Cascadia

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Knowing the nature of the Lithosphere-Asthenosphere Boundary (LAB), which separates the stronger lithosphere from the underlying weaker asthenosphere, is fundamental to understanding how plate tectonics works. For the oceanic lithosphere, the LAB is generally imaged as a negative seismic discontinuity and is widely thought to indicate the presence of partial melt. A melt-rich LAB would mechanically decouple lithospheric plates from the asthenosphere and thus facilitate plate motion. However, the fate of a melt-rich LAB is unclear after these plates descend into the mantle at subduction zones. To date, the LAB beneath subducting slab (hereinafter referred to as slab-LAB) has been reported only in subduction zones in Japan and New Zealand, and in both cases the age of the subducting plate is very old (~120-130 Ma). In contrast, no slab-LAB has ever been reported where young plates are subducting. Here, we provide strong evidence for the presence of slab-LAB at Cascadia, where the subducting plate is as young as ~10 Ma. Using teleseismic waveforms recorded by dense arrays and a coherent receiver function imaging technique, here we image the slab-LAB at Cascadia in the form of a large (9.81.5) decrease in shear-wave velocity over a very small (<3 km) depth interval. We consider the imaged slab-LAB to be compelling evidence for the continuation of the melt-rich plate LAB after subduction. Similarly large and sharp seismic velocity reduction at the bottom of both old and young slabs, as well as along the base of oceanic plates before subduction, possibly represents widespread presence of melt. The melt-rich slab-LAB may strongly influence subduction dynamics and viscoelastic earthquake cycles.

Mantle Upwelling, Continental Sutures, and LAB Structure Identified From a Suite of Seismic Data Types in the Eastern United States

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The eastern US was constructed over several Wilson cycles, with multiple continent-scale sutures preserved in the geologic record. During the breakup of Pangea, the eastern North American lithosphere was heavily modified, with implications for ongoing mantle dynamics along the margin. Previous seismological imaging has lacked needed resolution to assess how ancient boundaries and recent processes manifest throughout the lithosphere. We present a high-resolution, plate-scale seismic tomography model of the eastern US. We inverted seismic velocity using Rayleigh and Love wave phase velocity, Rayleigh wave ellipticity, and *Sp* and *Ps* receiver function data. This combination of data provides resolution from the crust to the asthenosphere, constraining both absolute velocity and the depths of velocity discontinuities. We produce maps of crustal properties, mantle velocity, lithospheric depth and mid-lithospheric discontinuities. A sharp step in lithospheric thickness at the Appalachian front explains mantle upwellings that may erode the base of the plate and shape modern Appalachian topography. We identify low-velocity structures in the lithospheric-mantle that align with the Grenville front and may be remnants of Rodinia assembly. Heavily modified lithosphere east of the Appalachians is a legacy of post-Pangean extension, CAMP magmatism, and ongoing dynamics.

Crustal Structure of Eritrea from Receiver Function Analysis

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Located near the Afar Triple Junction, Eritrea hosts the Danakil microplate and is undergoing the final stages of on-land rifting. To better understand the nature of the Eritrean crust and continental breakup, we calculate teleseismic receiver functions across Eritrea and Afar. We estimate the Moho depth and bulk crustal V_P/V_S ratio using the H-κ stacking method. The heterogeneity of our crustal thickness results (~35 km — ~19 km) indicates that the Danakil microplate has undergone stretching and crustal thinning, and that rifting is highly localised in the Gulf of Zula. By investigating the relationship between crustal thickness and topographic elevation in Eritrea and Afar, we estimate the regional crustal density as $\rho c \approx 2950$ kg m^{-3}, which is denser than the global average of $\rho c \approx 2880$ kg m^{-3}. Our results demonstrate very strongly positive residual topography in the region. We propose that this topography is supported by the mantle plume responsible for the onset of rifting in East Africa, generating uplift due to the presence of a hot thermal anomaly beneath the plate and by thinning of the lithospheric mantle. We also observe high V_P/V_S ratios of > 1.9 in Eritrea. Our results demonstrate the presence of partial melt in the crust, and that magma-assisted extension continues to be important in the final stages of continental breakup.

Surface-Wave Diffraction Stripes: Measurement, Observables, Explanation, Modeling and Inversion

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Peculiar stripe-like patterns of amplitude variations and arrival angle deviations of teleseismic surface waves have been observed thanks to large dense networks of broadband seismic stations, such as USArray in the United States, NECESSArray in China and recently AlpArray (2015-2019) in Europe. There are several properties of the stripes, which show that the pattern is not caused by the structure beneath the observation location—the large dense network, but rather imported with the wavefield to the network from outside. One of the most striking observables is the lateral shift of the stripes with varying periods of surface waves. We proposed and tested a hypothesis that these patterns are caused by diffraction and consequential interference after the wavefield has passed a single small-scale scatterer. The wavefield carries the imprint of the scatterer for thousands of kilometers and allows for localizing the position of the scatterer, its size and strength.

We summarize the observation of stripe-like patterns for several earthquakes recorded by the AlpArray seismic network, which was distributed over the greater Alpine region in Europe and consisted of 290 temporary and more than 300 permanent broadband stations. We show how for different earthquakes the interference pattern moves across the network when the period of surface wave changes. We give examples of patterns in group velocity measured at every station individually, in arrival angles (slowness vector, phase velocity) measured by sub-array beamforming and we show how the pattern emerges when we calculate the gradients of phase wavefronts similar to eikonal tomography. We observe the pattern also in the polarization of surface waves and their amplitudes. We discuss how all these observables match together and how the modeling explains them. We show that it is possible to invert the observed interference pattern to locate the scatterer which had caused it, giving examples of particular upper-mantle low-velocity bodies and plumes. We also discuss how the phase and group travel times distorted by interference can affect global and regional tomography.

The Continental Collision and Rifting in East North America Margin Revealed by Full Waveform Tomography

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The East North America Margin (ENAM) represent a passive continental margin that has undergone several stages of collision and rifting throughout geological history. Notably, the formation and breakup of Rodinia and later, the assembly and breakup of Pangea. The strong collision resulted in the uplift of the Appalachian Mountains, while the period of extension was accompanied by extensive magma upwelling and the formation of sedimentary basins. The complex geological history makes the ENAM an ideal natural laboratory for studying continental collision and rifting processes. Our study focuses on several regions with dense array deployment, and they are SESAME array (Parker et al., 2013) in Southern Appalachians, MAGIC array (Long et al., 2020) in central Appalachians and SEISConn array (Long and Aragon, 2020) in northern Appalachians. With three case studies, we aim to compare the similarities and differences in the evolution at different locations along ENAM.

We employed a joint full-waveform inversion (FWI) approach utilizing ambient noise data and teleseismic data based on the precise 3D Spectral Element Method (SEM) solver. This methodology enabled the creation of high-resolution isotropic shear wave velocity models in the three regions. Upon comparing these models, we observed a consistent variation in Moho depth along the Appalachians. Notably, the central and northern Appalachians exhibited a more pronounced depth variation than the southern Appalachians. Additionally, we investigated the anisotropic structure of these regions, revealing robust positive radial anisotropy along the terrane boundaries in all three areas, likely resulting from the Mesozoic rifting event. Nevertheless, the anisotropy pattern differed between the southern and northern Appalachians, suggesting distinct collision and splitting dynamics. The inverted models provide intricate subsurface insights beneath ENAM and represent a valuable dataset to enhance our comprehension of continental collision and rifting processes.

P-Wave Attenuation Structure and Melting Processes of the Tonga-Lau Mantle Wedge

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The fast-converging Tonga subduction zone and its adjacent Lau back-arc form a complex system where the melting mechanisms show significant along-strike variations. To estimate melt fraction and further investigate the thermal and rheological structures in the Tonga Lau mantle wedge, we present an

improved P-wave attenuation tomography model. We first incorporate independently constrained source parameters to invert for the path-average attenuation operator t*. Then, based on the refined t* dataset, we apply a Bayesian Markov chain Monte Carlo technique to image the Tonga-Lau subduction system's 3D P-wave attenuation structure. Compared to previous models, this new Qp model is built upon a more accurate 3D velocity tomography model and utilizes more precise parameterizations in a spherical coordinate system. The new results exhibit high attenuation anomalies in the Tonga-Lau back-arc mantle and beneath the Taveuni Volcano. With the help of the Very Broadband Rheology (VBR) Calculator (Havlin et al., 2021), we can quantitively estimate along-strike variations in melt fraction and temperature. Preliminary results show an increasing trend of melt fraction from south to north. The highest melt fraction reaches up to ~6.5% beneath the Central Lau Spreading Center.

Illuminating Earth's Inner Core Fine-Scale Heterogeneity With Small Aperture Arrays

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The Earth's inner core is seismically heterogeneous at scales of 1–10 km. The fine-scale heterogeneity is manifested in high-frequency (1–4 Hz) backscattered energy following reflections (*PKiKP*) from the inner core boundary and is very difficult to observe, resulting in a lack of a comprehensive probe. In this study, we utilize small-aperture seismic arrays—designed to detect tiny signals from underground nuclear explosions—to characterize the inner core heterogeneity in a global scale. We use all the viable data from earthquakes (Mw ≥ 5.7) within the past 2–3 decades recorded at distances of 50°–75° from an array. With array processing, we develop a framework for detection and extraction of the inner core scattered energy, which is characterized as emergent, growing, and spindle-shaped *PKiKP* coda. We found that individual seismic traces lacking clear evidence of *PKiKP* coda waves reveal the scattering characteristics when stacked together, implying the inner core scattering is ubiquitous. Furthermore, we employ a modified phonon-based simulation to model the scattering strength to construct the first global three-dimension inner core heterogeneity model. Our model shows the scattering strength substantially increases 500–800 km beneath the inner core boundary across the globe. The enhanced scattering implies an irregular solidification evolution of Earth's core.

Waveform Changes Due to Moving Scatterers - Application to the Inner Core

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Fine-scale heterogeneity in Earth's inner core (IC) has been identified from scattering of PKIKP. The differential rotation of the IC is expected to align with Earth's rotation axis according to geodynamical modeling and seismic evidence (Wang & Vidale, EPSL 2022). For a similar differential rotation of the IC, equatorial and polar raypaths may exhibit distinct changes in scattering (Pang & Koper, 2022). Understanding the sensitivity of different raypaths to the shift of IC scatterers can facilitate our interpretation of inner core motion.

Here we perform 2D wavefield scattering simulations using the spectral-elemental toolkit Salvus. We analyze the variation of forward-scattering and back-scattering waveforms as the heterogeneity is shifted radially along and transversely across the raypath. The radial and transverse movements of heterogeneity approximately correspond to equatorial and polar raypaths sampling the IC. The back-scattering and the forward scattering geometry approximates the PKIKP raypaths with different distances.

Distinct variation patterns in the PKiKP coda are observed between the two directions of shift (heterogeneity shift is 1 cell, with RMS variations about 10%) and the two raypaths. For forward-scattering, a radial shift almost doesn't change the waveforms, whereas transverse shifts result in significant waveform variations; for the back-scattering case, a radial shift mainly delays or advances the phase, while transverse shift leads to both timing and amplitude changes. The evolution with lapse time of the waveform similarity and time shifts, also have distinct patterns, which will be discussed in detail.

Distinguishing the effect of the moving scatterers across different geometries will contribute to constraining the rotation of the IC and will provide a deeper general understanding of scattering behavior.

2020-2030. A Golden Decade for Very Broad Band Planetary Seismology and Seismic Imaging of Mars and Moon Interiors

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The Mars NASA InSight mission re-started seismology in planetary science, 40 years after Apollo and Viking.

SEIS, InSight's French led international seismometer, operated from 2/2019 to 12/2022. Thanks to its ground installation and wind shielding, the very-broad-band (VBB) sensors of SEIS achieved ultra-low noise levels during the first half of the night. This enabled a very low detection threshold, down to moment magnitude M_W=1 regionally and 4 on a global scale.

More than 1300 events during the 4 years of operation were detected by the MarsQuake Service from VBB data, including a M_W =4.7 marsquake that excited surface waves and likely normal modes. Eight impacts were also confirmed by orbital crater imaging, two with M_W =4 and very large craters. Nearly half of the events were located near Cerberus Fossae, where possibly volcanic seismo-tectonics is ongoing.

Through these seismic events, SEIS provided the first seismic models of Mars, from the 40 km thick crust beneath InSight down to the core. These models revealed the stratigraphy of the crust, including through surface wave anisotropy, the structure and thickness of the thermal lithosphere and the presence of a molten silicate layer at the bottom of the mantle beneath a partially molten layer. Comparisons of these Martian interior and seismic properties with those of the Moon and Earth, obtained from Apollo and Earth seismic networks, are now possible, opening a new research field: comparative planetary seismology

And SEIS will continue its journey to the Moon with the JPL/CNES/IPGP Farside Seismic Suite, which will deploy in 2026 one of the spare sensors of InSight VBBs in the farside Schrödinger basin. FSS will operate this vertical VBB with performance at 1 Hz more than 10x better the Apollo seismometers. Data will be processed by the FSS LunarQuake Service and will be completed by Earth based impact flash monitoring. We therefore conclude with the science goals of this new mission in terms of deep interior imaging, as well as perspectives in terms of global seismic network on the Moon, if complemented by other missions deploying seismometers.

Earth's Structure from the Crust to the Core [Poster Session]

Poster Session • Thursday 2 May

Conveners: Keith Koper, University of Utah (kkoper@gmail.com); Jeroen Ritsema, University of Michigan (jritsema@umich.edu); Vera Schulte-Pelkum, University of Colorado (vera.schulte-pelkum@colorado.edu)

POSTER 1

Cenozoic Uplift and Volcanism of Hangai Dome, Central Mongolia Triggered by Lower Mantle Upwellings

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The mechanisms of surface uplift of Hangai Dome (>2 km) and formation of Cenozoic intraplate volcanism in central Mongolia remain vigorously debated. Here we directly investigate the mantle transition zone (MTZ) structure beneath central Mongolia to explore whether the deep mantle geodynamical processes have played a role. Our results reveal significant MTZ thinning of 8–13 km in three subareas mainly caused by the uplifted 660-km discontinuity (~10 km). In addition, the 410-km discontinuity is depressed beneath the Hangai Dome (~6 km) and the northern portion of the study area (10–15 km). These observations provide direct evidences for intracontinental mantle upwellings from the lower to the upper mantle, causing the Cenozoic uplift and basaltic volcanism of central Mongolia. Furthermore, these mantle upwellings are relatively sluggish compared to canonical mantle plumes based on the small magnitude of MTZ thinning and thus relatively moderate thermal anomaly within the MTZ (62–100 K).

POSTER 2

Single-Station Teleseismic Data Analysis and Structure Imaging on Both Earth and Mars

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Analysis of single station, multicomponent teleseismic data has been recently performed with success in high-resolution imaging of shallow crustal structures (up to ~10 km depth), bridging the gap in between fine-scale (~km) near-surface seismic exploration and large-scale (several tens to hundreds and thousands of kilometers) deep passive-source imaging. A key idea in such single station data analysis is to utilize the frequency dependence of amplitude ratios between the horizontal and vertical components of teleseismic body-waves, which is sensitive to the absolute velocity value and its variation with depth at the target station. The associated single-station based new imaging method is capable of achieving a vertical resolution of ~0.5 km, about one order of magnitude higher than other teleseismic methods commonly used for shallow crustal imaging. Here we present the details of the method and its applications to a number of continental tectonic zones of various structural features. We show that the method is flexible and effective for both cases of dense arrays and sparse station distributions. In particular, by expanding the single-station analysis scheme to mitigate the effects of strong noise and data insufficiency, we demonstrate the applicability of the imaging method to the InSight low-frequency marsquake data in constraining the subsurface structure of Mars.

POSTER 3

Full-Waveform Inversion of the Upper Mantle Beneath the Arabia-Eurasia Collision Zone

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Despite being one of the most recent major orogenic events, the timing of the Arabia-Eurasia collision is still debated. Much of the discrepancy arises due to uncertainties over the amount of continental subduction of the Arabian passive margin and the timing of a hard collision of cratonic Arabian lithosphere with Eurasia. However, subducted continental lithosphere and underthrusted cratons can be imaged using high resolution seismic tomography, as has recently been demonstrated in the Himalayan region (Liu, 2023). In this study, we perform a full waveform inversion of mantle structure beneath the Turkish-Iranian plateau, using regional earthquakes, which have good horizontal and vertical resolution in the upper mantle. We use a normalized cross-correlation misfit function, which fits both the phase and relative amplitude of multi-path arrivals (Tao et al., 2017). This allows us to extract additional information from complex triplicated waves that provide good coverage of the upper mantle. We present preliminary results of our model of upper mantle structure beneath the Middle East and use it to test different tectonic scenarios for the Arabia-Eurasia collision.

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POSTER 4

Finite Difference Approach to Seismic Wavefield Modeling Across the Hawaii-Emperor Ridge

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Volcanic seamount chains are widespread throughout ocean basins. P-wave travel time tomography allows for imaging the interiors of these volcanoes, but that requires proper waveform identification of seismic phases that propagate across complex volcanic structures. Current limitations on the number of seismic phases included in tomographic analyses results in less detailed images and a poorer understanding of geological structures than may be possible. In previous studies (Dunn et al., 2019; Watts et al., 2021; Xu et al., 2022; MacGregor et al., 2023), several seismic phases were identified in recorded sections collected along the Hawaiian-Emperor Chain. However, interpreting the origins of some of these phases remains challenging, and others remain a mystery. In this study, we developed an idealized seamount model based on the seismic structure of Jimmu Guyot (Xu et al., 2022) and calculate the seismic P-SV wavefield for various source and receiver positions using a finite difference wavefield modeling code (Levander, 1988; Lata and Dunn, 2020). Our goal is to model observed seismograms and identify additional phases, including P-to-S converted waves. We also intend to verify recent tomographic images of the Hawaiian-Emperor Seamount Chain made by travel time inversion via wavefield matching. By resolving any ambiguities and pinpointing new seismic phases, we aim to enhance future seismic images of the Hawaiian-Emperor Chain and contribute to improvements in our knowledge of the nature of specific structures, such as volcanic cores (a high-density and high-wave-speed interior core of the seamount), the hypothesized magmatic underplating of the oceanic crust by mantle melts rising beneath the volcanic chain, and the nature of the Moho and oceanic crust beneath these volcanic edifices.

POSTER 5

Global Shear-Wave Amplitude Observations using Full Waveform Modeling

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Amplitudes of seismic phases provide unique constraints on the elastic and anelastic structure of the mantle. In this study, we analyze observed and synthetic seismograms to explore how wave-speed gradients and the anelastic structure of the mantle influence the amplitude of major shear waves S, SS, SSS, ScS and Sdiff and how the existing global models explain them. Our observations are the ratios of the amplitudes of these body-wave phases and amplitudes predicted for the PREM model (Dziewonski & Anderson 1981) and Global CMT source parameters. We also define measurements as the logarithmic ratio of the amplitudes of multiple phases, such as SS/S and SSS/SS, to minimize source and receiver effects and discriminate the influence of the upper and lower mantle. These ratios from synthetic seismograms show much better agreement with those observed from real data. We do not see much variation in SS/S ratios according to their bounce point variation in continental or oceanic crust.

Using the 3D global seismic wave propagation solver SPECFEM3D_GLOBE for 55 global earthquakes we computed amplitude ratios for two global mantle and crustal models: 1) S40RTS (Ritsema et al. 2011) with and without Crust2.0 (Bassin et al. 2000), and 2) GLAD-M25 (Lei et al. 2020) with 1D Q models (PREM and QL6, respectively). Amplitude ratios for synthetic seismograms with 1D crustal structures cannot explain the observed amplitude measurement patterns. 3D mantle and 3D crustal models better explain the observed global patterns, and the 3D mantle models predict a consistent effect of the 3D heterogeneities on the amplitude ratios. We explore the possibility of using these measurements as misfit functions in adjoint tomography by looking at their kernels. We also try to understand the effect of the scale length of the heterogeneities in the observed amplitude ratios.

POSTER 6

Building a Community Velocity Model for the Cascadia Region and Beyond

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Multi-scale information on *P*-wave and *S*-wave velocities and density in a tectonically active region is fundamental to a deeper understanding of subsurface processes (e.g., mantle hydration, Moho topography, crustal lithology), as input to other science activities (e.g., seismicity relocation, Green's function estimation), and, especially at shallow depths, to better quantify seismic hazard. The recently NSF-funded Cascadia Region Earthquake Science Center (CRESCENT) paves the way to build a multi-scale community velocity model (CVM) of the Cascadia region (https://cascadiaquakes.org/cvm/). This model will be a first-order product for other CRESCENT working groups' science and will help make significant advances in our understanding of the Cascadia subduction zone structure and associated hazards.

The CRESCENT CVM working group will combine active and passive seismic data acquired onshore and offshore in a region spanning the entire Cascadia subduction zone, from the Juan de Fuca Plate to well into the backarc along the Idaho-Montana border and from the Mendocino triple junction (~38°N) to the Queen Charlotte fault (~52°N). We will start with low wavenumber data to resolve regional-scale structure into the upper mantle using Bayesian joint inversions of P-wave radial receiver functions and ambient noise-derived Rayleigh waves. Subsequently, upper crustal structure (lateral resolution of <5 km) will be incorporated using information from active source datasets, P- and S- wave travel times, and higher frequency ambient noise data from higher density networks including legacy and recent datasets. Later model generations will incorporate a geotechnical layer. Formal uncertainty analysis will be completed for each generation of the model and we will validate the final model against recorded waveforms (ideally up to >1 Hz) from regional and moderate-sized events. The various generations of the CVM will be available for CRESCENT-related science and community users in various formats. CVM building and validation is a Cascadia community-wide effort and mechanisms for contributing will be presented.

POSTER 7

Complex Upper Mantle Flow Beneath the Southern Korean Peninsula Constrained by Shear Wave Splitting and Numerical Mantle Convection Simulation

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Seismic anisotropy in the upper mantle, which can be developed by the alignment of anisotropic minerals, such as olivine, provides a means for indirectly analyzing mantle dynamics, including asthenospheric mantle flow. Seismic anisotropy beneath the southern Korean Peninsula (SKP) was measured by shear wave splitting analyses and the upper mantle flow was simulated through numerical mantle convection modeling. The SKP is located at the eastern margin of the Eurasian plate. Subduction boundaries between the Eurasian, Pacific, and Philippine Sea plates are located to the east of the SKP. A significant lateral variation in lithospheric thickness within the SKP has been reported, ranging from ~80 km in the east to ~130 km in the southwest across a lateral distance of ~200 km, implying the potential for a small-scale complex mantle flow driven by a sharp lithospheric thickness gradient. The fast direction of seismic anisotropy in the SKP can be separated into two groups: N-S direction dominant in the east and NW-SE direction dominant in the southwest. The deflected pattern around the southwest SKP was observed and interpreted to reflect asthenospheric mantle flow deflected around the thicker lithosphere.

In the mantle convection modeling, a horizontal mantle flow was initially driven by imposing a horizontal temperature gradient in the model domain. Similar to seismic anisotropy, the simulated mantle flow calculated with realistic lithospheric thickness variations around the SKP was also separated into two groups. Notably, significant deflection in asthenosphere mantle flow was simulated at the shallow depth (~100 km) around the thicker lithosphere in the southwestern SKP, whose pattern was roughly consistent with the observed seismic anisotropy. Our results showed that complex asthenospheric mantle flow in NE Asia can be developed by interaction between background mantle flow with laterally and vertically small-scale variations in lithospheric thickness at the continental margin.

POSTER 8

Advancing the Resolution of Mid-Mantle Structures: Full-Waveform Box Tomography of the Yellowstone Mantle Plume

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The Yellowstone mantle plume is a narrow, low shear-velocity feature in the lower mantle, exhibiting a horizontal deflection at approximately 1000 km depth, similar to other plumes and subducted slabs, suggesting a rheological change at that level (Nelson and Grand, 2018). To improve resolution at mid-mantle depths, we utilize full waveforms of body and surface waves.

Employing 'box tomography', we integrate a global 3D solver, SPECFEM3D_globe (Tromp et al., 2008), for wavefield calculation outside the region of interest, and RegSEM (Cupillard et al., 2012) for internal computations using the Spectral Element Method (SEM). The background global 3D model, SEMUCB_WM1 (French and Romanowicz, 2014), which faintly resolves a low-velocity plume beneath Yellowstone extending to the core-mantle boundary (French and Romanowicz, 2015), is used for initial wavefield computations, which are recorded at the box boundaries. This includes body waveforms from distant quakes for mid- to lower-mantle structure illumination.

To conduct box tomography, we initially compute the required global wavefields in the reference 3D model down to a 20 s period and record these fields on the box boundaries. Inversion iterations within the box reduce the cutoff period from 40 s to 20 s, with depth range expansion. The crustal structure is constrained using surface wave dispersion data down to a 16 s period. Our results, derived from multiple inversion iterations using a Gauss-Newton optimization and a physics-based Hessian computed with normal mode perturbation theory (NACT, Li and Romanowicz, 1995), will be presented.

POSTER 9

Imaging the Deformation Belt of Western Hispaniola Using Multi-Component Ambient Noise Cross-Correlations

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Hispaniola Island is located at a complex boundary between the North American and Caribbean plates, resulting in a series of fold-and-thrust belts and active fault zones. Several seismic imaging studies have been conducted to understand the regional structure of Hispaniola. These studies, combined with geological observations, provide an outline of the crustal structure in the area, revealing thinner crust (~20km) in the northern and southern domains and a thicker crust (~40km) in the central part of western Hispaniola. However, the resolution of these results is limited. Receiver function analysis is only sensitive to the structural discontinuities beneath stations, whereas local earthquake tomography is restricted by earthquake observations, in which event detection in this region is challenging.

Therefore, in this study, we investigate the crustal structure across western Hispaniola (Haiti) using a different approach. We perform multi-component noise cross-correlation and measure Rayleigh wave phase velocity and ellipticity (horizontal-to-vertical (H/V) amplitude ratio) within the period range of 3-18 s. The data used in this study are mainly from 27 broadband stations deployed from April 2013 to June 2014 along a north-south transect across the island. The H/V and phase velocity results exhibit consistent patterns related to the geology and tectonics of this region. Sedimentary basins exhibit higher H/V values, while mountain areas show lower H/V. In terms of phase velocity, higher velocities are observed in stations located in northern and southern Haiti, likely reflecting the more mafic crust composition compared to the lower velocities observed in the central part. We also conduct a joint inversion of H/V and phase velocity to construct a 2-D shear wave velocity model across western Hispaniola. This 2-D shear velocity model provides more constraints on the shallower crust (< 5km). A better understanding on the shallow crustal structure is particularly important for seismic hazard assessment in this area, which has recently experienced two major earthquakes in 2010 and 2021.

POSTER 10

The Crust was Strengthened or Weakened After Mantle Plume: Evidence from Tarim Basin

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Widely distributed early-Permian basalts and rhyolites in Tarim Basin were speculated as products of mantle plume, however the interaction between the mantle plume and the shallow cratonic lithosphere remains ambiguous. Here, we constrain the S-wave velocity structures to 15 km depth utilizing multi-frequency receiver function data from two temporary broadband seismic arrays in the Tarim Basin. There is a large-scale S-wave velocity discontinuity at bottom of Permian strata showing significant rising for the western basin, but without apparent undulations for eastern basin. Besides, massive high velocity anomalies at the western basin, spatially correlated with the previously proposed mantle plume head, suggest Permian plutonic intrusions in western basin. These intrusive heterogeneities may change the strength of the shallow crust and cause focused deformation under subsequent tectonic activities, leading to folding and faulting of strata in western basin during the Cenozoic. Our findings indicate that the activities of mantle plume may destroy the integrity of the craton by changing the composition distribution in the lithosphere.

POSTER 11

Using Multiple Voronoi Partitions to Conduct Array-Based Ambient Noise Surface Wave Imaging

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With the advancement of array-based surface wave technology, a breakthrough has been achieved in obtaining high-mode surface wave dispersion curves from ambient noise cross-correlation to detect subsurface structures. Compared to using only fundamental surface wave dispersion curves, including high-mode surface wave dispersion curves in multi-modal surface wave inversion can effectively enhance constraints on subsurface structures, especially low-velocity structures. However, the study area needs to be divided into multiple subarrays when conducting three-dimensional velocity structure imaging due to the necessity of array data for each dispersion extraction. The size and shape of these subarrays may impact the effectiveness of the final dispersion extraction.

In this work, we propose a method based on randomly generating Voronoi polygons for repeated subdivision subarrays to circumvent the need to select array size and shape. This method primarily involves iteratively generating random Voronoi polygons to create different partitions. These dispersion curves extracted from one partition are treated as samples of all points within the corresponding Voronoi polygon. After sufficient iterations, statistical methods can be employed to obtain dispersion curves for various points in the study area and estimate the associated errors. Furthermore, this method can address the issue of varying array scales required to extract different modes' dispersion curves. We will illustrate the specific methodology using the imaging of Lasso dense arrays as an example, hoping that this method will effectively enhance the applicability of array surface wave techniques.

POSTER 12

Challenges and Triumphs Seismic Surveying in a Historic Underground Metals Mine

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Seismic surveying within mine adits underground (e.g., >100 m) has many benefits, including the absence of low-velocity weathered overburden as well as no topography. Further, being literally immersed in the target zone means that structure and stratigraphy mapped in the adit are more readily correlated to the results of the seismic surveys. On the other hand, underground surveys present unique challenges, including logistics of deploying an energy source, emplacement of geophones in solid rock, reverberation from the adit, and safety. We present the results of seismic surveying in the Deer Trail Mine in south-central Utah (USA) discovered in 1878. The mine is located along the eastern side of the Tushar Range, which forms a transition between the Colorado Plateau to the east and the Great Basin to the west. The surveys utilized a narrow (~3x3 m) mostly horizontal adit, 120-510 m below ground surface. The country rock consists of highly fractured and mineralized Permian to Pennsylvanian quartzites, shales, and limestones. Exploration targets include shear zones and potentially reactive clean limestone intervals. A short (~375 m) test common midpoint (CMP) profile was surveyed with an accelerated weight-dropper (45 kg) energy source, using a source and receiver spacing of 3 m recorded over 96 channels. The test confirmed the ability to map very shallow (<50 m) small-scale structures, such as faults that were previously mapped in the adit. The production CMP survey covered ~1680 m with an explosive source (mostly 300 g in 1.5-m deep shot holes) recorded over 264 channels, source and receiver spacing at 6 m. A static recording array was used for both surveys with 4.5-Hz vertical geophones. The CMP profile imaged sparse horizontal and dipping reflectors down to about 500 m, tentatively interpreted as lithologic variations in the limestone or as shear zones. Our study demonstrates the potential for high-resolution seismic exploration in an unconventional and challenging setting to guide exploitation of deeply buried mineral resources.

POSTER 13

Searching for Blind Faults Beneath Metropolitan Los Angeles: Preliminary Results From the 2023 San Fernando Valley Array

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The San Fernando Valley (SFV) in Southern California is one of the most densely populated regions of the greater Los Angeles area. This region is prone to large damaging earthquakes such as the 1994 (M_w6.7) Northridge and the 1971 (M_w6.7) San Fernando events that both occurred on a blind-thrust faults. Many studies have investigated the structure of the SFV using seismic reflection data, borehole logs, gravity and magnetic data, and deep seismic refraction profiles. Despite these efforts, the resolution of existing Earth models for the region is relatively low. This limits the high-frequency content that can be achieved in wavefield simulations for accurate earthquake hazard modeling and our ability to interpret near-surface structures and identify concealed or blind faults.

To improve the structural characterization of the SFV basin, a group of 29 volunteers installed 140 three-component SmartSolo nodal seismic stations across the basin on 21 October 2023. The deployment was comprised of a 15-km long linear array of 49 nodes spaced ~300 m apart, across the Northridge Hills fault and near the epicenter of the Northridge earthquake and a grid of 91 nodes that covered the SFV with an interstation distance of ~2500 m. Our arrays recorded continuously for ~30 days and captured 21 magnitude>5.5 earthquakes with epicentral distances of 30-90 degrees. We will present preliminary results from ambient noise tomography and receiver function imaging to investigate the seismic structure of the basin and changes across faults. Our study aims to improve ground motion simulations for the SFV and contribute to more accurate estimations of earthquake hazards.

POSTER 14

Receiver Function Inversion at Erebus Volcano, Antarctica, With Multi-Station Weighting

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Erebus volcano, located on Ross Island, Antarctica, has an open convecting lava lake with Strombolian style eruptions. The volcano features a complex magmatic structure that is related to a hypothesized hot spot upwelling despite a lack of conclusive local crustal studies. Previous active source tomography and coda interferometry studies have noted strong shallow scattering structures associated with low velocities in the upper edifice, but the Moho depth has only been regionally constrained to an estimated 18 - 20 km depth. To better resolve this and corroborate other large-scale crustal structures, we use twenty-seven seismic stations distributed on the Erebus edifice from

the Tomo-Erebus, MEVO, and GSN seismic networks with over two hundred earthquakes between 2007 - 2010 to compute P-wave receiver functions (PRFs). These are supplemented by icequake and ambient noise derived surface wave dispersion curves, resulting in a joint Bayesian Markov chain Monte Carlo (MCMC) inversion for spatially weighted sub-arrays of the network. By using multi-station inversions, we assume the deeper structures are similar across stations but have greater variance closer to the surface to account for edifice heterogeneity. After inverting, we note a strong shallow discontinuity between 1 - 5 km, corroborated by ongoing scattering images, and a general Moho depth between 18 - 22 km.

POSTER 15

Shallow Imaging of the Valles of Caldera, Northern New Mexico: Preliminary Results From Ambient Noise Tomography

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The Valles Caldera in northern New Mexico is part of the Jemez Volcanic Field, formed from two rhyolitic eruptions <1.5 Ma. The caldera resides at the confluence of several major tectonic regimes; to the west, the caldera is bounded by the Colorado Plateau and Laramide structures and to the east, overlies the Rio Grande Rift. We present a preliminary ambient noise tomography model of the Valles Caldera and its relationship to the Rio Grande Rift, using data from the Los Alamos Seismic Network (LASN). In this inversion, we use 14 broadband stations from LASN which span ~40 km across the Caldera and Rio Grande Rift. Vertical (ZZ) component cross-correlations for 98 station-pairs were computed using one-hour overlapping time windows spanning from 2018 to the 2024. Phase and group velocity analysis are estimated using traditional frequency-time analysis. The LASN dataset, spanning over five decades, offers an opportunity for comprehensive temporal and spatial analyses across the Valles Caldera. Preliminary results show low Rayleigh wavespeeds beneath the caldera, extending beneath the east extension of the Jemez Volcanic Field and Rio Grande Rift.

POSTER 16

Lithospheric Modification in Northeastern Alaska Interpreted From Full-Wave Ambient Noise Tomography

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Subduction margins undergo long-term deformation over geologic time that can deform the overriding plate for hundreds of kilometers. Numerical modeling of subduction dynamics and deformation of overriding plates suggest far-field (1000s km) inboard deformation as the result of shallow subduction. Previous studies of the upper plate of northeastern Alaska focus primarily on data from surface deformation using geodetic measurements. However, the 3-D deeper structural modification of the overriding lithosphere is unclear. The Yakutat microplate in Alaska is a shallowly dipping subducting slab characterized by high coupling with the overriding North American Plate. The collision of the Yakutat microplate with the North American continent reactivated a system of right-lateral strike-slip faults across Alaska and Yukon, including the Denali Fault in southern Alaska and the Tintina Fault in eastern Alaska. Here, we use full-wave ambient noise tomography to produce a high-resolution image of northeastern Alaska, covering the eastern Brooks Range, the Porcupine Shear Zone, the Yukon Flats Basin, and the Tintina Fault. We will present the shear-wave velocity structure of the lithosphere and discuss the lithospheric modification and the surface geologic record in northeastern Alaska associated with the shallow subduction of the Pacific plate and the Yakutat microplate along the southern Alaska convergent margin.

POSTER 17

High-Resolution Moho Depth Mapping Beneath the Italian Peninsula and Carpatho-Pannonian Region Using P-Wave Coda Autocorrelation

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Peninsular Italy, renowned for its intricate tectonic history involving subduction and continental collision, has been a focal point for significant seismic activity, particularly along NW-SE trending normal fault systems. Recent destructive earthquakes in the Central Apennines emphasize the imperative for a comprehensive understanding of the region's crustal structure, earthquake mechanics, and high-resolution seismic monitoring. Meanwhile, the Carpatho-Pannonian region (CPR), has exhibited heightened seismicity in certain areas, necessitating focused attention due to its hazard implications. This study utilizes P-wave coda autocorrelation to image crustal discontinuities, including the Moho, in both Peninsular Italy and the CPR, contributing valuable insights to the understanding of their geodynamics.

Our results, derived from 251 broadband stations, present a Moho depth range of 20-60 km beneath the Italian peninsula. The SE-NW profile across the Po Plain delineates a shallower Moho towards the Tyrrhenian Sea and a deepening trend towards the northern Apennines. Central Italy exhibits a shallower Moho adjacent to both the Tyrrhenian and Adriatic seas, with a significant thickening up to 60 km in the central region. The substantial thickening of the Moho in central Italy suggests localized crustal uplift and compression, possibly linked to tectonic forces associated with the convergence of the aforementioned plates. Sicily's Moho depth ranges from 30-40 km, with a relatively thicker Moho observed in central Sicily. We observe the thicker Moho in a region where previous studies reported a higher strain rate. This further supports the notion that regions with increased geological activity exhibit a thicker crust. This correlation underscores the importance of considering crustal thickness variations in seismic hazard assessments, as areas with a thicker crust may potentially experience more significant seismic activity. This methodology will be extended to the Carpatho-Pannonian Region for a comprehensive analysis of crustal discontinuities and Moho depth.

POSTER 18

Shallow Seismic Structure of the Canary Islands Using Local Earthquakes Recorded on an Amphibious Seismic Network

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The study of the seismic structure beneath the Canary Islands using local earthquakes has been in the past hampered by the sparse distribution of recording stations and low seismic activity. Recently, the number of permanent stations from monitoring networks has significantly increased, from barely one seismometer per island in the early 2000s to more than 10 stations in each of the most seismically active ones. Similarly, temporary deployments of broadband stations have also taken place in most of the islands, further increasing the station density. Finally, ocean bottom seismometers have also been deployed to monitor recent volcanic eruptions. On the other side, the number of recorded earthquakes has also greatly increased. This is due mainly to the seismicity associated with the 2011-2012 El Hierro and 2021 La Palma eruptions, but also because of the improvements in the detection capabilities of the monitoring network.

Here we present new P and S wave velocity regional models of the Canary archipelago and higher resolution models for the islands of Tenerife-Gran Canaria, La Palma and El Hierro. The bulk of the arrival time data used to obtain these models comes from the Instituto Geográfico Nacional (IGN) permanent monitoring network. We have augmented this dataset by incorporating arrival time data from recent temporary deployments, obtained using Deep Learning phase pickers. Because of the increased coverage of this new dataset, we are able to image features such as crustal thickness variations, magmatic intrusions, and regions of shallow (crustal) and deep (uppermost mantle) magma storage.

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POSTER 19

Slab Morphology and Mantle Wedge Processes in the Tonga Subduction Zone Revealed by Body-wave Double-difference Tomography

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The Tonga subduction zone has the fastest convergence rate, and hosts about two-thirds of the world's deep-focus earthquakes (300-700 km). Previous studies of deep-focus earthquakes suggest a relic slab separated from the Tonga slab beneath the Fiji islands. Moreover, the mantle wedge dynamics are complicated beneath the Lau Back-arc Basin, as the slab-controlled flux melting interacts with the decompression melting beneath back-arc centers. In this study, we use both regional and global body wave datasets to image the Tonga subduction zone to about 800 km depth. The regional datasets include arrivals from ocean bottom and land-based temporary seismograph deployments. In our results, the high-velocity slab extends beyond the bottom of the mantle transition zone (MTZ), at least 200 km away from a separate high-velocity structure in the MTZ to its west. This high-resolution 3D velocity model will provide valuable information on the subduction dynamics, mantle wedge melting processes, and the origin of abundant deep earthquakes in the Tonga subduction zone.

POSTER 20

Direct Inversion of Ambient Noise Multi-Modal Surface Wave Dispersions for 3D Velocity Structures

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Ambient noise-based surface wave tomography of subsurface structures ranging from shallow sediments to the upper mantle has been carried out in various regions, which is crucial for understanding regional tectonic evolution and seismic hazard mitigation. Surface wave dispersions can be extracted by either the conventional two-station method or the recently developed array-based method. Yet, both encounter certain inherent limitations: the two-station method cannot extract high-mode surface-wave dispersion, while array-based methods have relatively low spatial resolution. In this study, we introduce a novel direct inversion scheme of ambient noise multi-modal surface wave dispersions. First, we calculate cross-correlations among all station pairs in a dense array following the standard ambient noise data processing workflow. Then, we apply the array-based Frequency-Bessel transformation to calculate multi-modal dispersion spectra for cross-correlation functions from station pairs distributed along the same line. Multi-modal dispersion data can be picked using an artificial neural network. Finally, we iteratively update the 3D velocity model by fitting the multi-modal dispersion data with theoretical predictions from the model. We validate our new method using data from a dense array in Southern Yunnan, China. We obtain a high-resolution velocity model of the study region, which aligns well with known geological structures. Our new method can potentially be applied to other regions with dense arrays for subsurface structural imaging.

POSTER 21

S-Wave Seismic Data Interpretation for Channel Sand Reservoir at Sanhu Area, West China

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The Qigequan Formation at the Sanhu area of the Qaidam Basin in western China is a significant gas production formation. However, the conventional P-wave seismic survey conducted in this region reveals the presence of extensive gas clouds that strongly attenuate P-waves, resulting in substantial uncertainty regarding the subsurface structure. To address this challenge, we undertook a 3D9C (three-dimensional nine-component) seismic survey, producing direct S-wave data unaffected by gas clouds, yielding remarkably clearer subsurface images with a higher level of confidence. The processing of the S-wave data largely utilized conventional P-wave processing techniques, with the exception of shear wave splitting, which produced distinct Fast (S1) and Slow (S2) S-wave datasets. The shear wave splitting includes estimation of the anisotropy orientation and rotation of the horizontal components into corresponding normal and perpendicular directions Notably, the S2 data exhibited superior quality compared to the S1 data, enabling us to apply various seismic attributes techniques to extract geological features. Among many seismic attributes, we present seismic envelope and spectral decomposition with RGB blending application results. To validate our findings, we cross-referenced the seismic attributes and inversion results with well-log and production data, revealing a pronounced spatial correlation between the gas reservoir and channel structure. Consequently, we have identified channel structures as the prime targets for potential gas reservoirs.

POSTER 22

Multi-Scale, Finite-Frequency Body Wave Tomography With Relative Kernels

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The subduction of the Chile Spreading Ridge beneath South America beginning 12-16 Myr ago opened a gap in the subducting slab beneath southern Patagonia. Paleo-reconstructions show a northward migration of the Chile Triple Junction to its present location around 46ºS, but structure anomalies and geodynamic processes associated with the slab window have been poorly understood. The geographical extent of the slab window was previously inferred from the spatial distribution of magma composition and the analysis of seismic waveforms from temporary seismic arrays (2004-2006) near the Chile Triple Junction. The recent deployment of broadband seismic instruments in Patagonia by the GUANACO experiment (2018-2021) and the Chilean National Seismic Network present an opportunity to image the slab window and associated structures in more detail. Here, we use teleseismic P and S wave travel time residuals to carry out finite-frequency tomography. We compute the travel time residuals in high frequency (0.3-1.5Hz) and low frequency (0.03-0.125 Hz) bands and invert them to P and S-wave 3D models taking advantage of the different finite-frequency kernels obtained from different frequency bands. Crustal corrections are determined from a recent regional scale shear velocity model of shallower structure derived from surface wave tomography and receiver functions [Mark et al, 2022]. Our new seismic models show the transition between the Nazca slab associated with fast upper mantle velocity anomalies and the slab window with slow velocity anomalies. The southern extent of the slab window and the presence of a thicker continental lithosphere observed beneath the Austral-Magallanes Basin are consistent with the recent surface wave tomography results. In this presentation, we will discuss the 3-D geometry of the subducted slab and the effect on the mantle flow pattern derived from shear wave splitting results [Ben-Mansour et al., 2022], the spatial distribution of volcanism (arc versus backarc regions) and the support of the present-day surface topography with a dynamic contribution from the mantle across Patagonia.

End-to-End Advancements in Earthquake Early Warning Systems

Oral Session • Friday 3 May • 2:00 PM Pacific

Conveners: Ronni Grapenthin, University of Alaska Fairbanks (rgrapenthin@alaska.edu); Angie I. Lux, Berkeley Seismology Laboratory (angie.lux@berkeley.edu); Mouse Reusch, University of Washington (topo@uw.edu); Brian Terbush, Washington State Emergency Management Division (Brian.Terbush@mil.wa.gov); Fabia Terra, Berkeley Seismology Laboratory (terra@berkeley.edu)

Improvement in Magnitude Estimation Performance with a Combined PGD-PGV Scaling Law for the G-Fast Earthquake Early Warning Module

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Early estimation of earthquake magnitude is essential for earthquake and tsunami early warning systems and rapid response to these events. We propose a new method to estimate earthquake magnitude using a scaling law relating peak ground velocities (PGVs) and peak ground displacements (PGDs) derived from Global Navigation Satellite Systems (GNSS) data from a global dataset (Crowell et.al, 2023). Peak ground velocities indicate the level of damaging shaking while peak ground displacements are diagnostic of the maximum moment release, so obtaining observations at the highest fidelity and understanding their relationship is crucial for rapid earthquake magnitude estimation through the use of scaling laws. We collected high-rate (1Hz) GNSS observations for earthquakes ranging in magnitude from Mw 4.9 to 9.1. The three-component GNSS velocities were computed with the SNIVEL software package, which uses the time-differenced carrier-phase method, and the three-component GNSS displacements were computed with the precise point positioning code GipsyX from JPL. The peak ground velocities and displacements were computed by taking the maximum of the square root of the sum of each component squared. With this dataset, we explore the evolution of PGV and formally combine it with the PGD scaling law proposed by Crowell et.al, (2013), which forms the core of the G-FAST module in ShakeAlert. We test the new law against the existing performance in G-FAST using the PGD-only approach, with regards to both timing of alerts and accuracy of magnitude estimates, and investigate the downstream impacts on ground motion and tsunami prediction in the context of operational early warning. Additionally, we investigate case studies of large magnitude events with ground motions over large areas to assess the performance of the PGV correction term. We finish by developing a framework for how this additional term would be implemented in the G-FAST earthquake early warning module operationally.

Finite-Fault Rupture Detector (FinDer) for Earthquake Early Warning and Rapid Impact Estimates: Recent Developments using Large International Earthquakes

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Rapid fault rupture information is important for estimating seismic ground motion and impact in large earthquakes, which is critical for earthquake early warning (EEW) and rapid response systems. The Finite-Fault Rupture Detector (FinDer) algorithm computes earthquake finite source models (either line-sources or complex rupture polygons) by comparing seismic amplitude distributions with precomputed templates. The algorithm has been adopted by the United States West Coast ShakeAlert EEW system and by other real-time systems, such as in Switzerland, Central America, New Zealand, and Italy. Recent improvements to FinDer address challenges of real-time operations, such as dealing with instrument failures during strong shaking, rupture along complex fault geometries, as well as fault slip estimation using FinDerS. We demonstrate FinDer's new features by running waveform playbacks of global earthquakes, including the 2023 M7.8 Kahramanmaraş sequence in Turkey, the 2016 M7.8 Kaikoura earthquake in New Zealand, and M7.8 scenario earthquakes along the San Andreas Fault in California. The resulting earthquake source models show that FinDer(S) is able to provide timely and accurate earthquake and ground motion information for EEW. FinDer(S) can also improve rapid impact estimates after damaging earthquakes by providing fault rupture information much faster than traditional finite-fault slip models.

Generalized Neural Networks for Universal Real-Time Earthquake Early Warning

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Deep learning enhances earthquake monitoring capabilities by mining seismic waveforms directly. However, current neural networks, trained within specific areas, face challenges in generalizing to diverse regions. Here, we employ a data recombination method to create generalized earthquakes occurring at any location with arbitrary station distributions for neural network training. The trained models can then be applied universally with different monitoring setups for earthquake detection and parameter evaluation from continuous seismic waveform streams. This allows real-time Earthquake Early Warning (EEW) to be initiated at the very early stages of an occurring earthquake. When applied to substantial earthquake sequences across Japan and California (US), our models reliably report earthquake locations and magnitudes within 4 seconds of the initial P-wave arrival, with mean errors of 2.6-6.3 km and 0.05-0.17, respectively. The generalized neural networks facilitate universal applications of real-time EEW, eliminating complex empirical configurations typically required by traditional methods.

Investigating Seismic Site Amplification for Improved Earthquake Early Warning in Canada

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A well-implemented Earthquake Early Warning (EEW) system can warn populations and critical infrastructure operators about imminent shaking due to earthquakes. The Canadian EEW network covers regions of high seismic hazard, dense population, and critical infrastructure. In some regions, site amplification due to soft soils and sediments are expected to cause deviations from predicted ground motion which impact EEW magnitude estimates. The goal of this study is to provide empirical site amplification factors that reflect deviations from expected ground motion with respect to a hard rock (reference) site at EEW stations. We calculate the horizontal-to-vertical spectral ratios (HVSRs) at each site using ambient seismic noise and estimate the predominant site period using a systematic Gaussian curve-fitting algorithm. From a total of 75 Canadian EEW stations investigated, 26% show site amplification compared to 6% of the Canadian National Seismograph Network (CNSN), which are predominantly located on bedrock. We have assessed the relationship between the existing catalogue of CNSN station magnitude residuals, predominant site period, and amplification at the site. While station magnitude residuals are used to estimate site-specific amplification at CNSN stations, EEW stations do not contribute to the Canadian National Earthquake Database (NEDB) magnitude estimates, therefore the HVSR ambient noise method is used for site-specific amplification estimates at these stations. Finally, we evaluate and compare EEW P-wave magnitude estimates with S-wave magnitudes from the NEDB. One method of calculating magnitude in the EEW system uses peak displacement up to the first 4 seconds of the P-wave arrival, while the NEDB catalogue relies primarily on S-wave-based magnitude estimates. Our comparative analysis aims to characterize the relationship(s) between EEW and NEDB magnitudes in western and eastern Canada, how site factors influence EEW magnitude estimates and how application of site amplification factors can improve EEW magnitude estimates.

Predicting Ground Motion Waveforms for Earthquake Early Warning Using Convolutional Long Expressive Memory Models

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Earthquake early warning systems are developed to mitigate immediate threats after the onset of large earthquakes and deployed worldwide including the west coast of the United states. Once detecting P-waves at sensors close to the epicenter, the system estimates the earthquake location, magnitude and fault geometry and predicts ground motion intensity parameters to issue a warning prior to the strong motion arrivals. Errors in the parameter estimation, especially magnitudes, lead to false alert or missing warning opportunities and the use of empirical ground motion models precludes accurate representation of the complex source, path and and site-term variabilities. Alternatively, ground motion intensities or waveforms can be forecasted by combining physics-based simulation and data assimilation, which can remove arrival detection and magnitude estimation, but their prediction accuracy remains insufficient.

We propose convolutional Long Expressive Memory Models, a novel sequence-to-sequence learning approach in machine learning (ML) to accelerate the inference time, while simulating complex spatio-temporal wave propagation phenomena. We test our approach by forecasting physics-based simulation waveforms for earthquakes along the Hayward Fault in the San Francisco Bay Area. We train the ML using >900 small point-source earthquakes (<0.5 Hz) recorded at sparsely distributed stations. Once trained, using the early portion of waveforms, the ML can predict the rest of waveforms on the fly at arbitrary sensor locations. The predicted and groundtruth waveforms show remarkable agreement, and the spatially heterogeneous peak ground velocities are well predicted. We then use the point-source trained model to predict large M finite-fault cases, a challenging domain shift problem for ML. Our ML method can predict up to M6 ground motions, suggesting strong potentials in generalization. To apply to real earthquakes, we envision to train ML models using many real small M earthquakes and a smaller number of larger M data, and achieve fast high-fidelity prediction based on observations.

Engineering Earthquake Early Warning

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The most cutting-edge advances in earthquake early warning (EEW) have been primarily concentrated on real-time seismology. However, to maximize the potential of EEW as a credible tool for seismic resilience enhancement, there remains a strong need to develop next-generation end-to-end decision-support systems that use interpretable probabilistic impact-based estimates and account for malfunctions (i.e., false alarms) towards more risk-informed stakeholder decision-making on EEW installation/alert triggering. This presentation addresses this challenge, showcasing a series of recent significant EEW contributions.

First, I present the results of a state-of-the-art feasibility study for EEW conducted across Europe, representing the only attempt in the literature to spatially combine traditional seismologically driven EEW decision criteria (i.e., lead time) with proxy risk-oriented measures for earthquake impact and alert accuracy. These results show that, under certain conditions, EEW could be particularly effective for areas in Greece, Italy, and Turkey. The findings offer a unique transnational perspective on EEW's potential relevant to various stakeholders interested in leveraging the technology.

I then present an innovative approach for enhanced risk-informed decision-making on triggering EEW alerts. The proposed methodology integrates earthquake-engineering-related seismic performance assessment procedures/metrics (e.g., costs, downtime, and casualties) with multi-criteria decision-making tools within an end-to-end probabilistic framework that robustly tracks uncertainties. Such a methodology enables explicit consideration of end-user preferences (importance) towards the predicted consequences in the context of alert issuance. The proposed approach is demonstrated using various case-study infrastructure systems in Europe, for which the optimal decision (i.e., "trigger" or "don't trigger" an EEW alert) is investigated across a range of ground-motion intensities finding that the best action for a given level of ground shaking can change depending on stakeholder preferences.

Toward Earthquake Early Warning in Nevada

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Nevada is one of the most seismically active states, with numerous active fault systems across the state and in bordering regions. Nevada has a notable history of large, M 6 and greater, earthquakes and increased risk due to the most populated areas lying in some of the most hazardous sections of the state. Earthquake early warning systems aim to lower the risk of earthquakes by sending alerts to potentially affected people before shaking arrives at their location. ShakeAlert is the current EEW system in place in the U.S., but it only operational in the West Coast states of California, Oregon, and Washington at the moment. Our research is focused on testing the feasibility of Nevada's seismic network for EEW and determining what changes to the network or EEW processes might be needed for ShakeAlert to expand to Nevada. The results obtained for Nevada could also provide new insights into EEW that can be applied to other parts of the US. Using hazard maps and current network configurations, we created upgrade scores to qualitatively show the current state of the network and the locations where adding new stations would lead to the most improvements. We explore this further using grids of potential new stations and simulated earthquakes to test the effects of adding new stations to the current network. One aspect of the ShakeAlert workflow is estimating the magnitude of an earthquake as it occurs using the peak displacement measured at individual stations. This relation was created using a limited data set that did not include Nevada earthquakes, so we are testing whether this relation holds true in Nevada or if a new regional relation needs to be created. We are also looking at using site terms and studying trends across geographic groupings to improve accuracy.

Evaluation of the Ocean Networks Canada Earthquake Early Warning System: Magnitude Estimation and Site Condition

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Ocean Networks Canada (ONC) began developing an Earthquake Early Warning (EEW) system for southwestern British Columbia in 2015, which has been operational as of April 2023. The system detects earthquakes based on rapid detection of P waves and determine epicentral location and magnitude. Alerts are then generated and sent to infrastructure subscribers. Here, we take a close look at the ONC EEW system by analyzing the estimated magnitude and site condition at individual stations.

Overall, the ONC EEW system somewhat underestimates magnitudes for larger events (>4) while overestimating smaller earthquakes compared to Natural Resources Canada and USGS. We attribute these discrepancies to several factors, including the use of different stations, procedures, and methodologies to detect earthquakes among different agencies. Based on the average difference between station and event magnitude, we observed that there are several stations that systematically generate larger or smaller magnitudes by as much as 1 magnitude unit (and higher). In general, with exception of a small number of stations at close distances, no strong evidence of non-linearity could be observed at the stations (onshore and offshore). Overall, offshore sites show site fundamental frequency (f_{peak}) and its peak amplitude (A_{peak}) in the range of ~1.7-6 Hz and ~0.4-1.2 (in base-10 log unit), respectively, whereas onshore sites show ~1-6 Hz for f_{peak} and ~0.3-0.7 (in base-10 log unit) for A_{peak}. There are slight trends in station terms versus f_{peak} and A_{peak} where station terms decrease with increasing f_{peak} and increase with increasing A_{peak}. The dependence of station terms on f_{peak} and A_{peak} provides an explanation for the high and low magnitude values calculated at several stations. As there is a correlation between f_{peak} and A_{peak} where lower amplification (A_{peak}) is expected for higher f_{peak} values, systematic calculations of high or low magnitudes at stations can be related to site condition with stations located on softer geological materials be more prone to higher magnitude estimates than those on hard rock conditions.

Impact Assessment of Eew Systems in Central America

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Since 2016, the ATTAC (Alerta Temprana de Terremotos en América Central) project has been developing national Earthquake Early Warning (EEW) systems across Central America, through collaboration between the Swiss Seismological Service at ETH Zurich and national seismic agencies in Nicaragua (INETER), Costa Rica (OVSICORI), Guatemala (INSIVUMEH) and El Salvador (MARN). The four countries now provide public alerts through mobile applications. As the national EEW systems have moved into an operational status, the selection of recommended protective actions that can reduce casualties becomes crucial. The essential premise of EEW is that seconds matter. Therefore, a well-educated public that responds promptly and adequately is indispensable to a successful outcome. However, no official 'written' guidance on recommended protective actions exists in any country in Central America.

We used a recently proposed framework (Papadopoulos et al., 2023) to combine the regional seismic risk model (Global Earthquake Model, Silva et al., 2018), EEW warning times depending on the spatial distribution of the seismic network, and the behavior of individuals during earthquakes (Orihuela et al., 2023) to quantify the impact of EEW systems on reducing earthquake-induced casualties. On average, when considering major earthquakes, the implementation of EEW systems has demonstrated the potential to reduce casualties (i.e, injuries and fatalities) within the range of 14-18%. This percentage can be substantially improved through the implementation of key factors: (1) protective actions tailored to the building characteristics; 70% of the region's buildings are single-story structures, immediate evacuation should be prioritized while occupants in multi-story structures might be better advised to drop cover and hold on (DCHO); (2) improving the public response, educational programs and earthquake drills can influence individuals to react promptly; (3) increasing the warning time by densification and expansion of the seismic network and improving EEW methods.

Performance of Operational Earthquake Early Warning Across Central America.

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Over the past year, operational public Earthquake Early Warning (EEW) alerts have become available across Central America via cell phone applications. Given the elevated earthquake risks, vulnerable building stock, and rising population density, the adoption of EEW systems in the region has substantial potential to safeguard lives. The "Alerta Temprana de Terremotos en América Central" (ATTAC) project, involving seismological agencies from Guatemala, El Salvador, Nicaragua, and Costa Rica, along with the Swiss Seismological Service (SED) at ETH Zurich, has concluded after 8 years with the release of public operational national EEW systems. Each of the four participating countries now offers public alerts through a mobile application available on both iOS and Android devices. As of January 2024, the Costa Rican Android application (the first that was released) has tens of thousands of users, providing notifications with less than an additional 4-second delay, 1.5 seconds in median. In Managua, Nicaragua, the Japanese-developed EWBS system is also used for fix-site alerting via digital television (also implemented but not publicly deployed in El Salvador and Costa Rica). Each of the independent national EEW systems utilises high-quality seismic networks and the ETHZ SeisComP EEW (ESE) system with the Virtual Seismologist and FinDer EEW algorithms. First alerts for on-shore seismicity are typically available within 8-15 seconds after origin time, while offshore or deep events are identified within 20-25 seconds. In this submission, we summarize the alert configuration of the systems and review the performance so far, with a focus on key events, including the October 2023 M5.3 earthquake in Central Costa Rica, one of the first key tests of the system. We also reflect on fluctuating usage numbers and early feedback on the system so far.

Exploring Five Years of Social Science and Education Research for Shakealert, the Earthquake Early Warning System for the West Coast of the United States

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As of May 2021, rollout of public alerting of the ShakeAlert Earthquake Early Warning (EEW) System, has been completed in Washington, Oregon, and California. Critical questions remain about what people understand and expect from ShakeAlert, including if they know what to do when they receive an alert. To evaluate whether the ShakeAlert System has been successful in answering these key research questions, the U.S. Geological Survey (USGS) developed the Social Science Working Group in 2019. The USGS collaborates with partners from universities, emergency management and other state agencies, the National Science Foundation, and USGS licensed alert distribution partners to implement a social science initiative focusing on three goals. First, to understand earthquake risk perception, protective action knowledge, and basic earthquake preparedness across Washington, Oregon, and California populations. Second, how to apply social science research to inform the ShakeAlert communication, education, outreach, and technical engagement (CEO&TE) programs. Third, to develop a monitoring and evaluation plan for CEO&TE programs for ShakeAlert. The ShakeAlert social science initiative focuses on research that is currently underway and plans future directions to reach our goals. This presentation outlines the various publications that have been published or are in draft, future projects, and how social science and educational research has been integrated into the ShakeAlert System to improve outcomes for users of the system.

The Development of a Real-Time Urban Earthquake Early Warning System for Asset-Level Protection for Increased Community Restoration

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A Real-Time Urban Earthquake Early Warning System is being developed at the University of British Columbia. This system is based on a dense grid of low-cost seismic stations mounted on infrastructure (i.e., buildings, bridges, power substations) every 50 to 100 m apart. The edges in the grid are represented with transmission line models that decouple the adjacent nodes with the wave's propagation time, making it very computationally efficient. Each station consists of a MEMS tri-axial accelerometer, a Raspberry Pi processing board and a 5G communication module. As soon as the wave is detected, the grid model will calculate, in a few milliseconds, the predicted values at all other nodes before the wave arrives. As the wave progresses, the predicted values are updated. With this solution, we can achieve a high spatial and high temporal resolution. The fine spatial resolution captures the variability in geological conditions within a city. Combining this high resolution with existing fragility curves, we can predict the level of damage at the individual infrastructure level. In addition, discriminating automatic protective actions can be taken, such as disconnecting electrical circuit breakers to prevent fires, a major cause of damage and death. Detailed real-time knowledge of the damage level at each infrastructure is integral for post-earthquake recovery. During a disaster, when multiple support systems fail simultaneously, decisions about where to deploy resources must be made based on the consequences to the community. These decisions require tools that consider each infrastructure's current state of damage and the strength of the interdependencies each has with the others. With the use of an interdependencies optimization tool, prioritized response actions can be taken to restore habitability to the community as quickly as possible for increased community resilience and well-being.

What It Takes to Implement Earthquake Early Warning in the Real World

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The ShakeAlert Earthquake Early Warning System, fully operational in California, Oregon, and Washington, is a *public-private partnership* between the US Geological Survey, several cooperating universities, and several licensed technical partners. The *public side* of the ShakeAlert System (i.e., USGS and partnering universities) is responsible for collecting and analyzing earthquake data. The *private side* of the ShakeAlert System (i.e., licensed technical partners) is responsible for delivering alerts and initiating automated actions to protect people and infrastructure. Without a robust marketplace of technical partnerships, earthquake early warning information would not reach the public. Therefore, when considering expanding EEW to the public in a new location, such as Alaska, it is crucial to consider the resources needed to build, grow, and sustain technical partnerships. This presentation will cover the process of developing and nurturing the technical partnerships needed for earthquake early warning implementation, including a discussion of common challenges and roadblocks faced during the ShakeAlert rollout on the US West Coast from 2019-2024.

From Shakealert to Post-Earthquake Assessment—Improving Situation Awareness of Building Managers and Occupants

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Early warning systems must be optimized through a combination of science and technology that provide a foundation to deliver alerts in the form of actionable information in a manner relevant to the recipient of the alert. The effect of the potential disconnect between the understanding of these systems' technical innovations and the layperson's human behavioral need can be seen in the perceived issues in the early deployments of some of the most robust early warning systems. If the system serves the scientific community but does not meet the needs of the information users, the value of the system can be called into question. Earthquake early warning systems (EEWS) serve multiple participants and must address the needs of each in a manner consistent with their expectations—detailed technical information for scientists and engineers, actionable information for emergency responders, and safety instructions for the general public.

Maximizing the effect of EEWS requires that they be integrated into the everyday systems and processes of those who rely on them. Typically, the warning comprises a simple, understandable display of instructions to *Drop, Cover, and Hold On*, including estimated timing and intensity associated with

their location. Following the shaking, however, emergency management personnel and responders require another level of information to help guide their actions and decisions. For this reason, our platform delivers earthquake early warning messages as an element of a larger workflow incorporating information on the impact of ground motion on their structures, details of potential non-structural impact within their structures, and a mobile app that enables occupants to submit injury and hazard reports. Emergency response personnel can use the platform to perform safety checks, evaluate the overall impact on their structures and occupants, and manage their emergency response. This approach informs and integrates the procedures of the response team as well as the occupants within the structures, resulting in a more comprehensive and effective system.

The Ojai California Earthquake of August 20, 2023: Earthquake Early Warning Performance and Alert Recipient Response in the m5.1 Event

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A magnitude 5.1 earthquake in California rarely generates more than momentary notice—a headline in local newspapers and a mention with footage on the evening news—then fades into obscurity for most people. But this earthquake which occurred near the city of Ojai is significant for seismologists, social scientists, emergency managers, policy makers and others who are engaged in implementing and improving earthquake early warning (EEW) technology and in assessing its value in public warnings. In this earthquake, ShakeAlert, the EEW system for the West Coast of the United States operated by the US Geological Survey (USGS), was publicly activated and, for the first time, a substantial number of those who received alerts provided feedback on various aspects of the alerts they received. To capture data related to public attitudes and assessments regarding this and future alerts, a supplemental questionnaire was developed and associated with the 'Did You Feel It?' (DYFI) earthquake reporting system, also operated by the USGS. The DYFI system received over 14,000 felt reports; 2,490 of these by people who received or expected to receive an alert prior to the onset of earthquake motion at their locations. This paper analyzes the aggregate results of these EEW user reports, touching on respondent's situation upon receiving the alert, characteristics of the alert received and, perhaps most important, how the alert recipient responded if received prior to feeling earthquake motion. The new DYFI EEW supplemental questionnaire also inquired about respondent views of alert usefulness and preferences in future alerts. Our report provides a first glimpse of a range of behaviors, attitudes, and assessments by users of the recently implemented EEW system for the US West Coast.

High-Rate Real-Time Gnss Installation and Data Acquisition at the Alaska Earthquake Center

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Global Navigation Satellite System(GNSS) is an increasingly integral part of assessing rare, but large, earthquakes. Geodetic capabilities provide an extra layer of scientific investigation which is not only prerequisite to earthquake early warning (EEW) in Alaska, but also provide a better understanding of the ongoing seismic activity in the region. To date, we have upgraded 7 seismic sites across Alaska to include GNSS receivers and have developed a framework for acquiring and archiving this data at the Alaska Earthquake Center (AEC). As part of this integration, we've had to navigate the entire process of adapting an additional technology, including site selection, installation, reliable communications back to our datacenter, acquiring the data, and building a preliminary quality control procedure. GNSS receivers are installed at existing seismic monitoring stations that are capable of supporting remote, real-time data acquisition using the same power and communication systems. Recent GNSS installations consist of a VeraChoke antenna with a Septentrio PolarRx5 receiver. The VeraChoke antennas are mounted on polar masts, which are anchored to a solid rock surface. We are using two applications provided by BKG (Bundesamt für Kartographie und Geodäsie) to acquire GNSS data: an NTRIP caster and client. Each receiver is configured to broadcast real-time data to an NTRIP caster, which serves as an accessible connection point for a user to access the GNSS data streams. The NTRIP client accesses the broadcasts by connecting to the caster, then saving the data streams to RINEX files. AEC collects 1 Hz observational data and stores it into 1 hour files. These recent installations and the workflows we built have allowed us to develop skills in field installation, data acquisition, data management, and quality control, hopefully paving the way for more effective and expansive GNSS applications in the coming years.

The Potential Contribution of Real-Time Distributed Slip Models to Subduction Zone Earthquake Early Warning in the Context of Ground Motion Thresholds and Alerting Strategy

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Earthquake early warning systems like ShakeAlert estimate source parameters (e.g., Mw and location) in order to calculate anticipated shaking. Users receive alerts where forecast ground motion (GMpred) exceeds a pre-set alert threshold, tA. Alert timeliness can improve if tA < tT, the target shaking level for which we hope to alert users (Minson et al., Sci. Adv. 2018). ShakeAlert uses two seismic algorithms that estimate parameters of a point or line source representing the earthquake. Large (e.g., M8.0+) subduction interface earthquakes' offshore location, magnitude, and rupture extent are a challenge to accurate real-time source characterization. This work evaluates if the BEFORES algorithm (Minson et al., JGR, 2014), which infers temporally-evolving, three-dimensional distributed slip models (DSMs) from real-time global navigation satellite system data, can improve performance. Previously (Murray, AGU Fall Mtg. 2023, NH13C-0690), I compared alert outcomes using BEFORES' DSMs to those from published post-event DSMs and point source models ("best case" parameter estimates) as well as models from ShakeAlert's existing algorithms. Outcomes were quantified by correct, missed, and over alerts relative to ShakeMaps (GMobs) using tA = MMI 4 and tT = MMI 6. For two events it was also possible to evaluate alert timeliness. Most source models had similar correct alert performance to ShakeMap for the chosen thresholds, even when GMobs and GMpred differed by >1 MMI unit. These thresholds led to over alerts (GMpred > tA, GMobs < tT) for large areas, even for the ShakeMaps. BEFORES caused larger over alert areas than retrospective DSMs but did not increase the total over alert area compared to ShakeMap for the earthquakes and thresholds tested. BEFORES showed potential to improve timeliness and reduce missed alerts. Here I present follow-on work suggesting BEFORES may improve alerting for higher tA (e.g., an MMI 5 "take action" threshold), and I consider BEFORES' contribution in the context of unilateral subduction interface ruptures and preemptive alerting of a large region if the Mw estimate exceeds a certain value.

Toward Earthquake Early Warning in Alaska

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The complexity of Alaska presents several challenges for earthquake early warning systems. These include the presence of offshore earthquakes, transform boundaries and crustal faults extending hundreds of kilometers, deep earthquakes, and a complicated coastline. This variety, combined with population centers spread far apart, make it challenging to anticipate early warning system performance and to design a network accordingly. As Alaska begins to plan for early warning, we present here a set of scenarios and proposed network plans. Our objective is to begin envisioning how, and how well, early warning might function in Alaska. We present warning time estimates for groups of deterministic earthquake scenarios along major faults in Alaska. These scenarios are designed to be meaningful test cases for Alaska EEW while also exploring how changes in source characteristics—such as magnitude, depth, location, and fault system—impact the timeliness of warnings. We use simple travel-time estimates, source time models, and the current seismic network to model hypothetical detection and alert times. We then compare warning times to peak ground motions obtained with ShakeMap 4 to determine the warning effectiveness. Our conservative results suggest the

potential for timely warning for shallow earthquakes for ground motions up to intensity V. More ideal scenarios, including deep earthquakes, could receive advance warning up to intensity VII. Informed by these results, we present preliminary concepts for how to build a network capability of delivering this level of warning or better.

Application of the Support Vector Machine Classifier in Earthquake Magnitude Estimation

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The ability of an Earthquake Early Warning (EEW) algorithm to resolve reliably the event magnitude from a few stations is critical for an efficient EEW application. When applied to a single-station seismic record, traditional approaches based on t_c and P_d methods exhibit somewhat larger errors than the machine-learning methods. We use the Support Vector Machine (SVM) method with a Gaussian kernel to predict magnitude from a single station triaxial record. Unlike other approaches, raw records are used without downsampling or converting them to a vector of parameters. Preliminary investigations demonstrated that SVM approach is superior to the Deep Neural Networks as it provides better accuracy both in the training and validation data sets. The subset of the KiK-net database generated by the NIED strong-motion seismograph network incorporates ~4,000 triaxial records of P waves over the magnitude range 5.5-7.6. This was used to train the SVM model and investigate the accuracy of the results by means of the normalized confusion matrix. Results demonstrated that the confusion matrix is almost diagonal, which suggests that the spectral norm of this matrix is a good measure of the accuracy of the solution. Several techniques were evaluated for the pre-processing of the P wave records to investigate their influence on the solution with the intention of providing a rigorous physics-based interpretation of the results.

The outcomes of this study will be implemented in the network based EEW system operated by the Greater Vancouver Water District. The system was designed, built, and commissioned in 2021/2022 as part of the pilot project "EEW and Strategic Response System". The project deliverables included a robust EEW application, and a Structural Health Monitoring service for some of the critical infrastructures operated by Metro Vancouver. Currently, the system is being utilized by operations staff within the water system infrastructure.

Enhancing Offshore Earthquake Early Warning with a Submarine DAS Array in Monterey Bay, California

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Detecting offshore earthquakes in real-time is challenging for traditional land-based seismic networks due to insufficient station coverage. Application of DAS to submarine cables has the potential to extend the reach of seismic networks and thereby improve real-time earthquake detection and Earthquake Early Warning (EEW). We present results testing modified point-source EEW algorithms (EPIC) with data from SeaFOAM DAS deployment (52 km-long submarine cable) in Monterey Bay, CA. The region is seismically active with the nearby San Andreas Fault system, and the offshore San Gregorio Fault system (SGFs) which the cable crosses.

Around 1.5 year's data has been collected by the permanent SeaFOAM project, including more than 10 offshore events on the SGFs. We developed a workflow that can be migrated to other DAS cables to detect earthquakes in real-time. We took a transfer learning approach with recorded local earthquakes to get a locally optimized PhaseNet-DAS machine learning model for P and S arrivals picking. We used a grid search method with available picks from the whole DAS array and a local 1D velocity model to locate the earthquakes. A calibrated empirical strain rate-to-magnitude equation is used to perform a real-time estimation of the magnitude. We extended our analysis to more recorded earthquakes and demonstrated the independent earthquake detection ability of an offshore DAS array. In the future, this DAS-specific EEW algorithm will be integrated into the existing EPIC algorithm for testing. This approach has the potential to extend earthquake detection for EEW offshore, thereby increasing warning times significantly.

End-to-End Advancements in Earthquake Early Warning Systems [Poster Session]

Poster Session • Friday 3 May

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POSTER 17

Improving Seismic Networks for the Earthquake Early Warning Mission

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A seismic network supporting the Earthquake Early Warning (EEW) mission must prioritize speed of detection for potential earthquakes of consequence. We present methods for estimating annualized station expected contributions to the EEW mission for improving network effectiveness in the presence of limited resources for station coverage and maintenance. The expected rate of a station contributing to earthquake detection depends strongly on location. Stations near high slip-rate faults are more likely to participate in EEW earthquake detection than are stations near low slip-rate faults or in locations away from active faults altogether. The annualized rate of participation in detection at any point can be obtained from data associated with the USGS National Seismic Hazard Maps.

A station's contribution can be measured in terms of the improvement in detection time that it provides, the area it covers, the areas around it at various shaking intensity levels, and the number of people who have more time to prepare for shaking at various intensity levels because the station is on duty. As others have seen, time to earthquake detection depends on nearby station density. For a network denser in urban areas and sparse in outlying areas, like the network for the USGS ShakeAlert system, a hyperbolic relationship is seen between detection time improvement and numbers of people helped by the improvement. For example, urban Los Angeles area stations improve detection by tenths or hundredths of a second, but millions are (marginally) helped, while rural stations can help detection by a second or more, but few live near intense shaking. When damage models are linked to shaking intensities, station contributions can be measured in terms related to protecting people and property, a core USGS National Earthquake Hazard Reduction Program priority. Understanding station contributions can inform maintenance priorities and station sitings or relocations to improve seismic network effectiveness and maintainability.

POSTER 18

Picket Fence: An Earthquake Alert System for the Ligo Detectors

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The Advanced LIGO detectors are leading the field of gravitational wave astronomy. The detectors measure the change in length of 4-km long resonant interferometers to attometer precision to achieve their goal. Not surprisingly, the resonance condition for operation is delicate and can be lost if elaborate isolation of external disturbances is not complete. The Rayleigh waves produced by earthquakes challenge this isolation. In the past five years, LIGO has

implemented a control configuration called earthquake (EQ) mode to allow LIGO instruments to maintain resonant operation or "lock" during earthquake events whose strength would have previously impaired their functioning, which helped restore some of their duty cycle. EQ mode works best when it can be used preemptively, before the arrival of surface waves to the LIGO observatories.

The 'Picket Fence' is a newly implemented early alert system aimed to increase the warning time for surface waves approaching the LIGO observatories, enabling the possibility to engage EQ mode before their arrival. It works by monitoring seismic signals from an array of seismic stations hundreds of kilometers away from each LIGO site. The stations are streamed in real-time using a SeedLink connection. The work presented shows the effectiveness of the Picket Fence in providing between 30 and 100 seconds of accurate forewarning for most teleseismic events of interest for the functioning of the LIGO detectors. This development has the potential to increase the duty cycle of the detectors, boosting their scientific output. We also show a preliminary study of the potential benefits of including such an early warning system into the automated control workflow of the observatories.

POSTER 19

Examination of Usage Rates for the Multi-Hazards San Diego County Emergency App to Improve Earthquake Early Warning

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One of the global targets of the Sendai Framework for Disaster Risk Reduction is to 'substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030'. To accomplish this, the systems need to be tailored to user specific needs, have a broad scope of communication channels, and disseminate critical timely hazard information to affected communities. The efficacy of these systems, including earthquake early warning (EEW), requires integrating ideas from a range of stakeholders, including government, academia, and industry. A key problem for smartphone applications is attrition, with a recent study showing that an earthquake detection app had high attrition rates of >90% within a year. In this study, we investigated the usage over time of the multi-hazard warning smartphone app *SD Emergency*, developed by the San Diego County Office of Emergency Services and Peraton, its IT provider. As the only multi-hazard smartphone app in the US that delivers ShakeAlert-powered EEW alerts, we hypothesized *SD Emergency* would have lower attrition rates. By comparing install and uninstall data for Android and iOS, we found that the app maintained a retention rate above 50% over the past 6 years. This was based on stable uninstall rates which we interpret as due to regular alerting (~70 alerts per year). Yet even on days with no alerts, there were twice as many installs as uninstalls. There were also frequent spikes in install rates during both natural (e.g., earthquake, fire, weather) and anthropogenic (e.g., boil water notice, oil spill) events. Fire accounted for 55% of all alerts and similarly accounts for ~60% of peaks in the app install rate. Install rates increased dramatically as the number of alerts per day increased, without commensurate increases in the uninstall rate. Considering that earthquakes accounted for <1% of alerts, the multi-hazard alerting strategy substantially improves the likelihood people will retain EEW capabilities, increasing the efficacy of alerting and maintaining critical communication pathways.

POSTER 20

Implementation of a Machine Learning Classifier in the Real-Time EPIC Earthquake Early Warning Algorithm

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Machine Learning (ML) has been a hot topic in numerous research domains in recent years. In the field of seismology, researchers have developed ML classifiers that distinguish between different types of incoming signals with a high degree of accuracy when applied to testing datasets. But how well do these ML classifiers perform when implemented in a real-time Earthquake Early Warning (EEW) system?

ShakeAlert is the US West Coast EEW system, which now delivers alerts of impending shaking from earthquakes to users throughout California, Oregon, and Washington. The Earthquake Point-source Integrated Code (EPIC) (formerly ElarmS) algorithm is one of two algorithms currently running in the production ShakeAlert EEW System. EPIC is fast, usually the first ShakeAlert algorithm to alert, and can create accurate point-source estimates of earthquake magnitudes and locations using a minimum of 1 sec of data from one station, and 0.5 sec of data from three additional stations.

We implemented the Meier et al., 2019 ML classifier into the EPIC algorithm with the goal of reducing the number of false triggers coming into the system. This version of EPIC ("mEPIC") has been running in real-time since April 2023. In this presentation, we give an overview of the real-time mEPIC algorithm and its performance over the past year.

POSTER 21

Engage With Your Regional Museums, Parks, and Libraries for Community Resilience

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Decades of evidence have demonstrated the unique educational impacts of free-choice learning environments (FCLEs), including their effectiveness for earthquake education and confirming their value as partners in end-to-end Earthquake Early Warning (EEW) communication systems. FCLEs include museums, parks, libraries, and other informal educational settings. Cross-disciplinary teams of researchers and educators, organized by USGS ShakeAlert®, have been studying conditions and opportunities to develop an emerging, evidence-based model of FCLE cooperation and mutual learning for the benefit of public EEW end users. This model is being realized through a partnership of Washington, Oregon, and California FCLEs called Earthquake Public Information Centers (EPIcenters).

To build this partnership, EPIcenter leaders, including the authors, have been conducting multi-method research. For example, researchers documented the history, milestones, and recommendations of three previous efforts, an earlier EPIcenter model, the Great ShakeOut, and the work of the associated ShakeAlert Educational Resources Working Group (ERWG). Researchers assessed the potential of FCLEs in Washington, Oregon, and California by documenting the number and type of FCLEs, their location relative to seismic risk, their existing earthquake education activities, and the geographic distance people need to travel to reach those activities. Researchers conducted interviews to learn about the effectiveness of recent collaboration models in the FCLE field. EPIcenter leaders also gathered input from current staff at FCLEs through interviews and questionnaires. This research confirms that FCLEs want to, and can effectively, support emergency response and public education; at the same time, the research confirms that to do so they need the support of their regional scientists, EEW technical partners, and emergency response resources. Therefore, to be effective, the EPIcenter partnership model needs the public to engage with their regional FCLEs so that they can integrate current resources, information, and response expectations into their activities.

POSTER 22

Recent Earthquake Early Warning Research and Developments at the Southern California Seismic Network

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We highlight recent earthquake early warning (EEW) algorithm developments conducted by researchers at the Caltech Southern California Seismic

Network (SCSN), with specific application to the ShakeAlert EEW system for the West Coast of the United States (US). ShakeAlert is a cooperative project between the US Geological Survey and partner institutions, including Caltech. Alongside providing seismic data streams to ShakeAlert using the infrastructure of the SCSN, the Caltech SCSN helps operate and develop several of the component algorithms in ShakeAlert, particularly the Finite-Fault Rupture Detector (FinDer) and the Earthquake Information to Ground Motion (eqInfo2GM) algorithms. The FinDer algorithm estimates earthquake source parameters by matching observed shaking to pre-computed templates. Ground-motion-based assessments of FinDer alert performance will help determine whether updating the ground-motion models in the templates will improve alert accuracy. The eqInfo2GM algorithm calculates median-expected shaking distributions used by ShakeAlert to determine alert regions. Proposed refinements to the ground-motion modeling procedures in eqInfo2GM, including adjustments to the ground-motion models and the representative site-effect grid, reconcile ground-motion prediction differences between the ShakeAlert grid and contour alert products as well as improve prediction accuracy.

We also discuss additional developments in EEW approaches that may be considered for future incorporation into ShakeAlert, including the ground-motion-based Propagation of Local Undamped Motion (PLUM) algorithm and Distributed Acoustic Sensing (DAS) applications. Recent PLUM developments include the addition of attenuation into the forward-prediction procedure, which brings PLUM predictions closer to the median-expected ground-motion predictions currently used in ShakeAlert. DAS-related EEW efforts focus on two areas: augmenting seismic data streams with DAS-derived data; and developing DAS-specific EEW algorithms that utilize machine learning and strain-based scaling relationships to rapidly detect and characterize earthquakes.

POSTER 23

Preliminary Multilingual Survey Results on San Diego County's Sd Emergency Multi-Hazards App to Improve Equity in Disaster Risk Reduction

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The USGS and its partners began testing public alerting with ShakeAlert® earthquake early warning (EEW) to cell phones in California in October 2019 and in Oregon and Washington in 2021. Public EEW aims to reach individuals' devices before strong earthquake shaking occurs, so they can take protective actions such as 'Drop, Cover, and Hold On' (e.g., McBride et al., 2021). Individuals can receive a ShakeAlert-powered alert on their cell phones via various smartphone applications, including the University of California-Berkeley's *MyShake* and San Diego County (SDC)'s *SD Emergency* app. However, there have been few tests to best understand if people who downloaded an early warning app remain engaged for the long-term, which could inhibit their usefulness. Further, the apps are likely missing individuals who speak English as a second language or who have limited English proficiency (LEP). California hosts the largest LEP population (>20% of residents) in the United States. SDC (and their app *SD Emergency*) serves a diverse community of over 3.3 million people with a population of ~34% Hispanic/Latinx in ethnicity and hosts a large immigrant and refugee population that speaks varied languages. We surveyed SDC residents to find out about (1) their earthquake experiences; (2) their hazard warning experiences; (3) their familiarity with the *SD Emergency* app and whether they use the app for EEW or other hazards such as wildfire; (4) barriers to alert comprehension; (5) their anticipated responses to EEW; and (6) potential improvements to the app that would best fit their language requirements. We will highlight preliminary results from the surveys offered in English, Spanish, Chinese, Tagalog, Arabic, and Vietnamese, which were the languages that SDC was most interested in. Building language equity into EEW broadly will help accomplish the United Nations Sendai Framework's disaster risk reduction goals to "substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030".

POSTER 24

Magnitude Station Corrections to Improve Initial Magnitude Estimates for ShakeAlert

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In the early stages of the ShakeAlert earthquake early warning (EEW) system, it was considered a success to analyze, locate, and report an earthquake warning promptly. The initial magnitude estimate of the earthquake, within the first few seconds, has a large impact on the area of alert. We have investigated how to better estimate the initial magnitude, including (a) using machine learning to train the dataset; (b) re-evaluating the initial magnitude scaling relationship estimate using a larger dataset; and (c) including amplitude station corrections to account for non-linear characteristics of station effects.

ShakeAlert does currently not use station corrections in normal automatic location and magnitude detection. We propose to include magnitude station corrections, which are an amplitude correction factor applied to the magnitude initial estimate. We have also developed station correction factors using vertical amplitudes to match the initial P-wave magnitude estimate model more closely. We began by developing a comprehensive list of magnitude station corrections for ShakeAlert sites in the West Coast of the US including UCB, Caltech, PNSN and NRCan network. We have made the assumption that the methodology used to develop the amplitude correction factor is not important since most of the networks use different methods in the development of the datasets.

At UCB, dML station corrections were developed using the methodology of Uhrhammer et al. 2011 which uses the horizontal amplitudes selected on synthetic Wood-Anderson time series. For ShakeAlert, it is important to have a correction for the P-wave (or vertical data) since the initial magnitude estimates use the first few seconds of event data in the time domain. Therefore, we expand the Uhrhammer study to vertical component data of ShakeAlert sites. For vertical data we filter, pick station amplitudes, and determine station corrections.

Preliminary results show the impact of the inclusion of station corrections on the initial magnitude estimates as shown by case histories for the Oct 2023 Isleton and Aug 2023 Ojai earthquakes.

POSTER 25

Low-Latency Digitization, Communication and Alerting for Earthquake Early Warning Systems: Güralp Minimus

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Earthquake Early Warning Systems (EEWS) must combine low-latency digitization, communication, and computational processes to be effective. This maximizes the time between the characterization of an event and the warning of the population, thereby providing the longest warning time. Güralp Systems Ltd. (GSL) has developed the Minimus digitizer with a range of smart features that reduce latency to 40ms from signal input to digital output.

Minimus makes use of standard processing techniques such as causal FIR filters to reduce the digitization delay. GSL has also developed and equipped Minimus with the proprietary GDI-link streaming protocol to further reduce the delays in data communication. GDI-link streams data sample-by-sample and will dynamically adjust to the available bandwidth, therefore providing a fast and reliable communication protocol compared to traditional packetization protocols. This results in the transmitted data having a dramatically lower mean latency.

Minimus combines familiar STA/LTA algorithms with simple machine-readable event messages to alert operators and populations to impending ground shaking. When in a triggered state, the Minimus will instantly send a Common Alert Protocol (CAP) event message to a designated receiver containing the station metadata that indicates an event has occurred. The Minimus will locally compute the PGA, PGV and PGD parameters from the triggered event and will subsequently send these calculations as a secondary CAP message. CAP messaging makes use of existing internet infrastructure and is already widely used in public communications which will aid EEW network operators with regards to implementation.

The Minimus has been designed as either a standalone digitizer or can be integrated into the Fortimus accelerometer and the Certimus broadband seismometer. The integrated systems provide compact and easy-to-deploy systems that are suitable for widescale EEW deployments.

ESC-SSA Joint Session: Climate Change and Environmental Seismology

Oral Session • Friday 3 May • 2:00 PM Pacific

Conveners: Robert E. Anthony, U.S. Geological Survey (reanthony@usgs.gov); Allison Bent, Natural Resources Canada (allison.bent@nrcan-rncan.gc.ca); Michael Dietze, Georg-August-University (mdietze@gfz-potsdam.de); Shujuan Mao, Stanford University (sjmao@stanford.edu); Robert Mellors, University of California, San Diego (rmellors@ucsd.edu); Siobhan Niklasson, New Mexico Institute of Mining and Technology (siobhan.niklasson@student.nmt.edu)

Multi-Decadal Analysis of the Global Microseism in Climate Context

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It has been recognized for over a century that the oceans produce a continuous microseism signal that is detectable everywhere on Earth. Standardized global digital seismographic networks such as the GSN and GEOSCOPE now facilitate the uniform analysis of microseism energy across more than three decades including recently accelerating anthropogenic climate change. The globally observable primary microseism signal at 14–20 s period is a particularly apt proxy for global near-coastal wave energy because it is produced by propagating ocean wave tractions on the seafloor at depths of less than a few hundred m and does not require the interfering wave conditions necessary for the secondary microseism source process. For continuous vertical component seismic records beginning in the late 1980s, robust trend estimation reveals increasing primary microseism amplitudes at significance at 41 of 52 long running GSN stations and decreasing trends at just eight sites confined to the North and West Pacific region and at two in the southern United States. Greatest absolute rates of increase are observed for PMSA on the Antarctic Peninsula with amplitude and energy trends through August 2022 () of 0.0370.008 nm/s^2/y (0.360.08 %/y) and 4.161.07 (nm/s)^2/y (0.580.15 %/y), respectively. Assuming linearity and consistent ocean-seismic coupling, the rate of global near-coastal ocean wave energy increase is 0.270.03 %/y for the full record and 0.350.04 %/y beginning 1 January 2000. 61-day-smoothed primary microseism signal station histories regionally cluster to beyond 50º of separation, demonstrating large spatial integration kernels. Similar analysis of the 8–14 s secondary microseism signal shows smaller temporal trends attributed to the additional ocean conditions necessary for its excitation. Primary and secondary histories show consistent station-specific seasonal phase relationships. Primary intensities also correlate with El Nino and La Nina conditions, with increasing energy in the southwest Pacific under positive ENSO conditions and in the southeast Pacific for negative ENSO conditions.

Seismic Imprints of a Hurricane Landfall: Deciphering the Atmosphere-Generated Signals From Large-Eddy Simulation of Turbulence

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One potential scenario of climate change is that tropical storms could become more intense, which will pose greater impacts upon their landfalls in coastal regions. The seismic ambient noise generated by these storms provides opportunities to study their imprints from a seismological view, and potentially facilitate the observation and understanding of their evolution.

We present a case study of Hurricane Isaac in 2012 which made landfall as Category 1 on the coast of Louisiana. This storm passed through the Transportable Array (TA) seismic stations on land, which had co-located seismometers and infrasound pressure sensors. One specific station TA.645A is right on the hurricane track and provides valuable in-situ surface pressure and seismic recordings within the hurricane. High-resolution wavelet spectrograms identify a clear calm hurricane eye. We demonstrate that within the period band ~ 20 - 100 s, seismic signals are directly contributed by turbulent surface pressure fluctuations through the local quasi-static coupling mechanism. The same turbulent pressure measurement can also be connected to surface wind reanalysis snapshots obtained from atmospheric studies.

We further perform numerical modeling of the seismic signals recorded inside the hurricane eyewall, where the strong azimuthal winds dominate. We use the open-source code Cloud Model 1 (CM1, Bryan & Fritsch, 2002) to perform a Large Eddy Simulation (LES) of turbulence within the hurricane boundary layer. This turbulent pressure field provides a realistic input for modeling seismic noise from the atmosphere, and we compute synthetic signals using quasi-static elastic Green's functions. The modeled surface pressure and vertical displacement have similar amplitudes and coherence patterns to those observed in the real data. This lays the foundation for future work that combines in-situ seismic observations of hurricane landfall with atmospheric modeling to better constrain hurricane physics. It also demonstrates how seismic data can supplement the currently limited atmospheric datasets obtained by reconnaissance flights into hurricanes.

How Fast, How Deep, and How Much? — Rapid Assessment of Groundwater Recharge From 2023 California Storms With Seismic Sensing

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From the last day of 2022, California was struck by a series of storms from multiple atmospheric rivers, inflicting extensive damage and hardship on Californians. These intense storms have also alleviated California's historical drought, rapidly refilling surface reservoirs; however, it remains unclear how much water, at which depth, and at what time scale California's depleted underground reservoirs have absorbed. Understanding these aspects is crucial for assessing the state's water deficit and facilitating data-informed water management.

In this study, we use existing seismological data to understand the natural recharge of aquifers in Metropolitan Los Angeles (LA) during the record-wet winter of 2023. With data from 65 broadband seismographs of the Southern California Seismic Network, we analyze spatiotemporal changes in seismic velocity (dv/v) using the ambient field across LA from January 1, 2003, to October 31, 2023. These dv/v measurements exhibit strong correlations with records of hydraulic head and satellite gravimetry, serving as an informative proxy for groundwater storage. At shallow depths, dv/v responds rapidly to precipitation events, while at deeper depths, dv/v shows a delayed response at seasonal to inter-annual scales. After the 2023 California Storm series, dv/v at shallower depths almost fully recovered, whereas at greater depths, less than 25% of total dv/v loss in the past two decades was recovered. Furthermore, our dv/v imaging across the LA metropolitan area highlights prominent aquifer replenishment in San Gabriel Valley and Raymond Basin, likely from mountain recharge. This study showcases the potential of ambient field seismology to provide new insights into groundwater fluctuations at different depths. This understanding is crucial for enhancing sustainable water management especially amidst extreme weather patterns.

Monitoring Groundwater Dynamics at Lyon Water Catchment Using Seismic Attenuation Variations From Train Signals

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Understanding and monitoring groundwater dynamics are crucial undertakings in contemporary hydrology and hydrogeophysics. Monitoring subsurface physical properties using single seismic stations poses a challenge. We introduce a novel methodology to monitor subsurface attenuation variations using train signals. We can measure the seismic attenuation over time by quantifying the relationship between these variations and the train signal frequency content.

This single-station approach allows local continuous subsurface monitoring, providing new observables to understand the groundwater dynamics. Lyon water catchment presents an excellent case study due to its recharge system and good instrumentation. It is a complex and strategic site that provides 87% of the city's drinking water. Being located near a highly urbanized area, the aquifer is very sensitive to pollution risks. The site uses an artificial recharge system through several infiltration basins built around the pumping areas to protect the groundwater from river pollution and maintain the groundwater level.

We applied this method during four weeks when two major events occurred at Lyon water catchment: a flood following the release of a dam upstream of the wellfield and a few days later, a 8-day controlled water infiltration experiment. By comparing measured attenuation with environmental observations (e.g., rainfall, bassin level, Piezometer level, noise correlation-based velocity changes), we can gain valuable insights into the complex interactions within the aquifer system.

Our research showcases the potential of using seismic attenuation variations from train signals to study and monitor groundwater dynamics in a context like Lyon water catchment. Seeking continuous monitoring offered by this method will lead to a deeper understanding of subsurface processes and contribute to better management of vital groundwater resources.

Merits of Installing Environmental Sensors at Seismic Stations

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The EarthScope Transportable Array (TA) in Alaska is a unique seismic network because most stations have co-located pressure, temperature, and wind sensors. We will point out some merits of having such co-located environmental sensors and stress their importance.

First, the combined analysis of seismic and pressure data allows us to separate two types of seismic noise; one is the ordinary seismic noise, consisting of propagating body and surface waves, and the other is ground deformation caused by the local pressure loading. This loading effect can be confirmed from two pieces of evidence; the coherence between seismic and pressure data and the phase difference between pressure and vertical seismic displacement. By selecting data from a high-pressure range, we can apply the compliance method and derive shallow elastic structures for a depth range of about 50-100m. Second, the combined analysis of temperature and seismic noise allows us to identify the major effects of near-surface melting in summer, primarily in the permafrost area. Some stations show a thousand-fold increase in horizontal noise in summer at 0.01-0.03 Hz in comparison to the frozen state in winter. This anomalous horizontal noise can be seen at low frequencies (< 0.1 Hz) and is most likely related to the tilt effects as its amplitude increases towards lower frequencies. Third, the way the noise level returns to the frozen, low-noise state after the major melting varies from station to station. For many stations, this return occurs well after the surface temperature becomes negative in September or October. Some stations require time until March of the following year to return to the frozen state. These data suggest that the melt layer remains at depth for a long time even after surface temperature drops below freezing, creating a sandwiched molten layer between the developing ice from the surface and the underlying permafrost ice. These results and perspectives have been gained because of the availability of co-located seismic and environmental data and underscore the importance of installing environmental sensors at seismic stations.

Leveraging Distributed Fiber Optic Sensing for Year-Round Observation of Sea Ice and Submarine Permafrost: Successes and Lessons Learned From the Beaufort Sea, Alaska.

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Arctic sea ice and submarine permafrost are key indicators and positive-feedback mediators of global climate change. Sea ice extent is a major component of global albedo, and sea ice thickness provides thermal insulation to the Arctic Ocean. Submarine permafrost in the Beaufort Sea is known to contain extensive reservoirs of gas hydrates which would release globally significant amounts of methane if thawed. The Arctic is insufficiently monitored, relative to its importance, due to its remoteness and logistical challenges. For the past three years, we have recorded distributed acoustic and temperature sensing on a commercial submarine telecommunications cable in the Beaufort Sea, Alaska, to test the capabilities of these technologies for temporospatial monitoring of polar coastal processes. We present an overview of our significant findings, including acoustic-gravity detection of sea ice extent, thickness, and dynamics, and tomographic and thermodynamic imaging of permafrost distribution. Sandia National Laboratories is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Storms, Sea Ice, and Microseismic Noise in Alaska

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This study investigates how environmental drivers like ocean storms and sea ice affect microseismic noise across Alaska. Ocean storms have long been understood to be the primary driver of microseism noise. At the same time, sea ice suppresses the formation of waves in oceans, dampening microseism production. By examining the long-term correlation of microseismic noise and ocean wave height, we find that the secondary microseismic noise (5-10s) across the whole state is mainly affected by the sea state in the Gulf of Alaska. We also find that the waves in the eastern Gulf produce higher amplitude microseism than the west. Findings from these long-term correlations are substantiated by observed patterns during individual storms. Similar correlation analysis also reveals that the microseismic noise in the 1-2s period band is primarily driven by ocean waves closer to the coast. Seasonally, in the 1-2s period, we observe an abrupt reduction of seismic power due to the onset of sea ice. Because the 1-2s period microseismic noise is driven primarily by waves near the coast, it is coastal ice that is primarily responsible for this dampening effect. These findings are useful in understanding the role of climate in microseismic noise across Alaska. Phenomena with societal significance are visible directly in the microseismic noise, including the onset and progressive break up of sea ice, the movement of storms across the open oceans, and the arrival and end of the annual storm season. In this study, we show how to calculate ocean storm parameters like position, track, and temporal evolution using microseismic noise records. Declining sea ice coupled with increasing extratropical cyclones is also known to accelerate the rate of coastal erosion in Alaska, posing serious threats to the Arctic communities and ecology. We identify the coastal erosion period from the microseismic noise in the 1-2s period band as it is influenced by both sea ice and coastal sea state. We also compare and contrast the yearly variation of the coastal erosion period in northern Alaska on a decadal time scale.

Correlation of Environmental Factors With Seismic Records on the Alaska Geophysical Network

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The Alaska Geophysical Network (AGN), maintained by the Alaska Earthquake Center (AEC), consists of over 250 remote monitoring stations located across the state of Alaska. Each station records real-time, or near real-time, seismic data. Roughly half the stations include weather and infrasound sensors collecting real-time data in parallel with the seismic sensors. Many of the stations also include continuous near-surface soil temperature sensors. This combination of co-located sensors combined with the broad geographic coverage of the network provides a robust and unique dataset for investigating and modeling a range of environmental and geophysical conditions, and their interplay, in arctic and subarctic regions.

Seismic data are influenced by a variety of environmental factors, including weather and ground conditions. Hence, seismic and network diagnostic records can be used to model environmental conditions in regions with sparse observations, and seismic network performance can be forecast based on environmental conditions. Some applications of this co-located, cross-disciplinary data we and collaborating organizations have been exploring are: associating seismic data with wind and sea ice conditions; utilizing weather data collected on our network to generate fire weather forecasts; and using infrasound data to estimate seismic velocity and earthquake magnitudes. At multiple stations, we have observed higher wind speeds correlate to increased

seismic noise. Environmental factors such as increased vegetation height, lack of snow cover, and thawing permafrost ground led to increased noise in the seismic records. In the Arctic, climate change is projected to increase vegetation heights via shrub expansion, decrease sea ice cover, cause less stable ground due to warming and thawing permafrost, and have higher wind speeds. Combining these findings, we anticipate increasing seismic noise in the Arctic over the coming decades.

An Extraordinary Tsunamigenic Rockslide Into a Greenland Fjord Rang the Earth for 9 Days

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Climate change is preconditioning large landslides in polar regions through several mechanisms including hillslope debruttressing from glacial retreat, permafrost degradation, and changes in precipitation. Tsunamigenic landslides have occurred recently in Greenland (*Kalaallit Nunaat*), but there have been no previously documented occurrences on the east coast of the island. On 16 September 2023, we observed an unprecedented monochromatic very-long period (VLP) seismic signal at 10.88 mHz that was recorded on some seismic stations for 9 days following the event and was found to originate from East Greenland. We demonstrate how this event started with a 25 M m^3 glacial thinning-induced rockslide impacting within Dickson Fjord which triggered a 200 m high tsunami that caused extensive damage to the Danish research base at Ella Island, ~65 km down fjord. Simulations show the tsunami stabilized into a 5 m high transverse seiche within Dickson Fjord, oscillating at a frequency similar to the VLP surface waves. However, the observed ultra-long seismic duration may reflect an elusive component of the source. Due in part to the event occurring after the summer travel and field season, no fatalities were associated with this event. Analysis of historical seismic data revealed four previously unknown VLP events of similar period; a subsequent event also occurred on 11 October 2023. The four most recent events have occurred since 2016 and, based on satellite altimetry, are correlated with landslides in Dickson Fjord. Ongoing warming will increase the societal risk posed by tsunamigenic landslides in polar regions including Greenland and Alaska.

Insights for Adjacent Sciences—Connecting Science, Art and Deep Knowledge for Climate Adaptation and Mitigation

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Climate change has exerted profound and far-reaching impacts on the world's water resources, including the atmosphere, glaciers, lakes and rivers, groundwater systems, energy, gas exchange, and living systems. While seismology and hydrology have historically operated as distinct disciplines, a promising avenue for advances lies in their potential synergy. A cross-disciplinary approach to earth systems change that integrates social and physical sciences, indigenous knowledge and artistic pursuits can significantly augment our understanding of climate change, thereby informing adaptive strategies and mitigation efforts. Here, we present insights for adjacent sciences derived from a decade of transdisciplinary research in Canadian water security supported by the Global Water Futures program. The authors are establishing integrated observatories for cold region hydrological processes, such as freeze-up and break-up, including their impact on gas exchange in various landscapes. Integrating existing seismic networks with hydro-metric stations can enhance our understanding of climate change, water security, and the development of effective adaptation strategies. The data collected in one field may have broader applicability across multiple disciplines, expanding the boundaries of knowledge-sharing. Collaborative endeavors involving artists, scientists, and custodians of deep knowledge can yield fresh perspectives and insights that hold substantial value for science, policymakers, and society. Tools originally designed for seismic data analysis not only benefit geologic investigations but are also useful in fields such as hydrology (e.g. river ice break up), social-ecological systems (e.g. Wetland drainage), and even biology (e.g. animal migration). Recognizing and valuing research contributions from diverse domains, irrespective of their direct relevance to one's field, fosters dynamic and productive transdisciplinary collaborations. By harnessing these multifaceted approaches, we can elevate our understanding of climate change's impact on water resources and generate novel solutions to enhance water security.

ESC-SSA Joint Session: Climate Change and Environmental Seismology [Poster Session]

Poster Session • Friday 3 May

Conveners: Robert E. Anthony, U.S. Geological Survey (reanthony@usgs.gov); Allison Bent, Natural Resources Canada (allison.bent@nrcan-rncan.gc.ca); Michael Dietze, Georg-August-University (mdietze@gfz-potsdam.de); Shujuan Mao, Stanford University (sjmao@stanford.edu); Robert Mellors, University of California, San Diego (rmellors@ucsd.edu); Siobhan Niklasson, New Mexico Institute of Mining and Technology (siobhan.niklasson@student.nmt.edu)

POSTER 26

Successful Deployment of an 21km SMART Cable With Force-Feedback Seismometer and Accelerometers in the Mediterranean Sea

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Autonomous Ocean Bottom Seismometer (OBS) deployments pose a large degree of risk due to the inherent lack of data communication during installation resulting in 12+ months before data collection. Cabled solutions provide real-time data during deployment, sometimes with the opportunity to adjust the instrument before it is left to operate remotely. However, cabled solutions are inherently financially and logistically challenging both in terms of seismic hardware and arguably more significantly, deployment hardware (ships, ROVs, cables, etc.). The geographical reach of these experiments is also often limited to within a few hundred kilometers of the coast. These constraints often mean cabled OBS are beyond the scope of most scientific bodies.

Güralp Systems, in collaboration with INGV, has successfully manufactured and demonstrated a method of reducing financial and logistical constraints and extending geographical range by utilizing force-feedback seismic instrumentation in cabled OBS systems. The recent successful deployment of the InSEA Wet Demo SMART (Science Monitoring And Reliable Telecommunications) cable displays a world first in how science can partner with industry to achieve this.

SMART cables are primarily telecommunication cables that secondarily serve as hosts for scientific monitoring equipment. Commercial viability for

these systems relies on the cable being laid in a commercially standard manner, thereby minimizing additional deployment costs and reducing barriers to cooperation with cable laying companies. GSL and INGV deployed 3 seismometer-accelerometer pairs housed inline repeaters along the 21km cable length using standard cable-laying techniques to show proof of concept. The system also features a series of high-performance temperature and pressure sensors that can be used for larger-scale oceanographic monitoring.

This pioneering installation using telecommunication cables marks a significant step towards drastically improving local knowledge of inaccessible oceanic regions as well as global azimuthal coverage for teleseismic events, all in real-time.

POSTER 27

Using Deep Learning to Detect Vehicle Related Signals From Seismic Records

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In the interest of safety and security, it is imperative for research and industry facilities to effectively monitor vehicle movements within their premises. While cameras have traditionally been employed for this purpose, concerns over privacy and susceptibility to light or weather conditions have prompted the exploration of alternative technologies. Seismic sensors, due to their unobtrusive nature and ability to capture ground motions generated by vehicle movements, present a promising solution. To assess the feasibility of utilizing seismic sensors for vehicle detection, we conducted a comprehensive study. We deployed three sets of nodal-type seismic stations in proximity to a road at the main campus of Oak Ridge National Laboratory. Each station set was collocated with a camera to cross-reference and validate the data. The labels of detected vehicles were processed using the images recorded by the cameras. We then use these labels, along with the corresponding seismic signals, to train a deep learning model. Over the course of the station deployment, an extensive dataset comprising more than 500,000 seismic signals and labels was gathered. Using this dataset, we trained a deep learning model designed to categorize whether a seismic signal contains a vehicle-related signature or not. As the deep learning model can use either a seismogram or a spectrogram as input, we evaluated the model performance for both cases. The results show that using a spectrogram leads to better model performance. Our model achieved an impressive F1-score exceeding 0.9. These findings underscore the potential of seismic sensors as a valuable complementary tool for vehicle monitoring, offering a resilient and privacy-conscious alternative to camera-based systems.

POSTER 28

Monitoring Groundwater Using Ambient Seismic Noise

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The management of groundwater resources forms a crucial component of national policies. Different countries around the world are experiencing crises in groundwater availability as a result of a number of economic, social, and environmental conditions. Therefore, efficient management of groundwater resources is dependent on accurate knowledge and understanding of the behavior and variability of the aquifers. Such knowledge is often lacking or limited to sparse and highly localized information. This study focuses on analyzing ambient seismic noise recorded in two different geological environments: the island of Malta (central Mediterranean) and the Río de la Plata Coastal Plain (Argentina). The latter features partially interconnected coastal aquifers developed in thick sedimentary deposits. In contrast, the Malta hydrogeology is mainly controlled aquifers that occur in limestone rocks. In the Argentina case study, the analysis reveals two HVSR peaks, with the first one associated with the sediment-basement interface and the high-frequency one linked to a shallower stratigraphic discontinuity. Temporal analysis of the high-frequency peak highlights cyclical patterns correlated with estuarine levels, suggesting a relationship between variations in seismic velocities and tidal dynamics. Comparisons with aquifer data support this interpretation. For the Maltese island, variations in amplitude spectra which can be related to the variation of the upper water table. This work has been supported by DEMUWA project which is financed by the Malta Council for Science and Technology through the Space Research Fund (Building Capacity in the Downstream Earth Observation Sector), a program supported by the European Space Agency. Funds were also made available through the IPAS (Internationalisation Partnership Awards Scheme), funded by the Malta Council for Science and Technology.

POSTER 29

Influence of the Hurricane Otis on the Mexican Seismic Network

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The hurricane Otis became the most destructive meteorological phenomenon ever recorded in Mexico. Strong winds up to 300km/h caused intense damage to the coastal infrastructure causing disruption that lasted for several weeks. This unexpected event started as a tropical depression which evolved into a category 5 hurricane within an unprecedented short period of time. From October 24th, 2023 (03:00 local time) through October 25th (00:00 local time), the system evolved from a tropical storm to a category 5 hurricane, causing widespread damage in the port city of Acapulco. As the hurricane approached the coast, the low pressure induced low-frequency seismic waves that spread out across Mexico being recorded by several permanent seismic stations. In this study, we examine to which extent this low-frequency waves travel within the crust and the role that the geometry of the subducting slab played in the confinement of the energy.

POSTER 30

Glacier Seismology Application

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Seismology at glaciers and ice sheets has the potential to remotely track water flow and changes in the frictional properties of glacier and ice sheet beds. To better understand the frictional properties of the bed of the Greenland Ice Sheet and its response to meltwater input from the ice sheet surface, we installed an array of GEObit and other compact, posthole-type seismometers. Following 5 months of continuous operation, visited only once to redrill the sensors following melt out to the surface, the sensors were recovered. Both the GEObit and other sensors behaved comparably, recording tens of thousands of small (<M1) icequakes. While the majority of icequakes originated from shallow depths near the ice sheet surface, hundreds of these icequakes have characteristics consistent with an origin at the ice sheet base. We examined the spatial and temporal patterns of these icequakes to reveal the heterogenous frictional properties of the ice sheet bed.

In this work GEObit equipment was used for the seismic monitoring of the glaciers and they performed great. The sensors (C100 borehole seismometers) were placed into post holes of 1.5 5m depth drilled into the ice. The dataloggers (model Sri32 - older version of the GEOthree datalogger) were placed at the surface, into Peli type cases. The seismographs were able to get power from a small 35Ah battery and a small solar panel because of their low power requirements. The sensor bandwidth is 10sec to 98Hz and the sensitivity is 1500V/m/s. The digitizer uses high resolution 32bit ADC and up to 1000sps. The data are stored into a microSD card with capacity 32Gbytes, enough to store more than a year's data. The sensors left to operate unattended for several months, recording at 100sps. At the end of the recording period, the data were downloaded from the microSD cards to the computer for processing.

POSTER 31

Estimation of the Source Region of Secondary Microseism Generated by Pacific Typhoons Using CTBTO Seismic Arrays

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Secondary microseism (SM) or double-frequency microseism, observed worldwide around the 8-second period, is known to occur due to non-linear interaction of opposing oceanic wavefields of similar wavenumbers (Longuet-Higgins, 1950). Hence, monitoring SM can serve as a proxy for comprehending oceanic activities and contribute to a better understanding of couplings between the atmosphere, ocean and solid earth. However, there is a debate regarding whether SMs are predominantly excited near coastlines in shallow water regions or whether it is possible to generate SMs in deep-sea regions. In this study, we initially investigated variations in power spectral densities of SMs at costal and island seismic stations nearby the track of Pacific typhoons in 2022, as well as at Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) seismic arrays in Asia and Australia. We then compared these variations with the ocean wave model of Wave Watch III. The source regions of SMs recorded at CTBTO arrays were estimated through the triangulation method, utilizing back azimuths obtained from frequency-wavenumber analysis. These source regions were then compared with the best track data provided by the Joint Typhoon Warning Center (JTWC).

POSTER 32

Global Observation of an Up to 9 Day Long, Recurring, Monochromatic Seismic Source Near 10.9 mHz Associated With Tsunamigenic Landslides in a Northeast Greenland Fjord

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We report the discovery of an unprecedented, monochromatic low-frequency seismic source arising from the fjords of North-East Greenland. Following a landslide and tsunami event in Dickson fjord on 16 September 2023, seismic waves were detected by broad-band seismometers worldwide. Both frequency and phase velocity of the waves are consistent with fundamental mode Rayleigh- and Love-waves. However, the decay rate of these waves is much slower than predicted for freely propagating surface waves. Therefore, we infer a long-lasting and slowly decaying source process. Although the 16 September 2023 event was by far the largest, analysis of historical seismic data has revealed five other previously undetected events, all with a fundamental frequency between 10.85 and 11.02 mHz. Of these six events, the signal of the largest two events initially decayed with a quality factor, Q close to Q=500. This increased to Q=3000 within the first 10 hours and could thus be detected for up to nine days. The smaller four events had a slow decay-rate (Q>1000) for their entire duration. In comparison, the global average attenuation of Rayleigh waves at these frequencies is Q=117 for PREM, thus precluding a single, impulsive source for these signals.

Gleaning archives of optical and SAR satellite images reveals that at least four of the six events could be temporally correlated with landslides in Dickson fjord. However, such rapid transient events cannot explain the long duration of the radiated seismic waves. Our modelling of the largest event shows that a transversal seiche in Dickson fjord, excited by a landslide induced tsunami, can account for both the monochromatic low frequency signal as well as its seismic signal amplitude and radiation pattern. However, our seiche modelling indicates that the seiche should have Q < 250. Therefore, it remains unclear what keeps the seiche going for the entire duration of the observed seismic signal. However, the phase coherence of the VLP signal leads us to conjecture that an undetermined, in-phase, force feedback mechanism may be at work to continuously add energy into the system.

POSTER 33

Exploration of Decadal Crustal Velocity Changes Associated With Tidal-Induced Strain Using Seismic Noise

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Earth's tide modulates the volumetric strain within the subsurface that impacts groundwater level. Through *in-situ* measurement in a well, it is possible to deduce hydrological response (i.e., permeability) by analyzing the time lags between predicted tidal forces and the corresponding changes in water levels. In this presentation, we explore a non-invasive, single-station method to understand the capability of monitoring subsurface permeability using a decade of continuous seismic data from northern Chile. We extract coherent wavefields by 6-component noise correlation at a single station. The velocity variations are measured with a 30-minute resolution based on the changes in the coda wavefields of correlation functions at frequency range of 3–7 Hz over time. The seismic velocity reflects subsurface elasticity and is sensitive to ground motion, precipitation, pressure and temperature changes. Our decade-long, time-lapse velocity variations exhibit diurnal and semidiurnal cycles likely influenced by solar tides and radiation. Furthermore, we observe a robust semidiurnal cycle related to lunar tides, *M2*. The *M2* cycle is expected to exclusively link to volumetric strain modulation and free from effects of thermal strain. Therefore, our discussion will center on the potential hydrological implications specifically focusing on the observed lunar tides cycle.

POSTER 34

Resolving Temporal Variations in Subsurface Velocity and Attenuation Structure Across the Taklimakan Desert Using Road Traffic Seismic Signals

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Monitoring temporal changes in subsurface structure is crucial for interpreting how the Earth's media interacts with factors such as temperature, fluids, and stress. In this study, we resolve the temporal variation of velocity and attenuation in the Taklimakan Desert using traffic-induced ground motions recorded by three broadband seismographs located near highways. We first compute the H/V spectral ratios of the 3-component data and track the swings of the peaks and valleys to estimate the velocity changes. To characterize Q-values, we then model the vertical spectra of ballistic waves generated by massive road traffic events. The results reveal temporal variations in the sand subsurface, with velocity changing by up to 4% and Q-value by up to 10% in the frequency band of 10-45 Hz. These changes show a positive correlation with seasonal temperature fluctuations but are negatively modulated by local precipitation with negligible lags. This suggests that changes in the cohesion of the shallow sand layer are primarily induced by thermoelastic strain and fluid effects.

From Earthquake Recordings to Empirical Ground-Motion Modelling

Oral Session • Thursday 2 May • 8:00 AM Pacific

Conveners: Carlo Cauzzi, ORFEUS, Swiss Seismological Service, ETH Zürich (carlo.cauzzi@sed.ethz.ch); Fabrice Hollender, CEA Cadarache (fabrice.hollender@cea.fr); Vincent Perron, CEA Cadarache (vincent.perron@cea.fr);

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From Satellites to Soil Response: Analyzing Body Wave Velocity Variations at Shallow Depths in Sync With Satellite Soil Moisture

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Several recent studies have shown that the cyclicity of meteorological seasons is imprinted as time variations in the velocity of shear waves, V_S, at shallow depths. This has been known for decades from laboratory tests but has only recently been verified using actual earthquake records. However, this dependence has not been sufficiently studied to understand its implications for geotechnical soil characterization or even soil response during earthquake shaking. In this direction, we study 1218 earthquake records from the ARGONET vertical array of accelerographs located on the Island of Cephalonia, Greece. The data, which are publicly available at https://argonet-kefalonia.org/data/argonet_data/, cover the period from June 2015 to October 2022, i.e., they are distributed over more than seven complete hydrological cycles. We apply the method of seismic interferometry by deconvolution to study the variations of both V_S and P wave velocity values (V_P) at different depth intervals corresponding to different station pairs of the vertical array. We compare results with satellite soil moisture data from the Soil Moisture Active Passive (SMAP) mission of the National Aeronautics and Space Administration (NASA), and with data from the European Centre for Medium-Range Weather Forecasts (ECMWF) in the framework of Copernicus Climate Change Service. The accuracy of the satellite soil moisture data for such a site-specific analysis is verified by comparisons with in-situ data from the meteorological and soil moisture monitoring stations of the ARGONET infrastructure. Our results confirm the already known seasonal variation of V_S and show a similar pattern for V_P, which is inversely correlated with the amount of water in the shallow soil layers. Satellite soil moisture data are found to be highly comparable to in-situ measurements, which is particularly encouraging for using them to study the interactions between meteorological factors and soil response during earthquake shaking not only at regional, but also at local scales.

Seeking for Dependencies of the High-Frequency "Kappa" Parameter of Earthquake Spectrum on Weather/climate Conditions

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Nowadays the influence of a site's surface geological conditions on earthquake ground motion is well known. Several techniques have been proposed and applied at many sites around the world evaluating their so-called Site Amplification Factor (SAF), as well as their high frequency decay empirical factor, kappa-zero (κ_0). SAF and κ_0 control the ground motion and its simulation at a site, and they are considered significant for reliable seismic hazard assessment. Toward understanding the factors that can shape the high-frequency part of the earthquake spectrum, we investigate the existence of seasonal patterns in the variation of the Standard Spectral Ratio (SSR) and delta kappa ($\Delta\kappa \sim \Delta\kappa_0$) of the CK0 surface station of the ARGONET vertical array of accelerometers (Cephalonia Island, Greece), installed on top of sedimentary layers, with respect to the CK83 borehole station, installed in the bedrock at ~83m depth. The SSR and $\Delta\kappa$ factors have been computed based on acceleration records of 964 earthquakes that have been recorded by the ARGONET array over a period of ~7.5 years. We detect and quantify the seasonal variation of these two factors, which clearly reflect the similar variation of the corresponding SAF and κ_0 factors of the CK0 station, reasonably considering that there is no weather effect at the depth of the reference station. Based on the SSRs, seasonal variation is clearly observed in the horizontal motion of CK0, but only in the high frequency range of 17-34Hz. A seasonal pattern is also observed in the vertical component of CK0, albeit in the even higher frequency range of about 40-55Hz. $\Delta\kappa$ is subsequently determined at 4 different frequency ranges (f_e to f_{end}), for f_e=6 and 10 Hz and f_{end}=25 and 35Hz. As expected, $\Delta\kappa$ bears the seasonal variation observed in the SSRs. Our results confirm the well-known dependence of κ on the frequency range used for its measurement and suggest that one of the reasons for this dependence, at least in soft soils, is the seasonal variation of their response associated with changes in their water content and possibly other weather/climate related factors.

Beyond Site Response: On the Importance of Installation Depth on the Quality of Seismic Recordings - Example of Measurements Carried Out at Epos-France Seismological Network Stations

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Recording ground motions is essential to estimate the seismic hazard. Signals from the databases are often considered to be in free-field, i.e. at the natural surface of the ground, without disturbances due to buildings or neighboring structures. Nevertheless, analysis of the seismological networks has highlighted the coexistence of numerous installation methods, and in particular the depth of installation (station installed in post-hole, in tunnel, in the basement of buildings…). We present results obtained at several sites, mainly Epos-France seismological stations, belonging to the French accelerometric (RAP) and broad-band (RLBP) networks.

At these sites, we set up temporary surface stations placed vertically above the deep permanent stations. We then calculated SSR ratios on signal segments corresponding to earthquakes. We observed strong signal de-amplifications at certain frequencies due to destructive interference between upgoing and downgoing waves. These effects are visible at high frequencies from very shallow depths (sometimes even less than one meter in the case of soft soils). We discuss the importance of these effects on the use of depth-recorded signals for ground motion parameters and magnitude estimation. We also draw attention to the disadvantages of using these stations as reference stations if no corrections are made (e.g. as part of the application of the generalized inversion method - GIT).

Perturbations of Free-Field Seismic Recordings Caused by Soil-Structure Interaction, From the Effects of Buildings to the Impact of Coupling Slabs: Preliminary Results From Empirical Studies Carried Out in Greece.

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A proper and reliable measurement of ground motion is essential for an accurate estimate of seismic hazard. Current ground motion databases used to develop Ground Motion Models (GMM) rarely provide information about the station housing and sensor installation conditions. Therefore, users often assume these sensors are installed in free-field condition, i.e. at the natural surface of the ground without disturbances related to nearby buildings or structures. Nevertheless, analysis of information collected from seismological networks worldwide has highlighted a large variety of sensor installation modalities, including the housing typology and seismometers coupling. Recent studies have shown that different installation conditions can have a significant impact at high frequencies on the recorded motion, in comparison with true free-field measurements. This study focuses on the impact of soil-structure interaction at different scales. First, the effect of buildings is

addressed by analysing ground motion recorded by sets of sensors installed inside and very close to structures hosting several Greek key accelerometer stations, with respect to free-field measurements. Moreover, those buildings are founded on different types of soil. We observe that the effect of the soil-structure interaction is more significant on soft sites, than on stiff to hard rock ones. Second, and at a smaller scale, we investigate the impact of soil-sensor coupling. To this aim, within the framework of the "ArgoSlab" experiment led in Argostoli on Kefalonia Island, Greece, about thirty seismometers have been installed (i) on concrete slabs of different size and shape, (ii) on seismic pillars, (iii) inside manholes, (iv) outdoor or sheltered, and then compared to free-field stations' recordings. To provide a reliable interpretation, our process has been based on both earthquake recordings and ambient noise in each case. Our results show amplifications (e.g. pillars installations) or deamplifications (e.g. stations in manholes) that can be significantly greater than a factor of 3 at certain frequencies, depending on the type of installation.

Seismic Station Installations and Their Impact on Recorded Signals and Derived Quantities

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The role of local geology in controlling ground motion has long been acknowledged. Consequently, increasing attention is paid to the assessment of the geophysical properties of the soils at the seismic stations, which impact the station recordings and a series of related quantities, particularly those referring to seismic hazard estimates and response spectra at low periods.

Not the same level of attention is dedicated to the seismic station installation, to the point that it is generally believed that housings and shelters containing seismic instruments are of no interest, because they can only affect frequencies well above the engineering range of interest.

Using examples from seismometric and accelerometric stations, we describe the (1) housing, (2) foundation, and (3) pillar effects on the seismic records. We propose a simple working scheme to identify the existence of potential installation-related issues and to assess the frequency fidelity range of response of a seismic station to ground motion.

Our scheme is developed mostly on ambient noise recordings and, thus, surface waves. The hope is that, besides the parameters that start to be routinely introduced in the seismic archives (VS30, soil classes, etc.), the assessment of the maximum reliable frequency, under which no soil–structure interaction is expected, also becomes a mandatory information.

In our experience, for some installation sites, the maximum reliable frequency can even be less than a very few hertz.

Three Relational Databases in Support of Model Development for Earthquake Hazard Products

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The U.S. Geological Survey (USGS)'s hazard products, including ShakeMap and the National Seismic Hazard Model, fundamentally rely on ground motion models (GMMs) provided by a broad community of developers. GMMs are needed for instrumental intensity metrics (IMs), macroseismic intensities (MI), and the relations that convert between them. The development and use of these models also require explanatory parameters such as earthquake moment magnitude, focal mechanism, site parameters (such as the time-averaged shear-wave velocity to 30-meters depth), depths to shear-wave velocity horizons, and surface geology. Given the global earthquake monitoring mission of the USGS National Earthquake Information Center, we are well positioned to provide many of the data and site parameters described above. We operate the "Did You Feel It?" system, which contains millions of MI records. We also maintain the Advanced National Seismic System Comprehensive Catalog (ComCat), which contains QuakeML (an Extensible Markup Language format for earthquake data) summaries of more than 2 million global earthquakes. Finally, our center leads the development of gmprocess, a software package used to process earthquake ground-motion data and generate IMs. Querying large numbers of QuakeML records from ComCat and associating them with IM/MI records is computationally intractable, as downloading QuakeML for many thousands of records and extracting information can take many hours. To facilitate the analysis of IMs, we are developing three relational databases for (1) instrumental IMs, (2) MIs, and (3) earthquake catalog data. The schema designs of these databases must capture all relevant information about each input data set such that users can efficiently access the information necessary to address a broad range of research and operational goals. By integrating these three databases with sources of site parameters such as surface geology, our goals are to (1) minimize time spent by researchers compiling data for engineering seismology studies and (2) optimize the process of model development to better support USGS earthquake hazard products.

A Magnitude Invariant Workflow for Automated End-to-End Ground Motion Processing

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The proliferation of seismic instruments, and associated explosion of ground motion data, will soon make it possible for ground motion models to compute the seismic hazard at site-specific scales. This exciting possibility, however, is hindered in part by the non-automated processing of ground motion time series for engineering applications. In this work, we used recent advancements in artificial intelligence and operator learning to address this bottleneck. Our ultimate goal is to develop a magnitude-invariant end-to-end workflow for automated ground motion processing. Here, we present two components of this work: P-wave arrival detection and time series denoising. Our P-wave arrival detection is based on the recently published algorithm PhaseNO; originally developed for continuous data, our implementation is tailored to strong motion events, detects the arrival of P-waves with a high degree of accuracy, and, as such can be used to identify time series with multiple events and evaluate whether they can be separated based on heuristic ground motion intensity criteria. The time-series denoising step is based on wavelet filter decomposition and short-time Fourier Transforms. Compared to filtering that relies on subjective criteria of choosing corner frequencies and accordingly limits the usable frequency range, denoising yields a much broader usable frequency range. Both P-wave arrival detection and denoising algorithms are evaluated on hybrid datasets of simulated noiseless and noise-contaminated broadband ground motions. The validated framework is applied to a strong motion dataset of magnitudes 3.0 to 7.1 events recorded between 2011 and 2021 in the Western United States containing approximately ten million three-component acceleration time histories. The fully parallel open-source workflow and processed time series will be made available to support ground motion model development efforts, such as the ongoing project NGA-W3.

Epistemic Uncertainty Associated to Parametric and Non-Parametric Git Results Related to Initial Parametrization and Target Region Dataset: Application on the Epos-France Database.

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Understanding ground motion behaviour and dependencies is essential for Seismic Hazard Assessment, and several approaches have been implemented such as the Generalized Inversion Techniques (GITs). They allow decomposing the Fourier amplitude spectrum of the seismic signal into the three main contributions of ground-motion: the source, the attenuation and the site response. However, these techniques rely on several initial assumptions, such as defining a geographical area where crustal attenuation is considered homogeneous or setting parameters necessary to run the inversions. These choices are not straightforward and can have non-negligible impact on the results, particularly in the case of a sparse dataset. Hence, it is necessary to assess epistemic uncertainty associated to results obtained by such approaches. To this aim, we perform sensitivity tests for two different GIT algorithms: one parametric (Grendas et al. 2022), where source and attenuation terms are constrained a priori using physical models, and one non-parametric (Oth et al. 2011), for which the physical models are fitted in post-inversion phase. These approaches are applied on the Epos-France database (Buscetti et al. in prep) containing recordings for M_l≥3 earthquakes that occurred in France and

neighbouring countries during the 1996-2021 period. First, plural inversions are performed in the Alps region (area with the largest number of recordings), where initial parameters vary. The results of these inversions allow us quantifying the epistemic uncertainties related to both, the inversion algorithm and the inversion parametrization on source parameters (M_w,f_c), attenuation parameters (Q,γ) and site terms, as well as to identify potential biases related to some inconsistent parametrizations. In a second step, the most coherent parametrization is used to perform inversions in different geographical areas of France, in order to discuss uncertainty relative to the chosen region and to illustrate the impact of the amount and quality of available regional data on the epistemic uncertainties associated to the GIT results.

Ground Motion Models Uncertainties and Variability: The Impact of Seismic Station Installation Conditions and Earthquake Catalog Quality

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In the framework of ground motion and seismic hazard assessment and particularly in low to moderate seismic activity regions, the use of locally recorded ground motions has recently gained in popularity, for example in adjusting existing Ground Motion Models (GMM) developed in other regions of the world or in developing non-ergodic models. However, in low-to-moderate seismicity regions as continental France, available ground motion recordings are mostly related to small magnitude earthquakes, for which the information associated to the earthquake source parameters (3D location and magnitude) is often affected by large uncertainties. Moreover, information about seismic station installation conditions (housing, type of soil-sensor coupling…) is most often lacking in ground motion databases worldwide, and ground motion developers generally assume that sensors are installed in free-field.

In this context, with the objectives of exploring possible biases and robustly characterizing GMM variabilities, this work illustrates the benefit of both, accounting for seismic station installation conditions and disposing of a good quality earthquake catalog in the development of empirical ground motion models. A simple GMM based on EPOS-France ground motion dataset (Buscetti et al., subm.) is developed exploiting available information on the sensor installation conditions and using earthquake catalogs of different quality. The results highlight that a significant portion of the site-related variability in GMMs is related to the impact of the variety of sensor installation modalities and that inaccuracies in the earthquake catalogs can be responsible for potential biases in GMMs event-related variability. Accounting for these metadata allows to improve the characterization of the GMM variability and, overall, to contribute to the improvement of seismic hazard studies accuracy in low-to-moderate seismicity countries.

Earthquake Ground Motion Insights From the USGS Lake Almanor, California, Aftershock Nodal Array Deployment

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We investigate both source effects, such as rupture directivity, and the effects of shallow geologic structure on site response, in a ground-motion analysis of aftershocks of the May 11, 2023, M5.5 and May 12, 2023, M5.2 Lake Almanor, California, earthquakes. The Lake Almanor earthquakes occurred near the 2013 M5.7 Canyondam earthquake sequence in the vicinity of Canyon Dam, an embankment dam on the north fork of the Feather River used for hydroelectricity generation. The 2023 M5.5 and M5.2 earthquakes both caused MMI 6 shaking and generated over 7000 and 1000 felt reports, respectively. On May 12, the U.S. Geological Survey deployed 34 nodal seismometers (nodes) around Lake Almanor in an approximately 40 by 25 km array that recorded more than 25 M > 2.5 aftershocks over the following 2 months at epicentral distances as small as 5 km and with dense azimuthal coverage. The nodes recorded continuous 3-component waveforms at a 2-ms sampling interval, and have been validated against permanent network seismic instrumentation. We use the USGS software gmprocess (Hearn et al., 2019) to perform quality control, apply filters and baseline corrections, and to compute waveform intensity measures (IMs) from the recorded nodal data and data from regional seismic networks. We compute residuals between a ground-motion model and the observed IMs, and then partition them into components representing repeatable source, path, and site effects. We utilize the azimuth distribution of stations to investigate rupture directivity effects and the correlation of path and site effects with the regional geologic structure. We leverage information about path and site effects from the recorded aftershocks to improve our understanding of the M5.5 and M5.2 earthquakes. Results from this analysis could be used to improve seismic hazard characterization for infrastructure in the Lake Almanor region.

Ground Motion and Entropy

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How ordered is earthquake ground motion? We examine this question through the framework of entropy, a concept from information theory that measures the uncertainty or disorder in a set of data. For example, a lower seismic entropy implies a higher certainty of specific ground motion levels occurring, whereas higher entropy levels could indicate more complex source, wave propagation, and site effects, leading to increased uncertainty in shaking predictions. Here, we seek to quantify the entropy of both ground motion phase and amplitude. To do so, we discretize 3-component acceleration waveforms in a spherical coordinate system, where each (East, North, Vertical) time sample is mapped to a pixel on a sphere of radius norm(E, N, Z). We partition all acceleration waveforms, from a data set containing ~18,000 earthquakes, 1.3 million waveforms, and ~10 billion total samples, recorded by the Japanese National Research Institute for Earth Science and Disaster Resilience (NIED) K-NET and KiK-net networks from 1997–2023, into logarithmically-spaced amplitude bins and equal-area pixels distributed over a sphere. We calculate entropy as S = -sum(P * log P), where P(bin) is the probability of a ground motion sample (E,N,Z) being in a particular amplitude bin or pixel. We find that ground motion amplitudes have lower entropy, or more order, than phases. Physically, this means ground motion amplitudes concentrate at levels far below the peak ground acceleration, whereas phases more evenly sample the focal sphere, though we observe peaks in phase angles near +-90 and 0 degrees polarity, coinciding with expected polarities of P-waves and S-waves, respectively. Our entropy calculations could aid in the generation of realistic ground motions, especially for the challenging problem of simulating physical high-frequencies.

Comparisons of Recent Prediction Models of Ground-Motion and Seismic Duration for Mexican Interplate and Intraslab Earthquakes Including the Vertical Component and V/H Ratios

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Ground motion prediction equations (GMPEs) are a key part of seismic engineering, since the peak ground accelerations (PGA), peak ground velocities (PGV) and spectral pseudoaccelerations (SA) are used to determine seismic intensities that engineering structures are expected to be subjected to under certain seismic scenarios. They are also employed for the so-called probabilistic seismic hazard assessment (PSHA) and are the basis of some provisions contained within seismic design codes. Predictive ground-motion duration models are not as common, although seismic duration is also a very relevant parameter to designing structural systems under seismic excitations. GMPEs and ground-motion duration models can be developed for the horizontal component, traditionally considered the most critical one in terms of seismic demands imposed to buildings, infrastructure and other engineering structures. However, recent literature points out the need for seismic prediction models for the vertical component, including the relation between seismic intensities from the vertical component and the horizontal component (V/H ratios). Recent GMPEs and duration models of the horizontal and vertical components of ground-motion for Mexico, based on updated databases which

include great earthquakes as the date coincidental 19 September 1985 and 2017 seismic events, are compiled and compared in this study. It is concluded that GMPEs and ground-motion duration models should be region-, mechanism-, site- and component-specific to be adequate for seismic engineering purposes. Salient findings of all the considered models are highlighted.

Using Proxies Obtained From Horizontal-to-Vertical Spectral Ratio to Reduce the Epistemic Uncertainty in Ground Motion Models

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The effects of site characteristics in ground motion models (GMMs) are usually predicted by shear-wave velocity of top 30 m (V_{S30}) or depth to 1.0 km/s shear-wave isosurface ($Z_{1.0}$). However, these parameters are limited to observations of the top 30m of the soil stratigraphy or inferred from models, respectively. Previous research showed that the horizontal-to-vertical spectral ratio (HVSR) technique can be used to estimate site fundamental frequency and its corresponding amplitude, which can, in turn, reduce uncertainties in GMMs. This study uses a large data set from the KiK-net strong motion network and presents a maximum-likelihood estimate of site fundamental frequency (f_{ml}) and its corresponding amplitude (A_{ml}) for 699 sites across Japan. First, ground motion recordings are selected and processed. The Fourier Amplitude Spectra and Response Spectra of the recordings are computed in this step. Second, the HVSR is calculated for the recordings. Then, fml and Aml are estimated for each site using previously developed methodology that is based on maximum-likelihood approach. The process of estimation is automated to diminish bias and quantify the uncertainty in the estimations. As a result, the estimated parameters (site fundamental frequency and the corresponding amplitude in the HVSR curve) are compared to an independent study in order to validate the automated approach and the maps for these parameters are presented. These additional parameters reduce the uncertainty (i.e., site-to-site variability) in estimates of response spectra by 2% to 19%, depending on the spectral period and the GMM used as a reference.

Are Ground Motions Different for Aftershocks or Earthquakes Doublets?

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As seismic hazard analysis moves away from the Poisson assumption, there is a need for ground-motion models for dependent events. We revisit the question of whether ground motion levels are systematically different between mainshocks, aftershocks, and earthquake doublets. Differing ground motion could imply inherently different source processes or interactions and is important for hazard and risk analyses. This question lingers, in part, due to how an aftershock is defined: in the NGA-West2 project, on-fault aftershocks, close in space and time to a corresponding mainshock, were singled out. Previous studies have shown that high-frequency ground motion (e.g., Abrahamson et al., 2014) and stress drop (e.g., Baltay et al., 2019) for these aftershocks is about 35% lower than mainshocks. This could be attributed to on-fault aftershocks re-rupturing weakened patches on the mainshock fault plane, and thus less efficiently generating high-frequency radiation. On the other hand, Abrahamson et al. (2014) found that ground motion for longer periods is larger for aftershocks, with the physical explanation outstanding.

We reevaluate these observations using recent stress-drop estimates and ground-motion observations over a range of periods, for the 2019 Ridgecrest sequence, the 2023 Turkiye sequence, and the NGA-West3 database, keeping the same aftershock definition as in NGA-W2. The M6.4 and M7.1 Ridgecrest, and M7.8 and M7.5 Turkiye doublets show no relative difference in ground motion between each of the two main events at any period, implying that interactions between these doublet events do not affect their generated ground shaking, and thus we should continue to treat them as independent events in ground-motion modeling. While smaller high-frequency ground motion for aftershocks is good news, it is important to consider these systematic disparities when developing non-ergodic ground-motion models from data that includes many aftershocks. If on-fault aftershocks truly have different source physics, giving rise to depleted or enhanced ground motion, this sheds light into stress interactions and fault asperities.

Why Did the Pulse-Like Ground-Motion Differ Three Times in Pgv and Tp Within a 3 Km Wide Near-Fault Region of the 2023 Mw 7.8 Turkiye Earthquake?

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Over 25 pulse-like velocity (VP) waveforms were observed in the near-fault region of the 2023 Turkiye Mw 7.8 earthquake, which were extracted by Shahi and Baker's (2014) method. The extracted pulse-like ground motions have a peak ground velocity (PGV) and pulse period (Tp) range of 25 to 184.2 cm/s and 1.8 to 15.6 s, respectively, which were in a distance range of rupture distance (R_{rup}) within 0.33 to 54 km. Significant intensity differences in the VP were observed at three stations within a 3 km wide near-fault region, Antakya, one of the major disaster regions, and observed as the second-largest PGV of the extracted VPs. The R_{rup} of the three stations is 0.33, 2.1, and 3.5 km for station codes 3126, 3123, and 3131, respectively. However, the corresponding extracted PGV and Tp showed a two- to three-times difference within the three stations from PGV of 119.9, 175.4, and 60.3 cm/s and Tp of 3.4, 2.6, and 13.2 s. This is difficult to explain by the median prediction of the modern nonergodic ground motion models. In this study, by removing a possible cause from the coseismic static offset (fling step), the directivity pulse is evaluated by the velocity-pulse simulation procedure (Huang et al., 2024), which is derived from the stochastic finite-fault ground-motion simulation method, a baseline correction method, and a fling-step removal model. The result indicated that the directivity pulse provides a 50 to 60 cm/s PGV, which was recorded by the rock site 3131 and enlarged two times from linear site response and recorded by the softest soil site 3126. The three times PGV observed at 3123 was generated by simultaneously linear site response and a super shear behavior at the near-source portion. The closest station, 3126, did not suffer the highest PGV in this region because of the soil nonlinearity in the latter portion of the S arrival. Finally, the longest 13.2 s Tp is caused by a 130 cm coseismic deformation from the fling-step, which occurred after the VP arrival and did not show an apparent longer period in the other two stations.

From Earthquake Recordings to Empirical Ground-Motion Modelling [Poster Session]

Poster Session • Thursday 2 May

Conveners: Carlo Cauzzi, ORFEUS, Swiss Seismological Service, ETH Zürich (carlo.cauzzi@sed.ethz.ch); Fabrice Hollender, CEA Cadarache (fabrice.hollender@cea.fr); Vincent Perron, CEA Cadarache (vincent.perron@cea.fr); Zafeiria Roumelioti, University of Patras (zroumelioti@upatras.gr); Paola Traversa, Electricite de France (paola.traversa@edf.fr)

POSTER 154

Frequency-Dependent Transfer Functions for Hydroseisms in Devils Hole

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Devils Hole is a highly sensitive aquifer system situated in southern Nevada that exhibits notable water level variations, referred to as seiches or hydroseisms, in response to significant seismic events worldwide. This study investigates the dynamic response of seiches in Devils Hole to ground displacement triggered by large earthquakes and aims to characterize the frequency-dependent transfer function governing the relationship between ground displacement and water level changes. We conducted a comparative analysis using USGS water level measurements recorded at a frequency of 0.2 Hz from multiple large seismic events that occurred between 2020 and 2021. These measurements were juxtaposed with long-period, three-component seismic data obtained from nearby seismic stations in Furnace Creek and Shoshone, California. Our analysis reveals that the hydroseismic activity is predominantly impervious to Love wave ground motion but is significantly influenced by Rayleigh wave motions, as well as subsequent wave reflections and refractions off the interior walls of Devils Hole.

We used a multi-filter analysis to derive Rayleigh wave dispersion curves from the water level data. We also applied spectral analysis techniques to discern the frequency characteristics of both ground motion and seiche signals. Preliminary findings suggest a repeatable frequency-dependent relationship between ground displacement and water level fluctuations in Devils Hole. For example, in the case of a 20-second Rayleigh wave with a 1 cm displacement, we observed a 20-second period of hydroseisms with an approximate displacement of 25 ± 10 cm. As the periods decrease below 20 seconds, hydroseism reflections from the interior walls of Devils Hole assume greater prominence in the signals, resulting in extended wave trains for water level fluctuations compared to the seismic Rayleigh waves. These outcomes contribute significantly to our understanding of aquifer response to seismic events. Ongoing research efforts include refining the transfer function analysis and further deepening our understanding of this captivating natural phenomenon.

POSTER 155

High Frequency Seismic Waves of Normal and Leaky Modes Excited by Heavy Trains

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Ambient seismic noise tomography has far-reaching applications from shallow sub-surface, regional, continental to global imaging scales over the past two decades. Recently, some individuals have successfully extracted both normal-mode and leaky-mode dispersion curves from high frequency seismic ambient noise recorded by dense seismic arrays using the frequency-Bessel (F-J) transform. These findings obtain more reliable Vs and Vp models by simultaneously fitting these two types of dispersion data, since normal-mode dispersion curves are more sensitive to Vs than Vp while leaky-mode dispersion curves are opposite. The influence factors, like the excitation sources and seismic velocity model, however, are not analyzed systematically in previous researches. Here we collect ambient noise recordings from a two-km long linear-shape seismic array laying along a railway track in New Mexico, the United States of America to process for obtaining hourly high-quality dispersion data by the F-J transform array stacking technique. We show that there is a strong positive correlation between the signal to noise ratios of dispersion curves of normal and leaky modes and the train traffic volume. This result tells us that we need to make full use of seismic noise generated by trains or even trucks to investigate the subsurface Vs and Vp structure utilizing dispersion data of normal and leaky modes, facilitating new findings for civil engineering.

POSTER 156

Progress on the Characterization of Epos-France Accelerometric (Rap) and Broad-Band (Rlpb) Network Station: Focus on Implemented Methodologies

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The characterization of seismological stations, whether they are broad-band or strong-motion, is essential for a better use of the databases. In particular, it involves determining several important proxies (such as the value of V_{S30}) or a complete velocity profile of S-wave propagation to the geophysical bedrock. We present the progress in the station characterizations carried out on the French seismological networks (RAP and RLBP), both in mainland France and the French West Indies. In addition to the results obtained, we present the acquisition geometries selected and the data processing applied, which is essentially based on MASW measurements to determine the dispersion curves of surface waves at high frequencies, and on FK-type processing applied to passive array data for intermediate and low frequencies.

Our acquisitions do not limit themselves to targeting a depth of investigation of 30 m for the sole purpose of determining the V_{S30} parameter. In most cases, the use of large array apertures (several hundreds of meters) let us characterize the depth and Vs of the seismological bedrock.

We also comment on the real improvements made possible by three-component FK approaches (e.g. RTBF, ARDS, ARTBF) proposed by Wathelet et al. (2018, 2024), compared with more conventional approaches (e.g. HRFK).

POSTER 157

Separation of Intrinsic and Scattering Seismic Wave Attenuation in the Crust of Central and South-Central Alaska

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Conducting a thorough analysis of seismic hazards is essential for evaluating the potential impact of earthquakes on both structural damage and loss of life in a given area, especially in regions like Alaska, known for frequent seismic activity. The precision of seismic hazard evaluations relies heavily on the dependability of ground motion prediction equations, which forecast the anticipated ground shaking at specific locations. However, in areas with notable disparities in crustal attenuation, such as Alaska, the reliability of these equations may be compromised. The average Lg Q in Alaska significantly surpasses that in the western U.S. and Canada, influencing seismic hazard assessments by affecting the magnitude and duration of ground shaking. Failing to consider these regional variations in crustal attenuation can lead to inaccurate hazard assessments.

To gain a deeper understanding of the underlying factors contributing to this issue, this research proposes the application of Coda Q analysis to investigate the roles of scattering and intrinsic crustal attenuation in central and south-central Alaska. The investigation will specifically target earthquakes with magnitudes ranging from 2 to 6.5, occurring within an epicentral distance of 20km to 200km between December 2014 and December 2020, with focal depths of less than 30km. Utilizing the Multiple Lapse Time Window (MLTW) method with the center frequencies ranging from 0.75 to 12.0 Hz, the study aims to distinguish between intrinsic and scattering crustal attenuation by analyzing seismic energy in three-time windows: 0-15 s, 15-30 s, and 30-45 s, measured from the S arrival. By analyzing the regionalized values of intrinsic and scattering attenuation and their frequency dependencies, the study aims to interpret the causes for regional variations of crustal attenuation of central and south-central Alaska. This understanding can potentially enhance geological and tectonic interpretations, ultimately leading to the refinement of ground-motion prediction equations applicable in seismic hazard assessments.

POSTER 158

How Can Shaking Observations From the MyShake Smartphone Platform Inform Free-Field Ground Motion Residual Estimates?

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Ground motion spatial variability can be significant, especially in short-period intensity measure metrics such as pseudo-spectral acceleration (PSA) at periods <1s and peak ground acceleration (PGA). As such, densifying data coverage could potentially reveal finer-level detail when modeling spatial distributions of ground shaking in individual events, as well as in ensemble empirical site response modeling. Acceleration waveforms recorded via the MyShake smartphone app provide one such dataset. MyShake has been delivering ShakeAlert earthquake early warning messages to the public since October 2019. It also provides recorded waveforms using the onboard accelerometer once triggered. This capability has enabled us to construct a waveform database that heavily samples the near-field (epicentral distances <30 km) for M3-5 events. Using MyShake data in California from 2019 to early 2023, we derive predictive models for smartphone-recorded peak accelerations, including one incorporating simple building corrections. Using our models, we calculate MyShake within-event residuals, and compare these to free-field residuals for PGA and 0.3 s PSA. We illustrate how these residuals illuminate small-scale structure in ground motion spatial trends in these, while also matching with independent empirical constraints of free-field site response. Finally, we discuss how MyShake residual correlation with free-field residuals could be used to reduce modeling uncertainties in schemes that model spatial distribution of ground shaking, such as ShakeMap.

POSTER 159

Estimating Hazard From Crustal Sources: An Empirical Observation Approach

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This study aims to estimate ground motion near the source. This estimation depends, at the very least, on factors such as the rupture type, the specific path of propagation, and site parameters. We employ an empirical approach based on the analysis of the Near Source Strong Motion database (NESS 2.0) (Sgobba et al., 2021). The empirical approach involves interpreting and plausibly estimating the main characteristics influencing rupture, which significantly modifies ground motions across various spectral periods in the near source. We estimate and compare Ground Motion Models (GMM) with intensity real data obtained from various tectonic regions and earthquake sources, assessing their residuals. Our analysis is structured into two parts. The first part focuses on individual parameters in each GMM for events with similar slip-rupture conditions. The second part involves a nested-residuals analysis, which can be initially divided into terms capturing effects not parametrized by GMMs.

The directivity effect causes shear-wave energy from all points on the fault to arrive at nearly the same time at the station in the direction of the rupture's propagation. Similarly, rupture velocity increases ground motion as the radiation for each point into the fault occurs faster, arriving at the station in a shorter time interval (Aagard et al., 2001). The significance of hypocentral depth lies in its control over the radiation pattern (Dujardin et al., 2021). Additionally, the depth of the top of the rupture influences slip behavior; as it deepens, fewer slips (shaking) occur in the softer surface material of the media (Aagard et al., 2001). Conversely, seismogenic depth determines the potential area involved in the rupture, as significant earthquakes (greater than ~6) typically nucleate at the base of the seismogenic layer, rupturing the entire seismogenic crust in depth (Scholz, 2019). This influence extends to the earthquake size.

POSTER 160

Multi-Resolution Basin Terms for Ground Motion Models in Central and Eastern North America

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Current ground motion models (GMMs) in Central and Eastern North America (CENA) rely on the time-averaged shear-wave velocity in the upper 30 m of the site (V_{S30}) as the primary site variable. Prior to recent publications (Boyd et al., 2023), sediment thickness and basin terms have not been consistently available in CENA. In recent years, CENA has seen an increase in the volume and resolution of ground motion datasets including recently published datasets like the Central and Eastern U.S. Earthquake Ground Motion Database: 2010 to 2020 (Thompson et al. 2023) which builds on previously published ground motion data such as NGA-East (Goulet et al, 2014). At the same time, new geologic, and geotechnical datasets such as and the Atlantic and Gulf Coastal Plains Sediment Thickness model (Boyd et al., 2023) and the UCLA Shear-wave Velocity Database (Kwak et al., 2021) have also been developed. The goal of this work is to integrate these datasets along with additional geospatial datasets to define a set of multi-resolution basin and site effect terms for use in CENA for ground motion modeling. By integrating these datasets, as well as other geospatial variables including basin geomorphology and geology, we gain a better understanding of path and site effects in CENA, with a specific focus on observed and simulated basin amplification of long-period ground motions (T > 1 s). The proposed multi-resolution basin terms combine surficial geology, geomorphologic basin classifications, sediment thickness data, hydrologic data, and geotechnical data, to create a spatially continuous basin term for use in GMMS in CENA. Linear mixed-effects regression will be used to decompose GMM residuals to investigate complex basin, site, region, and geology effects in CENA using the dataset, with a goal of reducing epistemic uncertainty in future CENA ground motion prediction.

POSTER 161

The Effect of Short Wavelength Topography on Seismic Recordings: Results of Experiments Conducted on Kefalonia Island in Greece.

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In recent years, seismological networks around the world have been considerably expanded, enabling the creation of databases with a rising number of earthquakes. Nevertheless, the description of the installation conditions of seismological stations are often missing from the networks metadata. In most cases, Ground Motion Models (GMMs) developers assume that these stations are in free-field conditions, i.e. located at the natural surface of the ground without nearby disturbing structures. However, the investigation of seismological networks has revealed the coexistence of many different installation methods, including, for instance the coupling of seismometers, housing of permanent stations, or the installation of some stations at the foot of a scarp. Recent studies have also shown that these installation conditions can have a significant impact on the recorded motion, compared with true free-field measurements. Among these various installation methods, this study takes a particular interest in the effect of topography at short wavelengths. To this end, an experiment has been conducted on Krani Hill on Kefalonia Island in Greece. Ground motion recorded at sensors installed along a profile going from the foot to the top of a cliff of about twenty meters high, are compared among them and with respect to a reference site. Other seismometers have been set up along the cliff, top and bottom, to analyze a potential polarization effect. Recordings of earthquakes and ambient noise have been studied to provide the most possibly comprehensive analysis. The results show a slight amplification of the signal at the top of the cliff and a clear de-amplification at its foot. The clearest effect is a marked polarization of the signal near the scarp.

POSTER 162

Geospatial Variable Based Site Terms for Nonergodic Ground Motion Models

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This work presents a non-ergodic site response model for California for use with the Boore, Stewart, Seyhan, and Atkinson (2014) (BSSA14) ground motion model (GMM), using geospatial variables. Geospatial variables such as elevation, water table depth, soil thickness, and distance to the coast have been found to capture the spatial pattern of geologic deposits (Wald and Allen, 2007; Zhu et al., 2015), and have been used to develop geospatial liquefaction models (Zhu et al., 2015; 2017). At the same time, ground motion databases have grown in recent years, making it possible to better capture the complexity of site effects spatially, and as a result, quantify the repeatable effects that local surface geology has on ground motion intensity. This project uses the DesignSafe Ground Motion database (Ji et al., 2022) for the state of California, containing over 57,000 ground motion recordings paired with geospatial variables as additional site terms beyond $Z_{1.0}$ and V_{S30} (e.g. elevation, depth to water, soil thickness, surficial geology). Ground motion residuals are calculated for the database between the observed peak ground accelerations (PGA) and the BSSA14 predicted PGAs, which uses V_{S30} as the primary site response parameter. Mixed effects regression is performed on the residuals using geospatial explanatory variables to partition the residual, in order to produce updated site terms that account for the corresponding influence of the geospatial variables. The developed non-ergodic geospatial site terms result in a reduction in inter-site residual variability for PGA values, when compared to the conventional V_{S30} based site terms. The development of a non-ergodic site term for use in California using geospatial variables highlights the predictive power of geospatial data and accounts for its impact on ground motion intensity.

POSTER 163

NGA-Subduction Region-Specific Ground Motion Models Using Machine Learning Algorithms

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In this study, we derive data-driven ground motion models (GMMs) on a global scale and region-specific basis for subduction earthquakes. We employ a weighted average ensemble model that combines four distinct nonparametric supervised machine learning algorithms: Artificial Neural Network, Kernel-Ridge Regressor, Random Forest Regressor, and Support Vector Regressor. To accomplish this, individual models are trained using a subset of the NGA-Sub dataset, comprising 9,559 recordings from 153 interface and intraslab earthquakes recorded at 3,202 different stations. Hyperparameter optimization is carried out through a grid search for each model. Subsequently, the four models are combined using an equal-weighted average ensemble approach, leveraging ensemble modeling to capitalize on the strengths of diverse machine learning algorithms and mitigate their respective weaknesses. The ensemble model incorporates moment magnitude, rupture distance, V_{S30}, Z_{TOR}, tectonic, and regional parameters as input variables. GMMs predict horizontal component ground motion intensity measures, including PGD, PGV, PGA, and 5%-damped PSA values at spectral periods ranging from 0.01 to 10 seconds in a logarithmic scale. While no specific functional form is defined, the response spectra, as well as the scaling trends for distance and magnitude in the weighted average ensemble model, are consistent and comparable to the other NGA-Sub GMMs, but with slightly lower standard deviations.

To analyze variability, a mixed effects regression is employed to partition total aleatory variability into between-event, between-station, and event-site-corrected components. The resulting global GMMs are applicable to interface earthquakes with magnitudes ranging from M4.9 to M9.12, rupture distances from 14 to 1,000 km, and Z_{TOR} values up to 47 km for sites with V_{S30} values between 95 and 2,230 m/sec. For intraslab events, the global GMMs are applicable to magnitudes ranging from M4.0 to M8.0, rupture distances from 28 to 1,000 km, and Z_{TOR} values from 30 to 200 km for sites with V_{S30} values between 95 and 2,100 m/sec.

POSTER 164

Ground Motion Models Using Machine Learning Techniques Based on the NGA-West2 Data

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In this study, we derive ground motion models (GMMs) for the average horizontal component resulting from shallow crustal continental earthquakes in active tectonic regions by analyzing a subset of the NGA-West2 dataset. This subset encompasses 14,518 recordings from 285 earthquakes recorded at 2,347 different stations. Constructing these models involves employing four nonparametric supervised machine learning (ML) algorithms: the Artificial Neural Network, Kernel-Ridge Regressor, Random Forest Regressor, and Support Vector Regressor, each producing an individual model. Then, a weighted average ensemble approach is employed to merge these four models into a robust unified model for predicting various ground motion intensity measures, including peak ground displacement, peak ground velocity, peak ground acceleration, and 5%-damped pseudo-spectral acceleration. The model incorporates moment magnitude, rupture distance, V_{S30}, and Z_{TOR} as input parameters.

The ensemble modeling strategy seeks to reduce drawbacks or deficiencies inherent in different ML algorithms while leveraging their advantages, and thus, addressing epistemic uncertainty. Despite the absence of a predefined functional form, the model effectively captures prominent features observed in ground motions, such as saturation, geometrical spreading, anelastic attenuation, and nonlinear site amplification. The response spectra and scaling trends related to magnitude, distance, V_{S30}, and Z_{TOR} are consistent and comparable with the NGA-West2 GMMs, which include several additional input parameters. A mixed-effects regression analysis is applied to divide the total aleatory uncertainty into between-event, within-station, and event-site-corrected components. The model applies to earthquakes with magnitudes ranging from 3.0 to 8.0, rupture distances extending up to 300 km, and spectral periods spanning from 0 to 10 seconds.

POSTER 165

Developing a Hybrid Ground-Motion Modeling Framework for the Himalayan Region of India

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In addressing the challenge of ground-motion modeling in the Indian context, where unavailability of recorded ground-motion data for the scenarios that dominate hazards across the major urban centers within the Indo-Gangetic plains is scarce, it poses a significant challenge. To overcome this limitation, conventional practice involves the utilization of ground-motion models (GMMs) calibrated on data from regions like California and Japan. To mitigate this issue, we develop a hybrid ground-motion modeling framework in which adjustments in global GMMs are performed to account for the differences in seismological characteristics such as anelastic attenuation and stress drop. Initially, we employ a strong-motion dataset from small-to-moderate magnitude events to derive seismological parameters aligned with the tectonic conditions of the study area (northern part of India). This involves a generalized inversion of Fourier spectral ordinates for the study region. In the next step, these parameters are adjusted with the magnitude and distance scaling of the global GMMs in the Fourier spectral domain. The adjusted Fourier spectra are then converted to response spectral ordinates using random vibration theory. Our analysis is based on a recently compiled and uniformly processed strong-motion dataset for the Himalayan region, comprising approximately 190 earthquake events with 798 records, where moment magnitudes (Mw) exceed 3 and recorded distances (REpi) less than 500 km. To illustrate the effectiveness of our proposed framework, we demonstrate its application using a host GMM (calibrated on the NGA-West2 database) for Fourier spectral ordinates (Bora et al., 2019). For comparative purposes, we also incorporate a response spectral GMM (Chiou and Youngs, 2014) into our study.

POSTER 166

Domain Confusion in Dispersions Picking Based on Neural Network and the Learning Features From Dispersion Spectrograms

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Ambient noise tomography has been widely used to obtain the shear-wave velocity for underground structure of the Earth, and there is a key point in dispersion spectrogram where people need to pick dispersion curves manually. By the frequency-Bessel (F-J) transform, the dispersion spectrogram not only provides reliable fundamental dispersion curve, but also rich higher modes of dispersion curves. However, manual picking will consume much time and energy for researchers. Consequently, using neural network to pick dispersions automatically has great significance. In the field of computer vision, the feature of data from different source domains has a certain degree of difference. If we ignore these differences in the data, the trained neural network will have an issue of data limitation, and the performance will be weak. By analyzing lots of dispersion spectrograms, we have summarized the learning features of neural network from spectrograms. In addition, based on our findings we have applied domain confusion in training and testing neural network. After domain confusion, we can make one neural network learn dispersion spectrograms from multi sources, and its performance is stronger than before. The trained neural network can effectively process large number of test data and help us easily obtain more dispersion curves automatically. The proposed study can provide a deep insight into the denoising of dispersion spectrograms by neural network.

POSTER 167

Monitoring Temporal Velocity Variations of Shallow Subsurface and Engineering Structures Using 6c Single-Station Measurement

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Monitoring seismic velocity variations offers valuable insights into near-surface processes like soil compaction and groundwater changes, aiding environmental studies. In engineering, these variations can indicate structural damage in buildings, bridges, dams, and tunnels. Continuous monitoring helps identify potential risks, enabling preventive maintenance and ensuring safety and resilience of structures. In this study, we propose a six-component (6C) single-station measurement. The proposed method relies on the joint analysis of translational and rotational ground motion recordings obtained from a collocated seismometer and rotational sensor. This innovative approach merges the capabilities of a small-scale seismic array with the cost-efficiency of single-station surface measurements. It enables the extraction of seismic velocities from both active and passive seismic sources. Unlike cross-correlation-based seismic interferometry methods, such as ambient noise tomography, the proposed measurement does not rely on the theoretical assumption of the equipartition of noise sources, which is normally not satisfied in practice. More significantly, the used amplitude-ratio-based algorithm for proposed measurement will suppress the influence of seismic sources and mitigate the wave propagation effects, making the method more sensitive to near-receiver subsurface structures. The proposed measurement ensures near-receiver sensitivity and repeatability, allowing for the detection of small perturbations in the subsurface and engineering structure properties even in dynamic environments with changing noise sources. As a result, the proposed measurement is well-suited for monitoring site-specific seismic velocity variations. We verified the efficacy of the proposed 6C measurement through both synthetic and real-world examples, including near-surface and engineering applications.

From Faults to Fjords: Earthquake Evidence in Terrestrial and Subaqueous Environments

Oral Session • Wednesday 1 May • 8:00 AM Pacific

Conveners: Danny Brothers, U.S. Geological Survey (dbrothers@usgs.gov); Tina Dura, Virginia Polytechnic Institute and State University (tinadura@vt.edu); Jenna Hill, U.S. Geological Survey (jhill@usgs.gov); Kristin Morell, University of California, Santa Barbara (kmorell@ucsb.edu); Belle Philibosian, U.S. Geological Survey (bphilibosian@usgs.gov); Derek Sawyer, Ohio State University (sawyer.144@osu.edu); Drake Singleton, U.S. Geological Survey (dsingleton@usgs.gov); Katleen Wils, University of Innsbruck (katleen.wils@uibk.ac.at); Rob Witter, U.S. Geological Survey (rwitter@usgs.gov); Mark Zellman, BGC Engineering, (mzellman@bgcengineering.ca)

Effect of Marine Reservoir Variations on the Temporal Correlation of Earthquake Evidence on the Central and Southern Hikurangi Subduction Zone

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A key question in New Zealand subduction zone hazard studies is if, or how often, the Hikurangi subduction zone ruptures both the central and southern parts of the subduction zone vs just southern section ruptures. To address this we rely on the temporal correlation of different types of earthquake and tsunami evidence from widely spaced sites. At several key sites the radiocarbon chronologies are constrained by terrestrial radiocarbon dates but at most, particularly marine terrace and paleotsunami sites, the chronology is dominated by marine radiocarbon ages. Calibration of the marine radiocarbon ages combines the marine calibration curve and a local marine reservoir offset (ΔR). Changes between versions of the global marine calibration curve (Marine20 vs Marine13 curves) have minimal impacts on modeled earthquake ages. However, over the past 3 years we have undertaken a study of marine reservoir variation around New Zealand and find regional differences in ΔR of up to 100 years. Focussing on the Hikurangi subduction zone, where marine reservoir measurements have increased from 14 to 45, we found an average ΔR for the whole margin is appropriate, rather than subdividing the margin as we have previously done. However, marine radiocarbon ages should not be acquired from two subduction paleoearthquake sites with limestone catchments or from molluscs from some particular environments. Overall it would be ideal to eliminate marine radiocarbon ages from the paleoearthquake chronologies as the uncertainties on individual ages are large but few alternative geochronology tools exist at many study sites. As we incorporate offshore turbidite ages from the central Hikurangi subduction zone into the margin-wide compilations of paleoseismology, understanding the offshore marine reservoir becomes increasingly important. The new marine reservoir values call for a re-evaluation of paleoearthquake temporal correlations, and examination of evidence for central and southern Hikurangi subduction zone ruptures.

An 8000-Year Holocene Earthquake Record From the Northern Cascadia Forearc: Evidence for Multiple Sources at Lake Crescent, Washington

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Lake Crescent is a deep, steep-sided lake within the forearc of the northern Cascadia subduction margin on the northern Olympic Peninsula in western Washington. Like other lakes worldwide, Lake Crescent's stratigraphy points to an earthquake-recording sensitivity that depends on the climate, sediment accumulation rates, and shaking intensity. Starting about 8,000 years ago, two distinctive types of event deposits began to accumulate in the lake. Four meter-scale mass transport deposits resulted from multiple large mass failures on subaerial and subaqueous slopes triggered by ruptures along the North Olympic Fault Zone beneath the lake. On the other hand, twenty decimeter-scale turbidites correlate to much smaller mass failures on the lake's subaqueous slopes. The turbidites have age ranges that overlap with regional offshore and onshore paleoseismic records, including those derived from deep-sea turbidites, Vancouver Island lakes and fjords, and Cascadia salt-water marshes. While these correlations suggest that most of the Lake Crescent turbidites formed during great Cascadia subduction earthquakes, we cannot rule out that some had other sources, including nearby crustal faults. Importantly, deposits correlative to two regional earthquakes that multiple researchers postulate to have occurred at the subduction interface around 500-600 and 800-900 years ago are absent to poorly developed at Lake Crescent but are represented in the stratigraphy of Ozette Lake, located 60 km to the west of Lake Crescent and closer to the subduction trench. The differences between these two lakes suggest that shaking during these subduction zone events was sufficiently attenuated in the landward direction so that Lake Crescent's underwater slopes were minimally affected. Additionally, no turbidites formed in Lake Crescent in the 324 years since the last great subduction zone earthquake of 1700 CE, implying that shaking from crustal earthquakes has not exceeded the necessary local threshold for turbidite emplacement during this period.

Variations in Mass Transport Deposits That Record Strong Ground Motion Events in Western Prince William Sound, Alaska

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The fjords of Prince William Sound (PWS) overlie the westernmost Alaska-Aleutian subduction zone, including the epicentral region of the 1964 M_w 9.2 Great Alaska Earthquake. In 1964, intense shaking generated widespread destabilization and failure of submerged fjord sediments, which in turn generated devastating tsunamis that impacted several coastal communities in PWS. While sediments in some fjords failed catastrophically in 1964, others did not, suggesting that a complex interplay between basin physiography, sediment accumulation, and shaking intensity determines the degree of instability that develops within each local fjord depositional system. In summer 2020, the USGS collected a suite of nested multi-channel seismic and high-resolution Chirp data in several fjords of western Prince William Sound, as well as short-barrel, percussion-driven gravity cores to characterize the top ~2 m of sediment.

The effect of the 1964 earthquake has previously been identified in several of the surveyed basins (e.g., Passage Canal and Dangerous Passage) as a 5-10+ m thick deposit. Deposits with similar character and stratigraphic position, but with variable thickness (~0.3m to 15m) are observed in every basin surveyed, and we interpret these deposits to result from sediment remobilization in 1964. The ubiquity of the 1964 deposit imaged in chirp and MCS data implies that ground motions were sufficient to remobilize detectable levels of sediment. The variability in deposit character, however, suggests that variations in sediment supply precondition certain basins for larger failures

than others. Using the 1964 deposits as a template, we investigate the potential relationship between pre-conditioning factors and strong ground motion in remobilizing sediment and extend this investigation past the historical period to previous strong ground motion events. The results of this study may have important implications for quantifying the relationships between seismic parameters (i.e., shaking intensity), and the sedimentary response (i.e., total volume remobilized and thickness of the resulting deposit).

Long Lacustrine Sedimentary Records in South-Central Chile Evaluate the Spatiotemporal Variability of Megathrust Earthquakes

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Along the Valdivia Segment of the Chilean subduction zone, giant full-segment ruptures such as the 1960 CE (M_w 9.5) earthquake occur on average every ~300 years. Between these events, great partial ruptures such as the 2016 CE, 1837 CE, 1737 CE or the prehistorical 1455 CE earthquakes are known to occur. However, their contribution to overall stress relieve remains unclear, mostly because the along-strike extent and down-dip location of such pre-instrumental ruptures are poorly constrained. Therefore, comprehensive studies on the spatiotemporal variability of these ruptures is crucial to validate earthquake cycle models and improve seismic hazard assessment in South-Central Chile.

Paleoseismic records obtained from short sediment cores in eleven lakes along the Valdivia Segment allowed us to study the along-strike extent of known (pre)historic partial ruptures during the last two millennia. New long-core records from Lago Rupanco and Lago Huillinco additionally allow evaluating the temporal and down-dip rupture variability by expanding the paleoshaking record to the last ca. 5000-8000 years (Lago Rupanco) and linking it to tsunami records (Lago Huillinco). The lacustrine sedimentary imprint of earthquakes causing strong shaking can consist of turbidites, mass transport deposits or in-situ soft sediment deformation structures. High-resolution core scanning (X-CT, XRF, MSCL, etc.) allows us to detect and characterize these event layers in numerous cores and identify those related to megathrust earthquakes to then assess the related earthquake shaking quantitatively. Correlation of regional tephra layers, for which precise ages can be obtained independently, improve the radiocarbon-based age-depth models, resulting in more accurate paleoseismic age control and estimations of recurrence intervals. These lacustrine records will significantly enhance our understanding of the spatiotemporal variability of full and partial ruptures of the Valdivia segment. The analysis of sedimentary records from different lakes will increase our process understanding on the formation of seismogenic and tsunamigenic event layers.

Quantitative Calibration of the Lacustrine Seismograph Using Sedimentary Imprints of Recent Megathrust Earthquakes in South-Central Chile

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Accurate seismic hazard assessment strongly relies on paleoseismic research, providing long timescales of past seismic shaking, hereby potentially also revealing earthquakes that were larger than the highest-magnitude earthquakes known from historical or instrumental records. In this respect, lakes often provide long and highly sensitive shaking records, and lacustrine paleoseismology has evolved into an invaluable methodology for reliable reconstructions of earthquake recurrence intervals around the world. A thorough understanding of the relation between the component(s) of strong ground motion (e.g. PGA, PGV, duration) and the resulting sedimentary signature is, however, still missing. As a result, characterization of the source parameters of paleo-earthquakes, such as magnitude and location, up to now relies solely on qualitative or semi-quantitative considerations.

Previous studies have aimed at calibrating the lacustrine seismograph by attributing the occurrence or absence of coseismic imprints (e.g. turbidites) to intensities of seismic shaking. These intensity values are usually expressed on the macroseismic scale, as such information is more readily available compared to instrumental data for recent as well as historical earthquakes. These are, however, relatively subjective ground motion measures, unable to capture the various aspects of strong ground motion. In this study, we determine the relationship between quantitative ground motion measures on the bottom of a lake and the sedimentary shaking imprints identified therein. To achieve this, we focus on the sedimentary signature of instrumentally recorded megathrust earthquakes in south-central Chile. This includes the 1960 M_w 9.5 Valdivia earthquake and the 2010 M_w 8.8 Maule earthquake. A compilation of existing sedimentological data shows that coseismic deposits related to either of these events are identified in over 20 lakes. By linking the imprint characteristics for both earthquakes to the local ground motions, we bridge the gap between sedimentology and seismology, opening perspectives towards quantitative characterization of paleo-earthquakes.

Seismic Imaging Beneath Iceberg Lake, Alaska: Sediment Characteristics and Fundamental Site Response Parameters Beneath a Drained Lake With an Alaskan-Aleutian Subduction Zone Paleoseismic Record

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The emerging field of lacustrine paleoseismology requires an understanding of a lake's response to earthquake ground shaking. We acquired seismic data across the drained Iceberg Lake, Alaska valley floor to characterize basin sediments and ground motions associated with earthquakes along the eastern portions of the Alaskan-Aleutian subduction zone. The glacier-dammed lake, located in the Wrangell-St. Elias National Park, drained in 1999. From exposed and cored lake-bottom sediments, the lake shows a 1500+ year history. Our hammer seismic profiles along three transects provide basin thickness and seismic velocity (Vs30) estimates for lake sediments and surrounding bedrock. Coupled with microtremor measurements from 12 three-component Nodal geophones, we calculate horizontal-to-vertical (H/V) spectral ratios that provide a predominant site frequency (F0) at each measured location.

We identify ~50 m of saturated sediments on top of bedrock at the basin depocenter, suggesting a long post-glacial (~14 ka?) record. Vs30 values are consistent with site D-Class stiff soils beneath the Iceberg Lake basin margins and interfluve, and E-Class soft soils within the central basin. F0 estimates from our Nodal data range from less than 2 Hz at sites that lie on the valley floor to more than 50 Hz at our bedrock station without sediment and therefore no low frequency basin resonance. Sites along the basin margins recorded intermediate F0 values, consistent with shallower bedrock depths compared to the basin center. We find a match between F0 derived from microtremor analyses and from Vs30 and bedrock depths derived from hammer seismic data. Through empirical relationships, we correct Vs30 for overburden pressure from past lake levels and compare lake floor slopes with Vs30 values to develop a basin-wide site response model. These data provide inputs to assess ground motions along subduction zones from megathrust, intraslab, and crustal earthquakes using lake sediments. By coupling our results with the lake's paleoseismic record, we improve our understanding of seismic shaking in subduction zone coastal environments.

The Subaerially Exposed Iceberg Lake Sediments: A ~1000 Yr Long Paleoseismic Record From the Eastern Edge of the Alaska Subduction Zone

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Paleoseismic records are scarce on and around the Yakutat terrane, at the eastern edge of the Alaskan-Aleutian subduction zone. In this region at the transition between subduction and transform tectonics, the earthquake hazard comes primarily from faults bounding the Yakutat microplate, and from within the subducting Yakutat slab. Several of these fault zones hosted historical earthquakes such as the 1899 Mw 8.1 Yakutat Bay, 1958 Mw 7.9 Lituya Bay and 1979 Mw 7.4 Saint Elias earthquakes. In such a complex setting, which is compounded by extensive ice cover, traditional paleoseismic methods (trenching) do not work well. In contrast, lacustrine paleoseismic shaking records have more potential to provide comprehensive paleoseismic records.

Here, we study the sediments of Iceberg Lake, a glacier-dammed lake in the eastern Chugach mountains, within the Wrangell - St Elias National Park & Preserve. The lake drained during several outburst floods after 1999 CE, which exposed the lake bed and, through active erosion, the lacustrine sediments. In August 2022 we examined 6 outcrops in various sedimentary settings, from sandy delta to deep basin. We described the exposures, created 3D outcrop models using Structure-From-Motion photogrammetry and sampled sediments. Between annually laminated background sediments, we identified sediment gravity flow deposits and in-situ soft-sediment deformation features, such as convoluted bedding, dewatering structures and sand blows, inferred to be related to seismic shaking in prior studies. Cross-correlation of these beds between sites, and with previously studied and dated outcrops and cores, reveal that the most recent deposits can be linked to historical 1899, 1958, 1964 and 1979 CE earthquakes. We further identify an event that caused widespread gravity flows around 1920 CE, as well as similar pre-1899 events, such as a significant one in the second half of the 17th century. We conclude that Iceberg Lake is an excellent recorder of seismic shaking and has strong potential of preserving a high-quality paleoseismic record for the northern part of the Yakutat terrane.

The Great Salt Lake as a Recorder of Sublacustrine Surface Rupture and Strong Shaking in the Wasatch Front Region, Utah

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The Great Salt Lake (GSL) is a broad (30-km-wide), shallow (≤15-m-deep), and low-relief saline endorheic lake adjacent to the Wasatch Front region of Utah. Here, we explore the GSL as a potential recorder of Wasatch Front earthquakes and attempt to disentangle evidence of strong shaking and sublacustrine surface rupture. We focus on the western margin of Antelope Island, where sublacustrine scarps along the Great Salt Lake fault (GSLF) span the eastern lake margin, and previous subbottom Chirp data and piston cores suggest Holocene surface ruptures as young as ~0.6 ka. In our study, Chirp data show GSLF hanging-wall deformation, growth faulting, and stratal onlap in support of multiple Holocene ruptures, with the youngest within ~1 m (~1.2 ms) of the lake bottom. We also interpret 14 <2-m-long gravity cores arranged in three fault-normal transects. Photo logs, X-ray computed tomography, multi-sensor data, and grain-size measurements show lacustrine sediments characterized by light to dark gray, flat to wavy laminated, brine-shrimp-fecal-pellet-derived silt and fine sand. These background sediments are punctuated by massive ≤41-cm-thick disturbance horizons, which range from homogenites to normally graded silt and sand beds with evidence of sediment resuspension and transport. After evaluating possible mechanisms of sediment disturbance, we are most confident in a tectonic interpretation. We describe and correlate these disturbance horizons among the cores and constrain their timing using radiocarbon ages of terrestrial plant remains and charcoal included in Bayesian models. Preliminary results suggest that GSL sediments record strong shaking from large-magnitude (likely surface rupturing) Wasatch fault earthquakes as well as the most recent GSLF rupture. We plan to refine the GSL disturbance horizon chronology, compare to compilations of terrestrial Wasatch fault paleoearthquakes, and evaluate whether the GSL acts as a reliable Wasatch Front lacustrine seismograph.

Sediment Shear Strength Development Within Terminal Basins of the Japan Trench and Lower Slope: Insights Into Seismic Strengthening and Earthquake Paleoseismology From R/V Sonne Expedition SO251 (Eager-Japan) and IODP Expedition 386

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Recent findings have demonstrated that the Quaternary sedimentary fill in hadal basins along the Japan Trench, consists of two distinct deposition styles: slow background deposition punctuated with rapid event beds of variable thickness. In this study, we examine this bimodal basin fill pattern to investigate shear strength and how shear strength changes over time during burial and exposure to seismic activity. We compare strength profiles of basin sediment to sites located on the lower slope where sedimentation is expected to be low and prone to sediment bypass, erosion, and seismic strengthening. We compile shear strength data from *R/V Sonne* Expedition SO251 (EAGER-JAPAN) that acquired piston cores in the basins and the slope, and IODP Expedition 386 that acquired 29 giant piston cores in 15 basin sites. We find: 2 distinct shear strength profiles: sediments in the deep basins have low-to-normal shear strengths while sites on the slope have anomalously high shear strengths. A further finding in the basin sites is that the shear strength profiles of thick near-seafloor acoustically transparent units in subbottom data have lower-than-normal shear strengths. We interpret: the low-to-normal basin strengths are likely representative of relatively high sedimentation rates including raid, episodic pulses of sediment from earthquake-triggered event beds. Further, in young event beds that are still undergoing consolidation, this may be used as a novel way to constrain age of the event bed to complement traditional age-dating techniques. In contrast, slope sites may be prone to a combination of erosion and seismic strengthening, leaving sediments strengthened.

Beyond the Waves: Integrating Rock Physical Properties for Deeper Seismic Understanding

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Technological advances are driving Earth Sciences into the era of big data. Machine learning (ML) techniques offer potential for the advancement of submarine paleoseismology because of the need to integrate large datasets made at various scales with physical properties offering microscale, sediment core offering mesoscale, and geophysical data providing macroscale insights. This data integration is vital for the goal of distinguishing between earthquake- and non-earthquake-generated event beds. At its simplest definition, an event bed can be treated as an anomaly for which anomaly detection ML can be applied to identify similarities or differences for faster analysis and characterization.

IODP (International Ocean Drilling Program) Expedition 386 collected a comprehensive dataset of cores, physical/chemical data, and geophysical profiles in the northern basins of the Japan Trench. Our goal is to test ML capabilities to complement traditional efforts to identify event beds. We focus on Site M0084 where an acoustically thick unit occurs near the top of the sedimentary sequence above a few other potential event beds that occur in otherwise relatively simple stratigraphy. First, we test ML application with synthetic seismograms to link cores to geophysical properties at this site as it is comprised of thick event beds, not prone to resolution issues. Next, we utilize convolution neural networks for anomaly detection of sediment core imagery to refine and incorporate synthetic trace results with the various datasets. In the future, this framework based on physical properties and geophysical data can be extended across the Japan Trench, incorporating more expedition sites for further event bed detection.

Repeated Coseismic Uplift of Coastal Lagoons Above the Patton Bay Splay Fault System, Montague Island, Alaska, USA

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Coseismic slip on the Patton Bay Splay Fault System during the 1964 Mw 9.2 Great Alaska Earthquake contributed to local tsunami generation and vertically uplifted shorelines on Montague Island, Prince William Sound (PWS) by as much as 11 m. Sudden uplift of the island caused coastal lagoons along the northwestern coast to gradually drain leading to changes in depositional environment from marine lagoon to freshwater muskeg which created a sharp, laterally continuous stratigraphic contact between silt and overlying peat. Here, we characterize the geomorphology, sedimentology, and diatom ecology signatures across the 1964 earthquake stratigraphic contact and three similar, widespread prehistoric contacts within the stratigraphy of the Hidden Lagoons locality. We find that all four contacts signal instances of abrupt coastal uplift with radiocarbon, 137Cs, and 210Pb dating methods constraining them to ages that, within error, overlap the timing of independently constrained megathrust earthquakes in PWS–1964 CE, 760-870 yr BP, 2500-2700 yr BP, and 4120-4500 yr BP. Changes in fossil diatom assemblages across the inferred prehistoric earthquake contacts reflect ecological shifts consistent with repeated draining of a lagoon system caused by >3 m of coseismic uplift, similar to the environmental changes across the 1964 earthquake contact. Our observations provide evidence for instances of splay fault ruptures that have occurred close in time, within less than a century, of four of the last eight megathrust earthquakes over the past ~4,200 years in PWS. These results provide new information about potential rupture dynamics and tsunami risks associated with future combined megathrust-splay fault system ruptures which should be considered in hazards assessments.

Re-Examination of the 1958 Huslia Earthquake Sequence and Regional Tectonics of the Northwestern Koyukuk Basin, Alaska in Light of Post-1974 Seismicity, Mapped Faults and Geophysical Data

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In 1958 a M_w 6.8 earthquake and several M_w>5.3 aftershocks occurred in the northwestern Koyukuk Basin near the village of Huslia (~ 400 km northwest of Denali). Tectonically, this region is located between the compressional forces due to the collision of the Pacific and Yakutat plates and extensional forces associated with the extrusion of western Alaska. Since 1969 several earthquake swarms with M_w 4-5 events have occurred ~50 km northwest of Huslia in the western Purcell Mountains, including a swarm in 2019-2022 with over 9500 events. Previous studies have suggested the 1958 mainshock occurred on a northeast striking, southeast dipping normal fault. This sense of rupture is inconsistent with the focal mechanisms and trends of post-1973 seismicity within the 1958 epicentral region that indicate strike-slip movement along northwest trending faults. A recently mapped east-west trending fault scarp located along the southern front of the Purcell Mountains is also inconsistent with northeast striking normal faulting. To better characterize the 1958 sequence and its relation to mapped faults and regional tectonics, we measure scarp profiles across the Purcell Mountains scarp, relocate historical seismicity, analyze first motions and waveforms of pre-1974 events, and model potential fields geophysical data. Our preliminary results suggest regional deformation is occurring along both east-west and northwest trending structures.

Confirmation of Late Quaternary Surface Faulting and Preliminary Slip Rates for the Iditarod-Nixon Fork Fault and the Boss Creek and Holitna Sections of the Denali Fault in West-Central Alaska

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The Iditarod Nixon Fork fault (INFF) and the Boss Creek and Holitna sections of the Denali fault (BCF and HF) in west-central Alaska are included as Quaternary faults in active fault databases and as crustal fault sources in the USGS 2023 Alaska Seismic Hazard Model. Information about the activity of these structures and their associated seismic hazard parameters (i.e. slip rate, recurrence, geometry) is sparse due to a lack of detailed studies. We evaluated these faults to address uncertainties and data gaps as part of a seismic source characterization for the Donlin Gold Project. The study included lidar collection along 130 km of the INFF, desktop geomorphic mapping and criteria-based evaluation of faults and lineaments within 100 km of the Project site, aerial and ground-based reconnaissance of prioritized faults and lineaments, and collection of 14C, ^{10}Be TCN, IRSL, and tephra samples to constrain ages of displaced surfaces and estimate slip rates for the INFF, BCF, and HF.

Along the INFF, our mapping and reconnaissance confirmed strong geomorphic evidence of late Quaternary faulting extending southwest of Moore Creek, AK, for 100 to 125 km. Right-lateral slip along the INFF has displaced tributaries of Bonanza Creek 18±6m. Using IRSL ages of ~32-38 ka and ~22-23 ka from two loess deposits that mantle the faulted surfaces, we estimate a preliminary maximum slip rate of ~0.5-1 mm/yr. Geomorphic evidence of Quaternary faulting is weak to absent for an additional 75 to 100 km of the fault extending southwest to the Kuskokwim River. Along the Denali fault, 14C ages from a test pit in an abandoned Holitna River channel confirms at least one surface rupture in the past ~1000 years, consistent with the presence of en-echelon fissures in muskeg at Itulilik Creek. Four ^{10}Be TCN ages from boulders on a displaced LGM moraine complex (20-23 ka) will be combined with offset reconstructions to estimate preliminary slip rates at the junction of the BCF and HF. These findings confirm significantly more Holocene slip farther west on the Denali fault than previously estimated.

A New Generation of High-Precision Dating Techniques for Coseismically-Killed or Damaged Trees

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Dendrochronological techniques are uniquely high precision, establishing the exact calendar year of formation for each tree ring in a sample set. Thus, if a tree was killed by seismic activity, the exact calendar year and even season of the earthquake can be determined by establishing the year of the final ring formed under the bark. If trees have been disturbed but not killed, growth or anatomical anomalies can also place seismic events in time.

High dating precision is typically accomplished via crossdating in which synchronous, time-specific growth patterns are matched among trees of a given species and region, beginning with live-collected trees, and extending back in time with dead-collected trees. There are, however, important limitations, even assuming wood is well preserved. Dead-collected trees must contain ring sequences long enough (usually 150 years or more) to establish confident growth-pattern matches. There must also be sufficient year-to-year growth variability and a minimum of irregularities or distortions. Yet wood samples often violate these criteria, especially roots, which are often the best-preserved part of dead trees.

Newly emerging techniques are likely to help overcome limitations of dating with ring widths. First, the oxygen-18 content of tree rings often covaries among trees, and even species, more strongly than width. Preliminary data in the Pacific Northwest indicates that wood samples with short sequences, distorted rings, and little year-to-year growth variability can be crossdated using oxygen-18. Single-year cosmogenic spikes in radiocarbon, known as "Miyake Events," provide another new approach for one-year dating precision of paleo-earthquakes. Finally, "wiggle matching" multidecadal series of radiocarbon values from tree rings may narrow uncertainties to within a year or two for wood that lived within the past several thousand years. Combined, these techniques could enable the dating of wood samples, including roots, that could not have been crossdated using ring widths, and initiate a new generation of high-resolution paleoseismic reconstructions.

Precisely Dating Seismically Triggered Debris Avalanches in the Northern California Coast Range

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Determining the timing and cause for prehistoric hillslope failures has proven difficult in the western US, yet critical as it ties directly into ground motion estimates for future hazardous events. This knowledge gap is important to confront, however, as these avalanche failures are candidates to have been triggered by earthquakes along active plate boundaries, where sources include crustal faults, plate boundaries, and intraslab events. Here, we identify two exceptionally large prehistoric debris avalanche failures in the Coast Ranges of northern California that are well suited for studying the timing (to the exact year) and cause (what triggered the failure) as the densely forested landscape enables the effective use of dendrochronology and high-resolution radiocarbon. This high precision geochronology allows us to identify time of failure, and the legacy of landslide studies in the region provides context for evaluating a climatic versus a seismic trigger as the most likely failure mechanism. We find that the two debris avalanche sites are physiographically suited to accommodate topographic amplification of seismic shaking, and through a suite of multiproxy evidence, we establish that likely time of failure of the two debris avalanches to be 1906 CE and 933 CE, respectively. In the first instance, the year 1906 CE is the year of the San Francisco earthquake on the Pacific/North American plate boundary, and in the second instance, the year of failure, 933 CE, falls within the broad age range (850-966 CE) that probably includes the year of the antepenultimate earthquake on the Cascadia subduction zone as recorded in coastal marshes in Humboldt Bay, California. The precise age on the 933 CE debris avalanche could trim down the uncertainty on a Cascadia subduction zone event from 116 years to one year. Utilizing debris avalanche records from sites suitable to record seismic shaking improves understanding of plate-boundary earthquake timing and extent of shaking.

Diatom-Based Coseismic Subsidence Estimates Spanning a ~4,500 Year History of Cascadia Subduction Zone Ruptures Along the Southcentral Coast of Oregon

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Estimating coseismic subsidence produced by past Cascadia Subduction Zone (CSZ) megathrust earthquakes is crucial for understanding rupture dynamics, particularly magnitudes of paleoseismic slip. Past CSZ earthquakes are expressed in tidal wetland stratigraphy as sharp contacts between saltmarsh peat and overlying intertidal mud, indicating rapid coseismic subsidence. Recent statistical methods (transfer functions) use microfossils (e.g., foraminifera, diatoms) to quantify coseismic subsidence across these abrupt peat-mud contacts. Transfer functions estimate the amount of coseismic subsidence by analyzing land/sea-level relationships before and after earthquakes. While foraminifera-based estimates reveal variability in subsidence along-strike during the 1700 CE CSZ rupture, equivalent foraminifera-based estimates for pre-1700 CE earthquakes are scarce. Tidal wetlands along the Coquille River estuary in southcentral Oregon preserve evidence of 12 CSZ ruptures over the last ~7,000-years, but preliminary work indicates low numbers of calcareous foraminifera in deposits older than the 1700 CE rupture, complicating reconstructions of subsidence. In this study, we use diatoms, a microscopic algae with resilient biosiliceous hard parts, as a complementary alternative for subsidence reconstructions due to their preservation potential in low pH environments. Using a diatom-based transfer function, we analyze seven CSZ earthquake contacts (1700 CE to ~4,500 yr BP) from Fahys Creek, a Coquille River tributary. Additionally, we present new (between 3-6) radiocarbon age dates for CSZ earthquake contacts, to aid in earthquake correlation. Our diatom analysis reveals variability in subsidence estimates over multiple earthquake cycles, suggesting variable rupture patterns for successive CSZ ruptures. The new subsidence estimates deepen our understanding of the heterogeneous nature of CSZ ruptures through time. Future work will entail combining estimates from Fahys Creek with estimates for pre-1700 CE CSZ earthquakes at other sites to build a comprehensive examination of along-strike rupture characteristics of the CSZ.

Constraints on Cascadia Subduction Zone Paleoearthquakes from Terrestrial Shaking Proxies and Coseismic Land-level Change

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The impacts and nature of past great Cascadia Subduction Zone (CSZ) earthquakes, and the risk posed to the Pacific Northwest from future events, are poorly constrained. Past work using evidence from written histories, paleoliquefaction, coastal subsidence, and near- and far-field tsunami deposits allow for a wide-range of earthquake rupture styles, magnitudes, and shaking intensities for a given 'event' in the geologic record. However, most studies focus on a single geologic proxy to investigate these events. Here, we present an integrated method for assessing the likelihood of simulated CSZ earthquakes using a combination of terrestrial shaking proxies and estimates of coastal land-level change throughout Cascadia. Complementary constraints on minimum and maximum paleoshaking intensities from coastal landslides, liquefaction, and fragile geologic features are combined with coseismic coastal subsidence estimates to leverage a diverse and geospatially continuous set of constraints on past CSZ earthquake rupture scenarios. This integrated paleoseismic record is compared to a suite of CSZ earthquake simulations for megathrust earthquakes of magnitude 8.65–9.15 with varying down-dip extents of slip and source characteristics to compute misfit between the geologic record and simulated ground motions. We assess misfit between the geologic record and simulations at a full-margin scale to assess global performance and identify local discrepancies along-strike to identify possible variations in source behavior. To assess the sensitivity of these results to different modeling approaches, we test different statistical methods for integrating the geologic proxy data, calculating the misfit, and incorporating geochronological uncertainty. Preliminary results show the sensitivity to how different geologic proxies are integrated on preferred earthquake simulations, as well as how incorporating subaqueous data (i.e., offshore and lacustrine) could further improve these models.

A Cycle of Memory Creation, Erasure, and Solid to Fluid-Like State Transitions Encoded Within Granular Assemblages Sheared by Faults

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A hallmark of many processes in Earth's subsurface [e.g., landslides, ground-rupturing earthquakes, liquefaction, and crystal-rich magmas] is the transitions in states that granular assemblages undergo, from structurally arrested to creeping to flowing. The frictional jamming and material memory theoretical frameworks argue that volume fraction and shear stress govern such transitions and that the material records the transitions. We use x-ray microtomography to determine if the three-dimensional re-arrangement and fracturing of grains within assemblages collected from two paleoseismic sites along the southern San Andreas fault record frictional jamming phenomenologies. Analyses reveal that fault zone granular assemblages transition between one or more interrelated but geometrically localized and mesoscopic deformation states that change assemblages' stability during the seismic cycle. These states include [1-2] bulk and localized grain re-arrangements, [3] individual grain fracturing, and [4] localized zones of grain fracturing. Grain re-arrangement is primarily a global phenomenon. Grain size and non-rattlers exert control over grain fracturing and re-arrangements. Coseismic shear erases anisotropic fabric memory developed during aseismic shear and introduces its own. Shear stress magnitude and elastoplasticity control memory creation and erasure and thus vary with distance from a fault strand. Our findings imply [1] that sheared fault zone sediments experience a cycle of memory creation and erasure accompanied by differing deformation phases and thus hold an invaluable record of how shallow faults move coseismically and aseismically, and [2] that frictional jamming and material memory remain promising unifying theories for granular flow, even considering naturally imposed disorder.

Lost and Found: Evidence of the Penultimate Earthquake on the Hebgen and Red Canyon Faults, Montana

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The 1959 Mw 7.3 Hebgen Lake, Montana, earthquake, one of the largest-recorded continental normal-faulting earthquakes, occurred on a structurally complex pair of overlapping normal faults (Hebgen and Red Canyon) at the eastern end of the Centennial Tectonic Belt near Yellowstone National Park. In this study, we document from historical photographs the short-lived existence of a steep prehistoric scarp above the 1959 surface ruptures. At several locations, the preexisting scarp was rapidly regraded as the 1959 scarp retreated upslope, and within a few decades, the scarp bevel had largely disappeared. Post-earthquake investigators had recognized that the 1959 scarps near south end of the Red Canyon fault were superimposed on similar older scarps (Myers and Hamilton, 1964); however, it's unclear the extent to which this observation has affected measurements of 1959 scarp heights and baseline studies of how scarps degrade with time.

A photo taken in 1959 at a site where we trenched the central Hebgen fault ("Section 31" alluvial fan) provides geomorphic confirmation of a displacement event inferred from subsurface relations. We present paleoseismic evidence of this young penultimate earthquake (PUE) and of a relatively long interval separating it from earlier faulting. Recycling of soil organic matter from older colluvial-wedge deposits into the PUE wedge complicates estimation of its age, although several 14C ages (~600 yr B.P.) on detrital charcoal and wood near the base of the PUE wedge are congruent with the youthful steepness (~30-40°) of the scarp as estimated from photography. An older scarp bevel above the 1959/PUE scarp at the Section 31 site is, in contrast, gently sloping (~20°) and stable enough to have a soil B horizon developed beneath it. Evidence on both faults indicates that slip in the PUE was similar to that in 1959, suggesting that event magnitude and pattern of rupture were also similar. The rapid post-1959 loss of morphologic evidence of the PUE scarp demonstrates that a simple fault scarp, even modest in size, should not be assumed to represent a single earthquake.

Unveiling Seismic Hazards: Paleoseismic Insights From the La Venta Fault in the Forearc Mountains, Mexico

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Understanding the potential earthquake activity of unknown active faults is crucial for assessing seismic hazards in continental interiors. Despite advancements, our knowledge of earthquakes on crustal faults away from plate boundaries, particularly in forearcs, remains incomplete. This study addresses this gap by utilizing paleoseismic records, conducting a LIDAR flight to develop a DTM in the highly vegetated mountains, mapping geomorphological features, performing a geophysical survey including electric resistivity and georadar, and excavating a paleoseismic trench along the central section of the La Venta Fault, named Agua del Perro. The trench revealed six rupturing events over the last 8000 years.

The surface expression of this fault is subtle, characterized by a gentle scarp, minor stream offsets, and a shutter ridge. Our data show evidence of surface fault rupturing with lateral displacement up to ~80 cm per event and vertical displacement up to 44 cm. The most recent event occurred around the 14th century, registering a calculated magnitude of Mw 6.9. Given the fault's location, our findings suggest a significant seismic risk to local communities along the fault and populations in larger cities like Chilpancingo, Acapulco, and Mexico City. The study also highlights potential damage to infrastructure, such as the La Venta Dam, and associated hazards, including flooding and rock falls. This research emphasizes the importance of recognizing the potential hazard posed by crustal intraplate faults away from plate boundaries in the forearc mountains.

From Faults to Fjords: Earthquake Evidence in Terrestrial and Subaqueous Environments [Poster Session]

Poster Session • Wednesday 1 May

Conveners: Danny Brothers, U.S. Geological Survey (dbrothers@usgs.gov); Tina Dura, Virginia Polytechnic Institute and State University (tinadura@vt.edu); Jenna Hill, U.S. Geological Survey (jhill@usgs.gov); Kristin Morell, University of California, Santa Barbara (kmorell@ucsb.edu); Belle Philibosian, U.S. Geological Survey (bphilibosian@usgs.gov); Derek Sawyer, Ohio State University (sawyer.144@osu.edu); Drake Singleton, U.S. Geological Survey (dsingleton@usgs.gov); Katleen Wils, University of Innsbruck (katleen.wils@uibk.ac.at); Rob Witter, U.S. Geological Survey (rwitter@usgs.gov); Mark Zellman, BGC Engineering, (mzellman@bgcengineering.ca)

POSTER 43

Lacustrine Paleoseismic Evidence From Two Large Lakes in Cascadia: Preliminary Comparisons of Post-Glacial Sediment Records From Ozette and Whatcom Lakes, Washington

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We present a suite of geophysical and geological evidence for earthquake-triggered mass transport deposits (MTDs) and related turbidite deposition in two of Washington's largest lakes: Ozette and Whatcom. Ozette Lake is ideally situated along the outer coast and above the locked portion of the northern Cascadia megathrust, but is relatively isolated from active crustal faults and intra-slab earthquakes. Whatcom Lake is farther inboard of the subduction zone where shaking is expected to be less severe during megathrust ruptures, but is more proximal to active crustal faults. High-resolution bathymetry data, sub-bottom Chirp profiles, and sediment cores (spanning the last ~14 kyr B.P.) are used to characterize the post-glacial stratigraphic framework of both lakes. We examine paleoseismic proxies within the lacustrine sediments, present an initial comparison of the two datasets, and explore implications for earthquake timing and recurrence between these two sites in western Washington. Both lakes contain stacked sequences of MTDs and Mazama ash marker-beds; the physical characteristics of the event deposits vary considerably depending on proximity to primary depocenters, steep slopes, and subaqueous deltas. In Ozette, more than 150 radiocarbon ages bracket the timing of 34 event deposits emplaced since ~14 kyr B.P; these are easily differentiated from watershed processes and interpreted to have been generated by intense megathrust shaking, yielding a recurrence interval of ~420 years. Stratigraphic analyses and radiocarbon dating from Whatcom reveal a more complicated depositional history. Thick (1–5 m) MTDs and thinner (<10 cm) turbidite event beds appear to have been generated from different sources of shaking, and possibly from non-seismic watershed processes. Some of the thick MTDs failed synchronously along submerged slopes during two distinct intervals of the Holocene, whereas more than 20 turbidites are observed within the same section. Shaking from nearby earthquakes (crustal faults?) may have triggered the MTDs, but determining a source for the turbidites is a focus of ongoing and future analyses.

POSTER 44

Earthquake–triggered Submarine Landslides in Kachemak Bay, Alaska: New Constrains on Distribution and Timing Based on Marine Geophysical and Geological Data

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Fjords of the Kenai Peninsula were severely shaken during the 1964 Mw 9.2 Great Alaska Earthquake resulting in widespread subaqueous slope failure. Destructive tsunamis generated by underwater landslides impacted several of the coastal communities, including ~6–8 meter-high waves in Resurrection Bay. Although less destructive, Kachemak Bay and the town of Homer also experienced intense sea waves in 1964 a few minutes after intense shaking began, damaging portions of the Homer spit and harbor, and causing overall subsidence. Early reports suspected submarine landslides in Kachemak Bay played a role, but direct observational evidence was not available. New geomorphic mapping in Kachemak Bay, based on NOAA multibeam bathymetry data, identifies a complex of submarine landslides along the southern flank of the bay with mass transport deposits that extend several kilometers into the basin. The headscarps are mostly concentrated along subaqueous deltas downstream of the Grewingk and Portlock glaciers. Large earthflows, slumps, and blocky failures are also observed near the head of the bay.

In summer 2022, the USGS collected a dense grid of Chirp subbottom profiles in Kachemak Bay to characterize the Holocene sedimentation patterns and examine the spatial and temporal distribution of submarine landslides. A suite of 27 sediment cores were collected to sample the upper ~2 m of sediment and develop preliminary age models. Preliminary analyses of these integrated datasets suggest that multiple phases of failure have occurred throughout the bay in the past. The most recent complex of deltaic failures appears to have occurred synchronously and most likely during 1964 earthquake (pending results of Cs137 dating). In addition to the stacked sequences of thick MTDs that are observed in several of the depocenters, 10–12 event beds (turbidites?) are seismically imaged within a small, isolated sub-basin and may provide evidence of repeated shaking events. Lastly, we present a preliminary assessment of landslide-generated tsunami sources and discuss the potential for Kachemak Bay to contain a valuable marine paleoseismic archive.

POSTER 45

Possible Quaternary Faulting on the Picuris-Pecos Fault on the Eastern Margin of the Española Basin, New Mexico

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The north-south-trending continental Rio Grande Rift (RGR) extends for ~1,000 km from Chihuahua, MX to northern Colorado, USA. Within the central RGR, the Española Basin is a ~60 km wide, west-tilted half graben with low seismicity rates, low slip rates on Quaternary-active faults (0.01–0.1 mm/yr), and a low geodetic extension rate. The western-basin-bounding Pajarito fault system has generated surface rupture during large (>M6) earthquakes during the Holocene, and there is strong evidence for late Pleistocene and possibly Holocene surface ruptures on other faults within the basin. On the eastern side of the basin, the Picuris-Pecos fault (PPF) forms the eastern boundary of the RGR. While most of the extensional strain is partitioned to active faults on the western side of the basin, we show that new neotectonic mapping on 1 m lidar-derived topography indicates that at least one strand of the PPF has displaced moraines that are undated, but presumably date to the last glacial maximum based on regional correlations. Field reconnaissance of the lineaments confirmed the presence of <1 m-high, down-to-the-west and down-to-the-east scarps that offset several moraine crests and younger surfaces between the moraines. On another strand, abrupt, NNE-trending topographic lineaments persist for at least ~7 km and are part of a discontinuous, ~65 km-long lineament set that traverses the western side of the Sangre De Cristo Mountains. The lineaments cross disparate geological units and topography, suggesting they have a tectonic origin. Field reconnaissance confirmed the presence of the lineaments, which form topographic benches that cross steep, bedrock-mantled slopes obliquely in places. ^{10}Be exposure dating of boulders on the displaced moraines and additional mapping along other lineaments on the trace of the PPF will improve our understanding of the most recent surface deformation and location of the PPF, in addition to better characterization of site-specific and regional seismic sources.

POSTER 46

Lacustrine Paleoseismic Investigation in the South Washington Cascade Range: Geophysical and Sedimentological Observations From Keechelus, Kachess, and Cle Elum Lakes

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Lacustrine sediments within Keechelus, Kachess, and Cle Elum Lakes, located within the Yakima River Basin in the western Cascade Range (WA, USA), may hold records of strong ground motion occurring within the Pacific Northwest. Multibeam bathymetry, high-resolution seismic profiles, and sediment core data recently collected from these three deepwater lakes image subaqueous landslides, buried mass transport deposits (MTDs), and tephra deposits, which aided the correlation of stratigraphic markers amongst the three lakes. Using 42 (1.0-1.8m) percussion-driven gravity cores, we analyzed the physical properties and age of sediment deposited during the last ~7.5 kyr B.P. Within each lake, we find a 50-100 m-thick sedimentary sequence that includes 10-15 m of Holocene sediments that conformably overlay thick late Pleistocene sediments. Three Mt. Helens tephra deposits are found in each lake, and Mazama ash was sampled in Lake Keechelus.

Stacked sequences of MTDs within each lake were mapped in 3D to determine each deposit's source location (e.g., delta versus non-delta). MTDs sourced from multiple locations are inferred to be shaking–induced. While we do not observe definitive evidence for deposits generated by historical megathrust (e.g., 1700), intraslab, or crustal (e.g., 1872) events, we present strong evidence for comparatively large and synchronous megaturbidite deposition in each lake at 2468-2716 cal yr B.P. The coincident timing, the large volume of remobilized sediment, and the depositional style suggest considerable ground motion occurred in the Yakima River Valley; therefore, we favor a proximal source of this shaking event (e.g., an active structure within the Olympic-Wallowa Lineament). However, we continue to assess other potential sources for shaking, such as the Southern Whidbey Island Fault or a Cascadia megathrust event. This study highlights the value of lacustrine paleoseismic approaches in regions where surficial fault deformation has been obscured in the geologic record or where traditional paleoseismic techniques are not feasible.

POSTER 47

Comprehensive High-Resolution Geophysical Mapping and Sediment Coring in Lake Chelan, Wa: A Deep, Steep Lacustrine Environment Dominated by Mass Transport Processes

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Lake Chelan (WA, USA), the third deepest lake in the contiguous United States, may hold records of glacial retreat and advance, volcanic eruptions, and earthquakes. For example, the 1872 Washington State Earthquake (M6.5–7) ruptured the Spencer Canyon fault near the southern end of Lake Chelan. Shaking from the 1872 earthquake was of such intensity that it altered local aquifers, triggered liquefaction of unconsolidated sediments, and large seiches within Lake Chelan. Lake Chelan may provide a geological dataset to calibrate the lake's lacustrine sedimentary response to the 1872 earthquake. In 2023, the USGS conducted a 3-week field operation in Chelan to acquire high-resolution multibeam bathymetry data, Chirp sub-bottom profiles, and sediment cores. These new data reveal pervasive morphological evidence for slope failure, mass transport deposits (MTDs), subaqueous deltas, and relic glacial features (e.g., kettles). Here, we present preliminary results of detailed geomorphic and stratigraphic mapping throughout the lake. Chelan can be divided into two physiographic basins: the deeper (up to 460 m) and narrower (~2–3 km wide) Lucerne Basin to the north, and the shallower (up to 130 m), wider (5–10 km) Wapato Basin to the south. The Lucerne Basin is dominated by very steep flanks and subaqueous deltas fed by fluvial catchments; the depocenters are dominated by coarser-grained sediment and stacked MTDs. The Wapato

Basin contains numerous slide scars, scarps, debris aprons along the gently sloping margins, and abundant kettle structures infilled with fine-grained lacustrine sediments. Sediment cores sampled several of the youngest MTDs; their relation to the 1872 earthquake is pending results of 14C and radionuclide dating. Furthermore, cores from condensed sections of the Wapato basin contain numerous ash deposits and bottom out in late Pleistocene glacial sediment. Our initial results suggest that Chelan contains several sources of MTDs, with the Lucerne Basin most affected by fluvial processes and the Wapato Basin being a better candidate for paleoseismic investigations.

POSTER 48

Introducing the Science Goals for the Cascadia Region Earthquake Science Center (Crescent) Cascadia Paleoseismology Working Group (Cpal)

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Funded in 2023 by the National Science Foundation, the Cascadia Region Earthquake Science Center (CRESCENT) is the nation's first subduction zone earthquake hazards center. The goals of CRESCENT are todevelop a better foundational understanding of Cascadia subduction zone earthquakes, promote diversity and train the next generation of geoscientists, and provide a systematic approach to collaboration between researchers in academia and government agencies with mandates to provide hazard information to the public. A fundamental challenge in characterizing hazards along the Cascadia subduction zone is the lack of an instrumentally recorded megathrust earthquake. Due to this limitation, we must rely on paleoseismic studies to characterize the frequency, timing, and associated coseismic displacement of prehistoric Cascadia earthquakes. Under CRESCENT, the Cascadia Paleoseismology Working Group (CPAL) will employ detailed stratigraphic mapping of subsidence and tsunami evidence and new high-resolution analysis of cores including CT scanning, geochemical, and microfossil analyses to reconstruct coseismic land-level change and tsunami inundation during past Cascadia subduction zone earthquakes. To help build larger quantitative paleoseismic datasets of subsidence along the Cascadia subduction zone, CPAL will develop a shared, community-built diatom and foraminifera database that will increase accessibility and standardize microfossil analysis. CPAL will also work with the members of the USGS Powell Center Cascadia Earthquake Hazards group to develop and expand an online database of geologic observations that provide evidence for subsidence, shaking, and ground failure from past Cascadia subduction zone earthquakes and inundation from associated tsunamis. CPAL will directly collaborate with modelers to integrate the new and improved quantitative paleoseismic datasets and utilize the database of geologic observations to validate numerical models of subduction zone earthquakes and tsunamis and better assess hazards along the Cascadia subduction zone.

POSTER 49

Detection Thresholds for Large to Great Subduction Earthquakes in South-Central Alaskan Marshes

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Coastal marshes provide records of the recurrence of great earthquakes in the Prince William Sound section of the Alaskan megathrust, with widespread evidence of surface deformation >1 m during seven great earthquakes in the last 4000 years. In the Kodiak section, there is paleoseismic evidence for four ruptures which occurred independent of the Prince William Sound section in the past 2000 years, each resulting in decimeter-scale subsidence. Based on records from subduction zones worldwide, it is suggested that subduction earthquakes ≤M_w8.5 displace the coast by <0.3 m and likely leave equivocal or no geologic evidence in coastal marshes. Recent studies suggest that in certain circumstances a detection limit of ~0.1 to 0.2 m may be possible. A better understanding of the lower limit of detection is essential for assessing seismic hazards of Alaskan earthquakes that are smaller than M_w9 but still pose significant risk.

We undertook fieldwork during September 2023 at Girdwood and Ocean View, Anchorage to test a methodology aimed at making marsh records of past great earthquakes in this region more complete. We focus efforts on the upper tidal marsh zone into the perimarine zone (where freshwater wetlands persist under the control of relative sea level). In these coastal peat forming environments, the most precise quantitative estimates of submergence can be reconstructed. At Ocean View, we traced the stratigraphic contact of the 785 ± 10 cal yr BP earthquake inland from the seaward extent of the marsh where it is expressed as a peat-to-silt contact until it changes to a peat-to-peat contact. This peat-to-peat contact, representing a known earthquake and associated submergence serves as an analogue to describe subsidence-derived changes in diatom assemblages from longer peat records. This allows us to assess whether, in perimarine to upper tidal marsh zones (where organic sedimentation dominates for the majority of an earthquake cycle), we can identify and quantify previously unknown episodes of decimeter-scale coseismic submergence representing earthquakes ≤M_w8.5 in this region over the last millennium.

POSTER 50

Geotechnical Properties of Quaternary Marine Sediments of the Eel River Plateau, Southern Cascadia Margin

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Submarine landslides are frequently triggered by earthquakes but there can be a variety of factors that trigger or precondition a slope to failure including weak layers in the sediment, storm waves, and sediment unroofing. Although earthquakes can trigger submarine landslides, active margins have fewer submarine landslides than passive margins despite having higher levels of seismicity. This observation supports the concept of seismic strengthening which suggests that sediment exposed to repeated earthquake shaking dewaters and densifies causing enhanced strength. We focus on the southern end of the Cascadia Subduction Zone, where the highest historical seismicity rate along the Cascadia margin has occurred due to the northward migration of the Mendocino Triple Junction, resulting in a broad regional uplift. Moreover, there is a high volume of terrestrial sediment input in this area from the Eel River and other fluvial systems that feed into the southern end of the Cascadia Subduction Zone. Despite the high levels of seismicity and the high volume of sediment accumulation, recent studies document a distinct lack of slope failure on the upper slope. Given this observation, we aim to understand the physical properties that contribute to the slope stability in this region, including whether there is enhanced strength or other mechanical differences that might play a role in enhanced slope stability. We measure undrained shear strength using a fall cone device, grain size, and Atterberg limits and integrate them with CT scans, photographs, physical property logs, and radiocarbon dates. Using this collected data we will be able to provide a new insight into the slope stability of the region that will further the understanding of the possible implications for regional geohazards and how they can affect offshore infrastructure.

POSTER 51

A Refined Chronology of Tsunami Deposition at Discovery Bay, Washington State

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A tidal marsh at the head of Discovery Bay preserves the largest number of tsunami deposits in Washington State (USA). The location is an excellent geologic recorder of tsunamis because of its wave-amplifying, funnel-shaped morphology, an abundant sediment supply, and a tidal marsh that has sufficient accommodation space and preservation potential to preserve deposits. At Discovery Bay there are as many as ten 2-10 cm thick tsunami deposits, and at least six thinner layers < 2 cm thick that span the last ~3,000 years. Some of the thicker deposits undoubtedly resulted from Cascadia subduction zone earthquakes, based on both tsunami modeling and deposit ages. However, the number of deposits at Discovery Bay exceeds the number of known Cascadia earthquakes in the same time span, so additional tsunami sources including crustal faults, tsunamigenic landslides, and distant Pacific subduction zones may also be represented. One of the thinner deposits is probably from the 1964 Alaska Prince William Sound tsunami, which was observed at the site.

Two decades ago, tsunami deposits were first described and dated at Discovery Bay. We build on previous efforts with new observations and chronologic data. In 2007, part of the marsh that had been previously diked was restored to marshland, thus allowing access to a wider distribution of deposits than originally described. We present new stratigraphic mapping of tsunami deposits from two 3 meter-long vibracores, 38 gouge cores, and three cleared channel bank outcrops. To confirm visual stratigraphy in the vibracores, we obtained high resolution CT density imagery and X-ray fluorescence data. New bracketing maximum and/or minimum radiocarbon ages and 137Cs concentration data were used to create multiple Bayesian age-depth models, each with different assumptions, to (1) determine which model is most appropriate for this dataset and (2) identify the differences in age estimates that may be imposed by model choice. Our new chronology increases confidence in regional source correlations and identifies deposits that likely have non-Cascadia sources.

POSTER 52

Reconnaissance Implies a Potentially Complete Record of Holocene Earthquakes in Esther Lake Above the Alaska-Aleutian Megathrust

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We investigated Esther Lake, Alaska, to evaluate its potential for lacustrine paleoseismology, specifically for its likelihood to yield a record of megathrust earthquakes. The lake is trenchward of prior lacustrine paleoseismology studies in southcentral Alaska, and it lies in the epicentral region of the 1964 M_w9.2 earthquake. Esther Lake is located in north-central Prince William Sound, formed after deglaciation around 12.9 kya, and lies in a mountainous region dominated by high precipitation and perennial headwater snowfields. Despite such hydrologic conditions, Esther Lake hosts no significant stream deltas, and thus little sediment enters the lake. We collected multibeam echosounder (MBES) bathymetry data, 2-16 kHz Compressed High-Intensity Radar Pulse (CHIRP) seismic data, and 20 short (<2 m) percussion-driven gravity cores that we scanned via computerized tomography (CT) and multisensor core logger.

The bathymetry and CHIRP data reveal sediment (<12m thick) is deposited in 9 isolated basins no more than 100 m across. The distinctive seismic stratigraphy of each basin is nearly identical, showing a succession of acoustically transparent ~1 m-thick packages separated by high-amplitude reflections. We divide the sediment, which is generally organic-rich and mineral-poor (<5%) into two main types: "event deposits" and "intra-event deposits". The intra-event deposits are typically dark brown fine-grained organic rich material, in which we find no identifiable macrofossils, and almost no mineral matter except distinctive light-colored tephras that display high radiodensity and magnetic susceptibility. We interpret these horizons as the high-amplitude CHIRP reflectors. The event deposits are brown organic-rich turbidites that fine upward and commonly contain organic macrofossils and granite-derived micas at the base. Initial radiocarbon samples have been submitted for dating. We infer that Esther Lake has the potential to have a nearly complete record of Holocene earthquakes dominated by megathrust events.

POSTER 53

Cataloging the Date of Last Event (DOLE) Across the Western U.S.

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The elapsed time since the most recent earthquake (the open interval) on a given fault is a primary constraint required for time-dependent seismic hazard analyses. Additionally, the timing of the most recent earthquake and paleoseismic chronologies are key targets in earthquake geology research. The high density of paleoseismic studies in California and along the Wasatch front, along with historical earthquakes, have focused attention of prior time-dependent probabilistic seismic hazard analyses (PSHA) in these regions. These hazard models generally yield a relative decrease in the probability of moderate-to-large ruptures on faults with recent ruptures (e.g., 1999 Hector Mine rupture, CA), and a relative increase of rupture rates on faults that may be late in the seismic cycle (e.g., Brigham City section of Wasatch fault, UT). To enable the proposed expansion of time-dependent PSHA analysis across the western U.S., we augmented the western U.S. NSHM fault sections database with paleoseismic and historic date of last event (DOLE) data. We added ~70 sites to the ~60 existing sites previously compiled within California and along the Wasatch fault. Additionally, we added ~10 historical rupture extents to the compilation. This compilation includes paleoseismic investigations as points and expands those site observations onto existing NSHM fault subsection geometries as lines. Translating site observations to rupture extents remains challenging, and we take a minimum-length approach as was done in previous time-dependent PSHA in California. On faults without a paleoseismic or historic event, we use a regionalized onset of historical settlement to demarcate the minimum time since a large earthquake has occurred. In addition to implementation in time-dependent PSHA, we hope this compilation will be useful to the earthquake geology community as we develop models of earthquake occurrence through space and time, better constrain geologic slip rates, and plan future paleoseismic trench investigations, among other applications.

POSTER 54

Tectonic Oversteepening, Sediment Accretion, and Lower Slope Failure in the Cascadia Subduction Zone—A Recipe for Abyssal Seismoturbidites and Insights Into Earthquake History

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Seismic strengthening and related processes are often cited to explain the dearth of large submarine landslides on active margins; however, recent examination of seafloor bathymetry has revealed extensive mass wasting of the continental slope along the Cascadia Subduction Zone. Hill et al. (2022) suggested these failures may be the primary source of abyssal seismoturbidites that comprise the longest earthquake records in the region. Deriving robust earthquake recurrence estimates from these records though, requires rigorous investigation of the processes of slope development and failure preconditioning. From 2019-2023, the USGS and MBARI conducted extensive geophysical surveys and geologic sampling along the Cascadia margin, including >6700 km of Sparker MCS and Chirp subbottom data, 470 sediment cores (380 <2m ROV-based vibracores, 90 6-8m piston cores), along with AUV 1-m bathymetry and subbottom data. These data offer an unprecedented look at the structure and morphology of the deformation front and provide insight to the mechanics of earthquake triggered slope failure. Northern Cascadia is characterized by steeply dipping, asymmetric, landward vergent thrust folds with steeper seaward limbs prone to translational block slides along bedding planes. In central Cascadia, low angle, imbricate thrust faults have created a stepped terrace morphology with steep ledges. Failures occur at the forelimb of the fold, exposing truncated strata at the seafloor. In southern Cascadia, steeply dipping thrust faults create lower relief folds, yet failures occur on the 4-6° seaward face of the frontal thrusts. Two factors appear key in preconditioning the slopes for failure: (1) the dynamic uplift and permanent deformation creates oversteepening; (2) accretion of abyssal plain sediment into the outer wedge provides unlimited recharge of relatively weak and unstable material. These two processes appear to be keeping pace with earthquake triggering and outweigh the effects of compaction induced strengthening.

POSTER 55

Marine Seismoturbidites in the Cascadia Subduction Zone: Filling the Gaps and Refining the Offshore Records of Earthquake Shaking

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The Cascadia Subduction Zone has a well-developed marine paleoseismic record, yet uncertainties in age and correlation among deposits over long distances, as well as questions about triggering mechanisms make it difficult to distinguish the length and magnitude of shaking in past events. Hill et al. (2022) proposed that pervasive mass wasting of the lower slope in Cascadia is a primary source of abyssal seismoturbidites that would avoid many of the pitfalls and arguments commonly made against turbidite stratigraphy and allow for new sampling locations that fill critical spatial gaps in the existing records. To test this hypothesis, we collected 8-9m piston cores from 20 new sites in central and northern Cascadia, on the abyssal plain proximal to the deformation front and from isolated lower slope basins. Several of these sites are complemented by detailed AUV bathymetry and subbottom data, along with transects of closely spaced, ROV-based <2m vibracores. Our preliminary age dating shows these new sites contain a robust record of Holocene abyssal turbidites that are most likely derived from strong earthquake shaking. Initial radiocarbon dating and age models from several of our sites suggest chronologic correlation of the seismoturbidites along large stretches of the margin. There are distinct differences in deposit characteristics (e.g., range of grain sizes or number of pulses) that vary over both time and space, and likely reflect the inputs of multiple slope failure sources during a given event. The type and degree of earthquake triggered slope failure is variable along the margin, such that some locations may contain extra and/or missing events, highlighting the need for detailed chronology. The spatial density of these new sites combined with the existing records offers a valuable opportunity to assess variability in earthquake rupture patterns along the Cascadia margin and provide insight into extent of slope failure along the margin. Our results also suggest similar seismoturbidite records may be found outside of submarine canyon systems on other subduction margins with a similar steep slope morphology.

POSTER 56

Urban Paleoseismology of the Taylorsville Fault - New Data and Challenges from one of the Last Remaining Trench Sites on the West Valley Fault Zone, Utah

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The intrabasin West Valley fault zone (WVFZ) in Salt Lake Valley, Utah, comprises two subparallel main strands—the Granger fault (western strand) and Taylorsville fault (eastern strand)—and is antithetic to the Wasatch fault zone (WFZ). Both strands trend through the densely populated Salt Lake Valley, making sites suitable for fault trenching very sparse. A scarp trenched at the Airport East site on the Taylorsville fault in 2015 has now been destroyed by urban development. In 2022, we conducted a fault-trench study at the Indiana Avenue site, one of the last remaining suitable trench sites on the Taylorsville fault. This site was previously a green-waste landfill; however, a relatively undisturbed, small (1.5 m) fault scarp crosses the site. The elevation of the site (1288 m) suggests it was submerged by multiple pluvial lake cycles during the late Pleistocene and Holocene, including lakes Bonneville and Gilbert. The site is at or just below the shoreline of the early Holocene highstand of the Great Salt Lake (1288–1289 m), and below shorelines related to the Gilbert lake episode (1294–1297 m). Our trenches exposed a sand deposit likely related to the regression of Lake Bonneville, a clay-marl deposit likely related to the Gilbert episode and very similar to deposits in other WVFZ trenches, a paleo-Jordan River floodplain silty-sand deposit, and several clay-rich wetland deposits. Both trenches showed evidence of fault-related monoclinal warping, but only one trench showed evidence of discrete faulting in the footwall. Trench depth was limited due to shallow groundwater at the site. Due to these constraints, our trenches only revealed evidence for one or possibly two surface-rupturing earthquakes. Radiocarbon and optically stimulated luminescence samples provide age control on deposits and earthquake timing. These data will help us compare ages of deposits and earthquake timing to the Airport East and other WVFZ studies, and improve our understanding of the seismogenic relationship between the WVFZ and WFZ.

POSTER 57

Middle to Late Pleistocene Faulting on the Puye Fault Zone, Española Basin, New Mexico

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The Española Basin in the central Rio Grande Rift (RGR) of northern New Mexico is a slowly deforming, 60-km-wide region with low geodetic extension rates (~1 mm/yr) and low-slip-rate (0.01–0.1 mm/yr) Quaternary-active faults. While previous work suggests that deformation is accommodated by the Pajarito fault on the western side of the basin, new evidence from neotectonic mapping on 1-m lidar-derived topography and offset geomorphic surfaces suggests that additional RGR faults may have higher slip rates than previously thought. We focus on the Puye fault, a distributed fault system in the central-western Española Basin. The fault zone has at least four subparallel primary strands that offset the same geomorphic surface with a primarily down-to-the-east sense of motion. The fault trends north-south and mapped scarps extend at least 12 km. The highest scarps record up to 12 m of net vertical separation. We excavated three 1- to 2-m-deep pits atop the faulted surface to collect cosmogenic ^{10}Be and optically stimulated luminescence (OSL) samples to constrain surface ages, pedogenic character, and calculate a slip rate on the Puye fault system. Based on soil development and correlation with similar regional surfaces, we estimate this surface could be Middle Pleistocene (~130 - 774 ka), pending geochronology results. If the age for the faulted surface is middle-late Quaternary, slip rates may exceed known rates on the Pajarito fault (0.1 mm/yr). In a wash that intersects the primary scarp, we observed ~1 m of down-to-the-east offset of fluvial sand and gravel units in a cutbank exposure. Pending OSL ages from the cutbank will test the hypothesis that this exposure records recent fault activity. The presence of smaller offset amounts on potentially younger inset deposits, if confirmed, would indicate the Puye fault system has accommodated several large earthquakes during the middle to late Pleistocene. The results of this work will be used to characterize the Puye fault and reduce uncertainties in inputs for site-specific probabilistic seismic hazard analyses at nearby dams and regional seismic hazard models.

POSTER 58

Chirp Correlation and Acoustic Characterization of Lacustrine Turbidite Deposits in Lake Ozette, Wa Using Ct-Derived Density, Synthetic Seismograms, and Advanced Chirp Processing

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Lacustrine turbidite deposits provide a high-resolution record of earthquake shaking. Turbidite deposits are characterized by graded, fining-upwards sequences deposited by turbulent flows, which can generate pronounced impedance contrasts in chirp data depending on the composition and thickness relative to background sediment. Turbidite acoustic expression is also controlled by the characteristics of the chirp sound source and the signal processing applied. Identifying turbidite beds within chirp data using a set of specific acoustic properties enables us to map the spatial and temporal distribution of the sandy turbidite beds and allows the selection of coring sites for sampling and dating. We utilize two composite sediment cores measuring 12-14 m in length, additional short cores, and chirp profiles from Lake Ozette in NW Washington to quantitatively characterize and precisely compare proximal and distal turbidite deposits from their source. Advanced processing is applied to the chirp data to broaden the frequency spectrum, allowing for detection of sand beds thinner than 1 cm. Where chirp data intersect the core sites, a stochastically representative wavelet is extracted for synthetic trace modelling. Gas expansion cracking in cores introduces inaccuracies in gamma bulk density measurements, resulting in synthetic seismograms that do not correlate with the chirp data. To obtain reliable density measurements, we use CT scans of the cores to determine the intensities of uncracked sediments, followed by the fitting of a regression curve limited to the gamma density values with void space in CT images < 2.5%. This regression curve predicts bulk density values using the CT intensity values that are combined with p-wave velocities to generate a synthetic seismogram. The resulting synthetics allow use to accurately correlate with the core-chirp data and demonstrate the acoustic variations of turbidites from proximal to distal sites. Additionally, our findings emphasize both the ability and limitation of using chirp data to observe variations in thickness, density, and vertical separation of turbidite deposits.

POSTER 59

How Do Large Lakes in the Seattle Area Respond to Different Sources of Seismic Shaking? Revisiting Lake Washington and Lake Sammamish With New High-Resolution Data

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The Puget Sound region is susceptible to a variety of seismic hazards, including intraslab and crustal earthquakes, as well as megathrust earthquakes from the Cascadia Subduction Zone. To better characterize these hazards, the USGS is working on a multiyear project at sites spanning the Olympic Peninsula coast to the eastern Cascades to understand how sources of ground motion from different faults manifest in the lake basins. Here, we present results from two large lakes in the Seattle area: Lake Washington and Lake Sammamish because both lakes are located within a zone projected to experience strong to very strong ground motions during a Cascadia megathrust event. Additionally, these lakes are also surrounded by several crustal faults, and have experienced historical shaking due to deep intraslab earthquakes. The USGS led two multi-week field campaigns in 2021 (Lake Sammamish) and 2024 (Lake Washington) acquiring high-resolution bathymetry data, chirp subbottom profiles, and sediment cores. In both lake basins, bathymetric data reveal multiple slope failures along the flanks, while chirp data uncover details of post-glacial sedimentation patterns, including evidence for older, buried mass transport deposits and deformation associated with the Seattle fault. Mazama ash deposits identified throughout the Lake Sammamish stratigraphy, in cores and subbottom data, provide chronological markers that are used to build preliminary age-depth models. Our preliminary interpretation suggests that most of the larger subaqueous mass transport deposits visible in the bathymetry are pre-Holocene, whereas previous work suggests that large failures observed in Lake Sammamish may be linked to earthquake(s) in the Seattle and Saddle Mountain fault zones in 923-924 CE. The apparent absence of subsequent large-scale slope failures here raises questions about basin's response to shaking from Seattle fault ruptures. Ongoing work includes detailed stratigraphic mapping, additional age dating of turbidite event deposits, and comparison with a series of lakes across latitudinal and longitudinal gradients in the Pacific Northwest.

POSTER 60

Variations of the 1959 m7.3 Hebgen Lake Earthquake Record in Four Proximal Lacustrine Systems, West Yellowstone Region, USA

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The M7.3 1959 Hebgen Lake earthquake in southwestern Montana is one of the largest earthquakes recorded within the Intermountain West, United States. Ground-shaking and hanging-wall subsidence caused an approximately 6-meter-high seiche in Hebgen Lake, liquefaction features in adjacent valleys, a massive landslide that dammed the Madison River to form Earthquake Lake, and increased activity in hydrothermal systems of the Yellowstone caldera. Accordingly, lakes within the southern Madison and eastern Centennial Valleys, ≤25 km from the epicenter, experienced shaking of Modified Mercalli Intensity VI-VII. We characterize how the 1959 earthquake signature is recorded in the stratigraphic record of four lakes in this area that have varying morphometric and hydrologic properties such as depth, shape, surface area, and catchment area. We present data from 24 sediment cores along transects of Wade Lake (9 cores), Cliff Lake (5 cores), Hebgen Lake reservoir (3 cores), and Henry's Lake (7 cores). Each lake records background sediment consisting of laminated to thinly bedded silt and sand with distinct sedimentary disturbances such as 1) normally graded sand beds, 2) massive, poorly sorted deposits, and 3) macro floral debris, all likely indicators of the 1959 Hebgen earthquake. To test this hypothesis, we use fallout radionuclide ^{137}Cs, where concentrations become measurable after 1954 CE and the maximum value indicates 1963 CE. Preliminary ^{137}Cs concentrations and their locations in the Henry's Lake core support the interpretation of the disturbance horizons being formed by the 1959 earthquake. Fallout ^{137}Cs data are pending to constrain the timing of disturbance horizons for the remaining three lakes. Comparing characteristics of the 1959 event deposit in these four lakes will illuminate how differences in lake morphometry or setting may impact lacustrine records of strong ground shaking. Ultimately these observations will help calibrate how Intermountain West lakes record strong shaking and facilitate comparisons to both terrestrial and lacustrine paleoseismic data globally.

POSTER 61

Evidence of Past Earthquakes Preserved in Coast Redwood Trees Along the Northern San Andreas Fault

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Prior to the 1906 San Francisco earthquake, the rupture history of the North Coast section of the San Andreas Fault is not well constrained. Current age bounds for the penultimate event are broad, generally spanning over a century (e.g., 1660–1812), based on radiocarbon dating of trench exposures and turbidites. Dendrochronology has the potential to provide much tighter constraints by crossdating growth rings associated with direct and indirect impacts to trees growing on or adjacent to surface ruptures, but past attempts to utilize long-lived coast redwoods (*Sequoia sempervirens*) failed due to difficulties in crossdating this species. Here, we leverage recently developed regional reference chronologies for a new dendroseismological investigation of *Sequoia sempervirens* trees and stumps along the San Andreas Fault near Gualala and Fort Ross, California. We developed the novel technique of using rope climbing to collect samples in the vicinity of external indicators of potential seismic damage on living trees, such as reiterated trunks that formed after top breaks, sympodial growth (expressed as trunk kinks), and rightening of trunk leans. We collected increment cores (up to 56 m above ground) from nine living trees, as well as sections from 23 stumps of historically logged trees that may extend the record further. These records are being analyzed for growth changes and anatomical indicators. We have found tree ring indicators of the 1906 earthquake including likely initiation dates for reiterated trunks, wood anatomical indicators, and locally absent growth rings. We show within-tree variation in the expression of dendroseismological indicators. We detail several disturbance events that may represent the penultimate earthquake, with the caveat that non-seismic causes cannot yet be confidently excluded because these trees grow in a disturbance-prone environment. As part of ongoing research, we plan for additional sampling of damaged trees as well as continuing our efforts to fully crossdate all samples in order to confidently identify the penultimate earthquake by its contemporaneous effects in many trees.

POSTER 62

Ground Surface Rupture Complexity on the Northern Alpine Fault, Aotearoa New Zealand

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Lidar data and field observations are used to investigate the factors influencing rupture morphology complexity along the Northern Alpine Fault in Aotearoa New Zealand. Structural and geomorphic mapping covering approximately 220 kilometres of the fault reveals enhanced rupture complexity at fault junctions and distinct variations in rupture complexity with geological and topographic variations. Measurement of fault zone widths at 50-meter intervals and fault corrugation analysis is used to quantify along-strike complexity. Rupture mapping results are used to speculate on rupture processes and extents in past and future Alpine Fault earthquakes.

POSTER 63

Using Modern Fires to Estimate Charcoal Age Inheritance at Paleoseismic Sites in California

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The age of past earthquakes is typically calculated from radiocarbon-dated sequences of late Holocene deposits. Radiocarbon dates on charcoal provide a maximum age for the deposits because the age of plant material burned, the frequency of fire, and the rapidity of transport for detrital pieces make the charcoal age older than the deposit age. This age difference, known as the "inherited age" can be tens to hundreds of years but most studies assume it is short and do not formally address the impact on event dating. To quantify inherited age in the California Transverse Ranges, we dated charcoal deposits from two recent fires that burned at two paleoseismic sites along the San Andreas Fault (the Grand Fire in 2013 at Frazier Mountain and the Bobcat Fire in 2020 at Pallett Creek). The genus (e.g., Quercus, Arctostaphylos) or plant part (grass, leaf, bark) were identified for each of 53 dated samples prior to dating. We find that (1) inherited ages are the same at both sites despite differences in catchment size and fire histories, (2) short-lived or annual plant parts (grasses, leaves) or composite samples of fine charcoal are typically younger than twig or wood samples from longer-lived genus, and (3) combining all dates, the average charcoal age precedes the date of the deposit by ~25 cal years (300-year 95% range).

We next use the distribution of inherited ages as an empirical prior in Bayesian modeling of late Holocene deposits within OxCal (Bronk Ramsey, 2021). First, we correct the inherited age distribution to account for larger radiocarbon calibration uncertainties for dates prior to 1955 CE. The corrected inherited age distribution has mean age of ~90 cal years (470-year 95% range). Second, we examine how using this corrected distribution impacts layer and earthquake ages in a synthetic stratigraphic model. We find that layer and earthquake ages are younger when the prior is applied, but rather than a static offset, the effect is variable and limited by the amount of time between dated layers. Future efforts will examine the effect on existing paleoseismic sites such as Pallett Creek and Frazier Mountain.

POSTER 64

Refined Timing and Estimates of Coseismic Subsidence at the Southern Cascadia Subduction Zone: Combining Modern Dendrochronology, Age Modeling, and Relative Sea-level Reconstruction Techniques in the Eel River Valley, CA

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Geologic evidence from tsunamis and great earthquakes in the Cascadia Subduction Zone is observed at dozens of sites along the coasts of California, Oregon, Washington, and British Columbia. Paleoseismic data at the southernmost of these sites, the Eel River valley, is key to determining the along-strike heterogeneity in rupture characteristics during the most recent, 1700 CE, and older subduction zone earthquakes. Three decades ago, paleoseismic data was first documented at the lower Eel River valley, but conventional dating techniques and microfossil-based paleoenvironmental reconstructions provided coarse estimates on the timing and amount of coseismic subsidence. These coarse estimates place limited confidence on correlations between the Eel River event stratigraphy and more precise chronologies at sites further north. Recent advancements in age-depth modeling, dendrochronology, and paleo-environmental reconstructions provide the opportunity to reexamine the tidal wetland sequences at the Eel River valley.

To improve estimates of earthquake timing and coseismic subsidence, we apply a radiocarbon sampling strategy that includes inter-event stratigraphy, construct multiple Bayesian age-depth models, use a fossil foraminifera Bayesian transfer function, and employ dendrochronological dating on tree roots. We reoccupied previously described sites to collect new sediment cores. We present preliminary results based on 15 radiocarbon ages and changes in fossil foraminifera assemblages across two mud-over-peat contacts. In-growth-position Sitka spruce root wads emerge from cutbanks at two sites along the Eel River. These root wads are just below the shallowest subsidence contact, which is capped by silty sand. We collected 25 root samples to obtain tree ring widths and stable oxygen isotope data to correlate between individual trees at the two sites, crossdate to nearby old-growth redwood records and potentially determine the calendar year-of-death. Refined earthquake ages and more precise coseismic subsidence estimates will advance understanding of past Cascadia earthquake ruptures and their ensuing hazards.

POSTER 65

Off the Beaten Path: Preliminary Results of Reconnaissance Paleoseismic Surveys in Remote Alaskan Lakes

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South-central Alaska contains hundreds of remote lakes that cannot be accessed by road but are nevertheless in locations that experience strong ground motions related to Alaska-Aleutian plate boundary seismicity. To facilitate scientific investigations of these remote lakes, the U.S. Geological Survey (USGS) developed a highly portable surveying platform (including transportation via float plane), capable of collecting both high-resolution sub-bottom and multi-beam bathymetry data, as well as ~2m long percussion-driven gravity cores. This study will show preliminary results from two remote lakes, Chelatna Lake located ~150 km north of Anchorage and Allison Lake located south of Port Valdez.

Chirp and bathymetry data in both lakes show evidence for widespread slope failures, including a large 4+ meter thick mass transport deposit (MTD) that extends across the entire lake basin in Chelatna Lake. Sediment cores contain varved stratigraphy (i.e., annual laminations), which are interrupted by silty-sand fining upwards event deposits, interpreted as either seismically or climatically generated turbidites, as well as some tephras. Radionuclide age models (i.e., Cs137/Pb210) suggests that both lakes have recorded historical earthquakes including the 1964 Mw 9.2 Great Alaska Earthquake. The sediment record at Chelatna Lake contains evidence for up to 23 earthquakes in the last ~1800 years. The combination of varved stratigraphy (with potentially annual age resolution), the sensitivity to both historical earthquakes and climate events, together with evidence for older (likely) earthquake-triggered MTDs, motivates expanded coring operations at both lakes. In the Summer of 2024, a collaboration between Northern Arizona University and the USGS will deploy a UWITEC hybrid coring platform capable of recovering 12-18m long piston cores. Cores of this length have the capability of recovering long records that may span many earthquake cycles and extend the climate proxy record to the early Holocene or beyond.

POSTER 66

A Comparative Study of Earthquake Ground-Shaking Site Effects From Lacustrine Sediments in a Subduction Zone Setting Using Active and Passive Seismic Methods

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Lacustrine paleoseismology has evolved into a primary technique to reconstruct the recurrence of ground motion at a given site. Different types of sedimentary shaking imprints (e.g., turbidites, landslides) have been linked to various seismic ground motion parameters (e.g., intensity, duration, frequency

content). Understanding the depositional characteristics of such imprints thus has great potential to improve local seismic hazard estimations. By defining ground-motion threshold values for the appearance and absence of certain coseismic imprints, earthquake magnitude and source location can be estimated via ground-motion modelling. However, up to now the input for these models has remained limited to rather qualitative measures of strong ground motion that are poorly physically constrained (i.e., macroseismic intensity). This is partly related to the gap in our understanding of the site characteristics of lake sediments, as direct observations of seismic shaking on the bottom of a lake are scarce.

To get a first idea on the variability of ground-shaking site effects in lakes and how these relate to the depositional environment, we study two sites in southern Chile and south-central Alaska located at ~200 km from the subduction trench by analyzing ambient noise geophone array registrations as well as hammer seismic data. The Alaskan site consists of a 4.4 km² drained proglacial lake in mountainous terrane (Iceberg Lake) containing ~1500 years of outcropping sediments in an actively eroding environment. In Chile, measurements were performed along the shores of the 860 km² piedmont Lago Llanquihue, where lake sediments with an (up to now) unclear age are buried at shallow depth. Preliminary analysis shows that Vs30 values are very similar, while H/V spectral ratios and fundamental frequencies are more variable within and between sites, emphasizing the need for detailed site studies in any lacustrine paleoseismic study. Ongoing analysis will focus on understanding the origin of these differences, and how this knowledge can contribute to the interpretation of other lacustrine paleoseismic records.

POSTER 67

Temporal Clues Point to an Along-Strike Cascadia Megathrust Rupture Sequence Between 680–950 Years Ago

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Globally, subduction zones have ruptured piecewise in sequences of great earthquakes, yet conclusive evidence of along-strike ruptures of separate sections of the Cascadia megathrust, occurring within decades to centuries, is scarce. Here, we reevaluate ages for stratigraphic evidence of earthquakes over a ~270-year interval and show that the ages are consistent with three separate ruptures of the northern, central, and southern sections of the Cascadia megathrust. Most ages for coseismic coastal subsidence, tsunami inundation, and seismic shaking use radiocarbon methods with age uncertainties that span decades to centuries. Many studies use the overlap of age ranges (probability density functions, PDF) to infer maximum rupture length based on temporal correlation of dated evidence from Cascadia sites tens of kilometers apart. We take a different approach and look for differences in ages, in the interval 680–950 years ago, for great earthquakes at 10 sites that span a distance of 860 km between the Strait of Juan de Fuca, WA and Humboldt Bay, CA. Prior studies used PDF overlaps of ages in the same time interval at these sites to infer a ~610 km-long rupture between Humboldt Bay and the Columbia River. However, when grouped by site proximity and combined using OxCal (Bronk Ramsey, 2009), the PDFs fail a X^2 goodness-of-fit test. The statistically different combined PDFs along strike support an alternative hypothesis of sequential rupture of the southern (950–870), northern (890–790), and central (760–680 cal yr BP) sections. Stratigraphic support for piecewise rupture includes: tsunami and shaking deposits in Bradley Lake that suggest ruptures of adjoining central and southern sections; and contact W at Willapa Bay, which may mark less coastal subsidence during a northern rupture. Although statistical tests cannot rule out full-margin rupture, the data also support the hypothesis of along-strike rupture sequences. New dating techniques (dendrochronology, luminescence) and alternative age models can further test full-margin versus piecewise rupture hypotheses to improve Cascadia earthquake hazards assessments.

From Geodynamics to Earthquake Rupture, Models That Cross Time- and Length-Scales

Oral Session • Friday 3 May • 4:30 PM Pacific

Conveners: Matthew Knepley, University at Buffalo (knepley@gmail.com); Louis Moresi, Australian National University (louis.moresi@anu.edu.au)

Linking Geodynamic-Seismic Cycling Models With Earthquake Dynamic Rupture Models: 5 Choices to Consider

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By linking a subduction zone geodynamics and seismic cycling model (SCM) to a dynamic earthquake rupture model (EQM), we produce a realistic megathrust earthquake from initial conditions that are physically consistent with one another and long term subduction. The SCM (van Dinther et al. 2013, 2014) begins with a geodynamics phase, then transitions to a seismic cycle phase in which slip instabilities arise spontaneously without a prescribed fault. The material properties, stress field and fault strength parameters at the start of one SCM slip event are mapped to the EQM. The fault geometry is set a priori in the EQM using the locations of maximum strain rate over the entire SCM slip event. The EQM is run with SeisSol (Pelties et al. 2012, 2014), which captures the complete rupture dynamics and seismic wave propagation. We highlight certain linking choices for discussion and future consideration: (1) 2D to 3D mapping: We assume that the fault geometry, material properties, stress and frictional parameters from the 2D SCM are constant in the along-strike direction in the 3D EQM, a technically simple approach that likely does not reflect subduction zone characteristics. (2) Poisson's ratio, ν: The SCM assumes incompressible rock with $\nu = 0.5$, which is valid over long time frames, but not appropriate for modeling earthquake rupture dynamics. We choose $\nu = 0.25$ for the EQM, but note that ν influences slip magnitudes. (3) Static fault strength: We assume that the effective mean stress in the SCM is equivalent to the effective normal traction along the EQM fault, which appears appropriate up to ~30 km depth in these models, but alternatives could be considered. (4) Frictional weakening: Coseismic weakening is better modeled in the EQM than in the SCM, challenging our use of the SCM to assign dynamic coefficients of friction and slip-weakening distances. In addition, the SCM includes rate-strengthening in shallow sediments, which is honored in the EQM only by varying the coefficients of dynamic friction here. (5) The topography developed during the SCM is not mapped to the EQM.

Using a Multi-Cycle, Physics-Based Earthquake Simulator to Explore Rupture Connectivity for Seismic Hazard: The Aotearoa New Zealand Example

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Recent earthquakes demonstrate how complex earthquake rupture processes can be: examples include the multi-fault 2016 M7.8 Kaikōura (Aotearoa New Zealand) and 2019 M7.1 Ridgecrest earthquakes and the 2023 Kahramanmaraş earthquake sequence (Türkiye). It is important to account for the possible future occurrence of multi-fault earthquakes and sequences in seismic and tsunami hazard models. However, this is often challenging due to uncertainties on the timing of paleoearthquakes and the short duration of the historical record. To date, efforts to incorporate multi-fault rupture into seismic hazard models have often relied on empirical relationships, which are constrained by few $M \geq 7.5$ earthquakes, and multi-fault earthquakes have been largely ignored in probabilistic tsunami hazard models. Physics-based earthquake simulators like RSQSim — built on simple models of loading and stress transfer across a fault network — offer an alternative pathway toward identification of groups of faults that may rupture simultaneously in a multi-fault earthquake or closely spaced in time during complex earthquake sequences.

We present a 90 thousand-year synthetic earthquake catalog created using RSQSim and a 3D model of 469 crustal and subduction faults. We compare rupture connectivity of synthetic events in this catalog with the ruptures used as inputs for the 2022 Aotearoa New Zealand Seismic Hazard Model (NZSHM22). We find that: (1) Rupture connectivity of earthquakes in our synthetic catalog is high, with 46% of MW≥7.0 earthquakes rupturing multiple faults; (2) the longest earthquake ruptures in the synthetic catalog are significantly shorter than the longest ruptures in NZSHM22; and (3) inclusion of the Hikurangi subduction interface in the model increases rupture connectivity among crustal faults, but not the overall along-strike length of crustal ruptures. Further sensitivity testing is required, but initial models indicate that physics-based earthquake simulators represent a promising way to generate multi-fault earthquake inputs for seismic and tsunami hazard models.

Bridging the Gap Between Millions of Years and Milliseconds in Visco-Elasto-Plastic Subduction Earthquake Sequence Models

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Deformation in subduction zones is characterized by the interaction of multiple deformation processes that occur over a wide range of temporal and spatial scales. Basing earthquake sequence models on continuum mechanics allows simulating a large spectrum of visco-elasto-plastic deformation, including earthquake dynamics, spontaneous fault evolution, lithospheric deformation, mantle flow, and topographic evolution [1]. Such seismo-tectonic models have been unable to resolve coseismic time scales, hence not providing insight into all stages of the seismic cycle. Understanding the interaction between slab, overriding plate, and mantle on sub-year time scales has therefore been difficult. We simulate the coupled mechanical and thermal evolution of a subduction zone with a visco-elasto-plastic rheology. We self-consistently evolve a mature subduction zone with a heterogeneous subduction channel by simulating the subduction of a 2D slab for 4 million years. Adopting an invariant reformulation of rate- and state-dependent friction and an adaptive time stepping scheme [2] enables us to span the gap between millions of years of tectonic evolution and milliseconds of seismic rupture. We resolve all relevant time scales of the seismic cycle in a realistic subduction zone setting. Depending on the characteristic slip distance and the ratio of seismogenic zone width over nucleation size W/h*, we generate slow slip events with slip rates between 10^{-8} m/s and 10^{-4} m/s and earthquakes with slip rates on the order of m/s. Earthquake nucleation and propagation is fully resolved and leads to the generation of seismic waves. Earthquakes nucleate in the heterogeneous subduction channel near the 350°C isotherm and propagate upwards to arrest at the up-dip velocity-strengthening segment. We will comment on technical challenges, enabling cross-scale modeling of increasingly complex scenarios and its potential.

References

[1] van Dinther et al., JGR, 2013b, doi.org/10.1002/2013JB010380

[2] Herrendörfer et al., JGR, 2018, doi.org/10.1029/2017JB015225

Fully Dynamic Earthquake Cycle Modeling to Explore Interactions Between Large Earthquakes and Slow Slip Events on Heterogeneous Faults

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Recent observations show interactions between large earthquakes and slow slip events (SSEs). To understand physics underlying these observations, we need to resort to physics-based models that can capture both spontaneously dynamic rupture during large earthquakes and quasi-static deformation processes (including slow slip events) between earthquakes. These models cross multiple time- and length-scales. In this study, we apply a recently developed method for this type of models, a Finite Element Method (FEM) dynamic earthquake simulator, EQdyna, to perform fully dynamic earthquake cycle modeling on a shallow-dipping subduction plane to investigate interactions between large earthquakes and SSEs. The method distinguishes itself from classical, quasi-dynamic earthquake simulators in the community that do not capture spontaneous rupture propagation. We are particularly interested in how heterogenous frictional properties on the fault plane dictate generation of large earthquakes and SSEs and their interactions over multiple earthquake cycles. In our models, multiple asperities with unstable slip frictional properties are distributed on a subduction plane with conditional stable frictional properties. We vary the asperities' sizes and locations to explore their effects. Our preliminary results successfully reproduce depth-dependent modes of SSEs observed at the Hikurangi subduction zone in New Zealand that shallower SSEs happen more frequently with shorter durations at low stress. Notably, our findings elucidate distinct loading effects of SSEs associated with small asperities at different depths on large earthquakes. In addition, models with numerous tiny asperities reveal a higher SSE occurrence frequency, suggesting these areas act as barriers for large earthquake rupture propagation.

Insights Into Fault Interactions in Central New Zealand Using Paleoearthquake Records and Earthquake Simulators

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Forecasting the probability and magnitude of future large magnitude earthquakes is typically dependent on available paleo- and historical earthquake information. In Aotearoa-New Zealand (A-NZ) historical records (post 1840AD) demonstrate that many large earthquakes (e.g., >Mw 7.0) rupture multiple faults with complex rupture patterns and/or trigger additional earthquakes. To improve understanding of the importance of temporally clustered earthquakes, we compare the timing of earthquakes between active faults in central A-NZ using paleoseismic and historical records and a synthetic earthquake catalogue. To support this comparison we have revised paleoseismic records for key faults to determine the frequency of spatial-temporally clustered earthquakes. These short geological records (e.g., < 20 kyr) are compared to synthetic earthquake catalogues produced by physics-based RSQSim simulations for timescales of ~300 kyr. The paleo-record indicates that earthquakes on neighbouring faults are often close in age, suggesting spatio-temporal interactions between faults. Due to uncertainties in the radiocarbon dating, this clustering could arise from multi-fault ruptures and/or triggered slip in separate earthquakes. Both scenarios are represented in the RSQSim catalogues, with co-rupture of the Hikurangi subduction thrust and upper plate faults being common. Multi-fault and triggered earthquakes both suggest stress interactions between faults on timescales of seconds to hundreds of years and temporally variable seismic hazards. These fault interactions have important implications for time-dependent seismic hazard in central A-NZ and will be explored further using RSQSim models.

From Geodynamics to Earthquake Rupture, Models That Cross Time- and Length-Scales [Poster Session]

Poster Session • Friday 3 May

Conveners: Matthew Knepley, University at Buffalo (knepley@gmail.com); Louis Moresi, Australian National University (louis.moresi@anu.edu.au)

POSTER 94

Bridging Spatial and Temporal Scales in Modeling Coseismic and Interseismic Crustal Deformation with PyLith

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We present an overview of PyLith's current capabilities for modeling coseismic and interseismic crustal deformation across a broad range of spatial and temporal scales. PyLith is an open-source finite-element code designed for modeling earthquake faulting processes by solving partial differential equations, with faults modeled as dislocations on interior interfaces. For solving the elasticity equation PyLith includes two formulations: (1) an implicit formulation without inertia (quasistatic), which is generally used for modeling interseismic viscoelastic or elastoplastic deformation on time scales of years, and (2) an implicit-explicit formulation with inertia (dynamic), which is generally used for modeling coseismic elastic or elastoplastic deformation on the time scales of seconds. We use finite-element discretizations, time-stepping algorithms, and solvers from the Portable, Extensible Toolkit for Scientific Computation (PETSc) to provide users with scalable options for modeling deformation on spatial scales ranging from tens of meters to hundreds of kilometers and temporal scales ranging from milliseconds to hundreds of years. Our multiphysics formulation provides flexibility in specifying a variety of physics with one or more governing equations; we have implemented elasticity, incompressible elasticity, and poroelasticity. We are currently working towards including adaptive mesh refinement capabilities to broaden the range of spatial scales modeled in a single simulation. This is also a stepping stone towards coupling the quasistatic and dynamic formulations to model earthquake cycles with propagating seismic waves during coseismic deformation and viscoelastic relaxation during interseismic deformation. PyLith is developed and distributed through the Computational Infrastructure for Geodynamics (https://geodynamics.org/resources/pylith) and includes source code, binary packages, online documentation (https://pylith.readthedocs.io), video tutorials, and a Docker container for software development.

POSTER 95

Spatiotemporal Evolution of Postseismic Stress and Aftershocks Following the 2010 Mw 8.8 Maule Earthquake

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Following major earthquakes in subduction zones, transient deformation and aftershocks occur. The spatiotemporal behavior of seismicity and its controlling physical mechanisms continue to be debated among geoscientists. Here, we focus on the space-time distribution of postseismic stress changes and aftershocks in subduction zones with a case study of the 2010 Mw8.8 Maule earthquake in Chile. Previous studies have identified pore pressure diffusion as a possible mechanism of the aftershocks that followed the 2014 Mw8.1 Iquique earthquake and linked the spatial migration of aftershocks around the rupture region of the 2015 Illapel earthquake to poroelasticity. Motivated by these examples, we design three-dimensional finite-element models to explore the seismic and aseismic megathrust behavior during the Maule earthquake sequence. We first compare results from our 3D models with the coseismic displacements of the Maule event. We then use time-dependent 3D models to simulate postseismic afterslip, poroelastic rebound, and viscoelastic relaxation and characterize the spatiotemporal patterns of the deformation and Coulomb stress change. Poroelasticity produces positive and negative Coulomb stresses above and below the fault plane, respectively, with its temporal decay faster than viscoelastic Coulomb stresses. The viscoelastic scenario produces mainly positive Coulomb stresses that are concentrated within and below the slab, with stress amplitudes depending on the viscoelastic rheology and crustal thickness. However, the viscoelastic stresses are at least two orders of magnitude smaller than poroelastic stresses, indicating its potential impact mainly on long-term triggering of seismicity. We next compare the characteristics of postseismic deformation and stress changes in our models with the aftershocks from Maule to understand the mechanisms that control seismicity evolution in space and time.

POSTER 96

Geodynamic Modeling of Flat Slab Subduction Driving Microplate Tectonics in Alaska

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The Aleutian-Alaska subduction zone (AAS) forms the northern boundary of the Pacific Ring of Fire, a tectono-physiographic term for the collection of subduction zones that outwardly flank the eastern, northern, and western perimeters of the Pacific Ocean. The AAS is characterized by ocean-ocean subduction in the west (Aleutian segment) and by ocean-continent subduction in the east (Alaska segment). We present high-resolution, 3D visco-plastic models of the Alaska subduction zone that examine the effect of laterally variable plate coupling on the 3D dynamic feedback between the upper- and down-going plates. In particular, the models examine the role of localized increased plate coupling in the flat slab region on the microplate motion of the portion of south-central Alaska located both above the flat slab and south of the Denali fault, hereafter referred to as the southern Alaska microplate (SAK). The results show a variably coupled subduction interface and weak Denali fault shear zone produce higher plateness for the SAK and a better fit to observed variability in long-term slip rates along the length of the Denali Fault shear zone. Further, by incorporating a 3D tectonic configuration, the models show the SAK (not the North American plate (NAM)) overlies the flat slab segment of the subduction zone. Given that the 1964 Great Alaska earthquake epicenter occurs where SAK (not NAM) is the upper plate, the models suggest a large-scale tectonic framework for this event wherein the SAK plays a key role; namely, the tectonic regime of southern Alaska is analogous to that of oblique flat slab subduction driving large-scale motion of the SAK, with the Great Alaska earthquake situated in this domain of restricted escape. This implies that the long-term tectonics of the Denali fault shear zone and flat slab subduction interface are interconnected through the motion of the intervening SAK. Therefore, treating these features as interconnected may be important for future hazard assessment modeling in Alaska.

POSTER 97

Fast and Slow Earthquakes in Alaska: Insights From Three-Dimensional Thermal Structure and Slab Dehydration

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Fast and slow earthquakes are predominantly generated along faults constituting active plate boundaries. Characterized by repeated devastating earthquakes and frequent slow slip events and tremors, the Alaska megathrust presents a chance to better know the complicated dynamics of a subduction system changing from steep to shallow dips associated with enigmatically abundant fast and slow seismic events. Based on three-dimensional thermal modeling, we find that the downgoing metamorphosed oceanic crust containing bound water releases a large amount of fluid and causes the recurrence of fast and slow earthquakes by elevated pore fluid pressure and hydrofracturing. The seismogenic interface and the slow slip events (SSEs) identified beneath the Upper Cook Inlet coincide well with the slab metamorphic dehydration regions. The observed slow earthquakes with quasi-stable fault slips preferentially occur, accompanied by high dehydration and temperature downdip along the transition zone.

POSTER 98

Modeling the Proposed Deep Slab-Deformation Processes Behind Potential Precursory Signals Preceding Large Subduction Zone Earthquakes

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Recent studies suggest that large-scale, transient signals in GNSS velocities, satellite gravity measurements, and intermediate-depth foreshock occurrences may precede large earthquakes in subduction zones. Specifically, investigations focused on the 2011 Mw 9.0 Tohoku-Oki and the 2010 Mw 8.8 Maule earthquakes found that these precursory signals preceded the respective main shocks by 2-8 months. If correctly resolved, these deformation signals appear to record a rapid geodynamic process occurring deep within subduction zones and may be instrumental in the initiation of some megathrust earthquakes. While qualitative models have been proposed to explain the physical processes behind these potential precursory signals, such as an intra-slab extension, mineral phase changes, and large-scale fluid flow, numerical models exploring Earth's geodynamic response to these processes have yet to be investigated.

Here, we use the finite element code Pylith to model geodynamic processes that plausibly occur deep within subduction zones, and that could produce the potential precursory signals observed. Given the high density of GNSS stations across Japan, we focus on the deformation preceding the 2011 Mw 9.0 Tohoku-Oki Earthquake. We model the intraslab extension and mineral phase change processes to obtain predicted surface displacements and compare those to GNSS observations of deformation prior to the earthquake. We explore how changes in rheological properties and subduction zone structure impact modeled predictions of surface displacement and gravity measurements for the tested geodynamic mechanisms. The model predictions and data comparisons will provide valuable insights into the plausibility of the proposed physical processes in generating the observed geodetic signatures. Furthermore, these models will help to establish how transient deformation deep within subduction zones may be expressed at Earth's surface independent of their timing with respect to great earthquakes.

POSTER 99

Geodynamic Models Connecting the Seismic Timescale to the Tectonic Timescale

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In Yang et al [2023], we demonstrated a numerical approach to solving the coupled tectonic and seismic-rupture problem in three dimensions using a modified version of the Underworld *python* software package that is optimised for tectonic and geodynamic modelling (www.underworldcode.org). We were able to meet a number of simple benchmark cases by introducing momentum terms and a non-linear, viscoelastic constitutive model with rate-state frictional behaviour in *a priori* specified fault zones.

This is a very intense computational problem that identified a number of pain-points for generalising our formulation to understand the two-way interaction between tectonics and earthquake cycles. These include: very large variations in resolution between fault regions and the embedding lithosphere; and comparable changes in the timestepping requirements between tectonic deformation and co-seismic deformation. In Underworld, the tracking of material properties, momentum / stress-history terms, and damage over significant strain is handled by a swarm of Lagrangian particles which we determined also required very high resolution.

We report our latest developments on a spatially-adaptive, unstructured, highly parallel, Lagrangian/Eulerian numerical tool (Underworld3) which is specifically targetted at problems of this nature. Underworld3 is designed to be particularly user-friendly - it integrates with the *jupyter* notebook system, is fully introspective and is fully integrated with the *sympy* package which allows mathematical introspection as well as the usual ability to probe running code that is common in *jupyter*.

Yang, H., Moresi, L., Weng, H., & Giordani, J. (2023). Numerical Modeling of Earthquake Cycles Based On Navier‐Stokes Equations With Viscoelastic‐Plasticity Rheology.*Geochemistry, Geophysics, Geosystems*, *24*(9), e2023GC010872. https://doi.org/10.1029/2023GC010872

How Well Can We Predict Broadband Site-Specific Ground Motion and Its Spatial Variability So Far?

Oral Session • Wednesday 1 May • 8:00 AM Pacific

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Site Response Characteristics from Ambient Noise Data Recorded on Degrading Warm Permafrost in Bethel, Alaska.

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Permafrost is experiencing accelerated warming due to anthropogenic activities and climate change. The intricate relationship between permafrost degradation and seismic attributes is significant to regions where both phenomena are prevalent, as it can exacerbate seismic hazards. There is a notable knowledge gap about this relationship. The current study aims to address the gap by analyzing twelve months of recorded ambient noise time series data from two accelerometers located on warm permafrost in Southwest Alaska. Both accelerometers were three-component EpiSensors connected with a 24-bit Delta-Sigma converter with a dynamic range of approximately 136 dB per channel (Etna-2 of Kinemetrics). Data from each sensor was sampled at 250 samples per second. An open-source, web-based application called HVSRweb was employed for horizontal-to-vertical spectral ratio (HVSR) processing; a processing window length of 60 seconds was used to create 60-time window lengths of 60 seconds each. The microtremor HVSR method provided insights into how the site response differs between winter and summer seasons. Comprehensive analysis of the time series data collected from the two seismic sensors during winter and summer revealed an obvious correlation between the frozen or unfrozen active layer conditions and ground motion amplification. Ground motion amplification was notably higher during summer with an unfrozen active layer. The peak fundamental frequency (f_0) of the HVSR has also been shifted towards the higher frequency side during the winter months due to frozen ground. These findings demonstrate the relationship between permafrost degradation and ground motion amplification, emphasizing the importance of permafrost degradation on seismic attributes. These observations are crucial for understanding and predicting the potential impact of permafrost degradation on the built infrastructure in future seismic events.

Improving the Performance of the SSRh Site-Response Assessment Techniques on a Dense Array in the Koutavos Basin (Greece)

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Earthquake site effects have a major impact on the seismic hazard. However, evaluating the site response over a broad frequency range and with a high spatial resolution remains difficult. Empirical site effect assessment has shown good reliability up to high frequencies but relies on earthquake recordings, which requires long station deployments. In contrast, seismic ambient noise can be rapidly recorded anywhere at any time. The hybrid standard spectral ratio (SSRh) combines both the spectral ratio from earthquake recordings at a few sites and the spectral ratio from ambient noise recordings at many sites from short duration deployments. Here we present and discuss the SSRh results from a dense array of 51 seismic nodes deployed in the Koutavos Basin in Greece. We report a good agreement between the SSRh method and the referenced method based on earthquake observations. Furthermore, we quantitatively evaluate the performance of applying various statistical and signal processing procedures in order to improve the SSRh method.

A Simple Way of Estimating Site Effect With Respect to a Distant Rock-Reference Site: Application of the Standard Spectra Ratio Technique Based on Coda Waves

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In recent years, site effect is considered having a major impact on the earthquake ground motion. Site effects can be described by the Site spectral Amplification Factor (SAF) which is directly controlled by surface geological conditions (briefly: hard rock to loose sediments into valleys). Several simple or more sophisticated techniques have been introduced in recent decades, with advantages and disadvantages leading to certain limitations. One of the most commonly applied SAF estimation techniques is the so-called Standard Spectra Ratio (SSR) (Borcherdt, 1970). However, this technique can only be applied if there is a rock reference station close to the studied site. This condition is obviously restrictive for all sites where no reference/rock station is installed nearby. In this study, the SSR technique is studied and examined based on Coda wave recordings, using time segments corresponding to the same travel time, based on more distant reference stations (thus bypassing the criterion of the nearby reference site). It should be noted that this technique, named SSRc (for SSR on coda waves), is simple to implement. It is an alternative to the more complex methods developed previously by Philips and Aki, (1986) and Grendas et al.,(2022a), which also use Coda waves, attempting and partially succeeding in relaxing the criterion of proximity to the reference site. The valid application of this new SSRc technique is supported based on analytical attenuation equations and synthetic parameters, as well as based on actual earthquake data. More specifically the SSRc technique is successfully applied here at several stations in two different seismicity contexts in wester Greece and southeastern France with high seismicity and low-to-moderate, respectively, using relatively distant reference stations (e.g. up to ~100km). The computed average SAF results, as well as their uncertainty, are encouraging compared to corresponding results extracted by alternative methodologies and different dataset, supporting thus further application and investigation of the proposed, and rather simple, SSRc technique.

CD-VAE-GMG: Conditional Dynamic Variational Autoencoder for Earthquake Ground Motion Generation

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Simulating earthquake ground motions is crucial for assessing seismic hazards and ensuring the safety and resilience of critical infrastructure. However, obtaining ground motion data across a wide geographic area with high spatial sampling is challenging and resource-intensive, especially for regions with infrequent seismic activity. This work proposes a novel Conditional Dynamic Variational Autoencoder (CD-VAE) framework to predict new seismograms from unobserved earthquakes at new sources and site locations. Specifically, we leverage the Short-Time Fourier Transform (STFT) to extract the time-frequency information and utilize the probabilistic autoencoder to learn the latent distributions based on the amplitude spectrogram. Both prior and posterior distributions are constructed with variational sequential models (i.e., recurrent neural networks) to facilitate capturing temporal dynamics. Furthermore, we apply the phase retrieval method to estimate the phase information from the reconstructed amplitude spectrogram and use inverse STFT to recover the corresponding waveforms. Moreover, our model is conditioned on specific physical parameters, such as earthquake magnitudes and the coordinates of sources and stations. This method is easy and stable for optimization compared with previous Generative Adversarial Network (GAN) models. We use a rich set of small-magnitude earthquake records from the San Francisco Bay Area. From 1.4 million horizontal component traces recorded at 266 sensors for 737 earthquakes, we select 5194 traces based on S/N ratios. The generated ground motions follow the PGV-magnitude and PGV-distance relationships of the observations. The Fourier amplitude spectra values show good agreement between observed and generated data over an entire range of frequencies (2-15 Hz) used in this study. We further checked the kinematics of the waveforms by picking P and S wave arrivals using PhaseNet. S wave arrivals are well reproduced while generated P arrivals tend to be earlier than the observation. These evaluations demonstrate the effectiveness of the proposed methods.

Euro-Mediterranean Hard-Rock Reference Ground Motion Model by Git-Based Site Response Deconvolution

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In the framework of site-specific seismic hazard assessment, the definition of reference motion is a crucial step. Reference motion is generally associated with hard-rock conditions, characterized by S-wave velocity (V_S) exceeding 2000 m/s. However, ground motion recorded at sites with such conditions is poorly represented in existing strong-motion databases. Thus, the validity domains of most empirical ground motion models (GMMs) are not representative of reference rock conditions. In order to overcome this limitation, we apply a deconvolution of site responses from strong-motion recordings to estimate ground motion at reference conditions in the Euro-Mediterranean context.

The first step was to compile a large database by aggregating the ESM database and additional data from the Greek, French, and Spanish networks. The second step was to estimate site response at network stations by carrying out parametric and non-parametric generalized inversion techniques (GIT). A careful selection of hard-rock reference stations was chosen to constrain the inversions. The database signals are then deconvolved using the site terms obtained by GIT, which makes it possible to virtually bring the sites of the entire database to very high V_S values (bedrock conditions).

GMMs are then determined for reference conditions and the results are discussed.

Observed Strong Motions and Site Effects During the Jan. 1, 2024 Noto-Hanto Earthquake in Japan and Its Reproduction Based on a Priori Information

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On January 1, 2024, the Noto-Hanto earthquake of Mw7.6 occurred a little offshore of the Noto Peninsula in Japan. The shaking caused devastating damage to wooden houses in rural cities and towns and local roads and expressways on the peninsula. The casualties were over 200, and the number of collapsed buildings could be over 10,000. The primary source of strong ground motions was the western side of the whole fault segment, which was extended bilaterally to SSW and NNE directions for about 70 to 80 km from the epicenter at the peninsula's tip. About 20 strong motion stations are operated by NIED and JMA within 60 km of the fault. The source was a south-dipping thrust fault, the activity of which forms the Noto Peninsula. The highest observed PGA was 2.7 g at one K-NET (NIED) site, ISK006 in Shiga Town, while the highest observed PGV was 1.5 m/s at ISK005 in Anamizu Town. We have visual evidence of the cyclic mobility phenomenon at ISK005, so the pore water pressure may play an important role at this site.

Before the earthquake, we performed the generalized inversion analysis (GIT) to separate source, path, and site terms from about 60,000 strong motion records in Japan for both the S-wave portion with the maximum duration of 15 seconds and the whole duration of motion. The resultant horizontal site amplification factor for the former is named sHSAF, while the latter is wHSAF. If we have no significant basin effects, their spectral shapes are quite similar, with some amplitude difference up to 2 times. If the sites are located inside sedimentary basins, a large discrepancy in amplitude in the smaller (0.1 ~1 Hz) frequency range can be seen because of the strong generation of the basin-induced surface waves. At 20 sites inside the Noto Peninsula, we cannot find such a site with a large contribution of the basin-induced surface waves, and therefore, we can use the 1D assumption to extract sHSAF or wHSAF from the observed data. We would like to show the validation exercise for our strong motion prediction technique based on GIT by using the observed strong motion data in the epicentral area of this earthquake.

Exploring the Spatial Correlation of Ground Motions During the 2019 Ridgecrest Earthquake Sequence

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We consider patterns in spatial correlations of recorded ground motions during the 2019 Ridgecrest earthquake sequence. Ground motions are known to vary widely from their median expected values, yet their spatial distributions are not entirely random. To accurately estimate hazard across distributed systems we must understand how ground motions correlate over a range of inter-station distances. The spatial correlation of ground motions has been widely studied, but data are lacking at short interstation distances. The 2019 Ridgecrest earthquake sequence presents a unique opportunity to examine spatial correlations at a range of interstation distances. Following the Ridgecrest earthquake, the permanent seismic network (Hauksson et al., 2020) was augmented with tens of strong motion and broadband sensors that were installed for several months (Cochran et al., 2020). Additionally, nodal seismic sensors were deployed for two-months at 585 recording sites with station

spacing as low as 100 m (Catchings et al, 2020). Using the gmprocess software package (Hearne et al., 2019), we determine peak ground velocity (PGV) and acceleration (PGA) for 16,416 recordings from 120 earthquakes (M3.3-M5.0). For each event and station pair, we compute the correlation of the within event residuals determined from the fit to the median ground motion model of Boore et al. (2014), considering local site conditions (Thompson 2020). We use the typical assumption that all locations separated by a given distance will have the same correlation and fit the results with an exponential semivariogram model (e.g., Baker and Chen, 2020). We find a nominal correlation distance (i.e., range measured from the fit to the exponential model) for PGA and PGV of approximately 20 km, similar to what has been found for other regions. We also explore whether the correlation distances vary spatially by determining correlation distances for sets of stations distributed around the Ridgecrest source rupture.

Use of Weak Motion Data to Constrain Site-Specific Ground Motion Estimates

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With the increasing recognition of the importance of non-ergodic components in a seismic hazard analysis, it is becoming increasingly more important to obtain site-specific amplification functions along with their uncertainties. The most common approach is performing site response analyses backed by detailed site characterization with measures of uncertainty. However, even detailed site response is still associated with significant epistemic uncertainty. An alternative approach would be utilizing recorded ground motions recorded at the site, if any, to constrain site effects. This approach is only viable if sufficient records are available at the site, which is generally not the case. However, for a seismically active region (such as California), rate of occurrence of small magnitude earthquakes (i.e., M_w<4.5) can be high enough for weak ground motions to be recorded using a temporarily deployed station within a practical timeframe, especially for the design of critical structures. This then raises the question: Can weak ground motions resulting from small magnitude events be used to constrain site effects? This study attempts to answer this question by investigating weak ground motions recorded in California from earthquakes with magnitudes ranging from 2.5 to 4.5. Using the ground motion recordings near two sites in Northern California, a generalized inversion technique was used to constrain source, path, and site terms, from which the site-specific transfer function with measures of uncertainty was estimated. The estimated transfer functions were compared with analytical transfer functions computed using 1-D site response analyses for two stations. The analytical transfer functions at these sites are slightly larger than the empirically constrained counterparts, thus overpredicting ground motions. Single-station variability at these stations suggests the empirical transfer functions are stable when there are enough ground motion recordings at the site. The approach proposed in this study can be employed to empirically constrain site response using weak recorded ground motions.

Ergodic and Non-Ergodic Ground-Motion Models for Small Magnitude Earthquakes in the San Francisco Region

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An important issue in the propagation of seismic waves at high frequencies into numerical simulations is the lack of knowledge of the 3-D velocity structure at short wavelengths. Empirical ground-motion data include the effects of the 3-D crustal structure at high frequencies, but to have enough observations, record- ings from small-magnitude events are used. To use the small-magnitude data to evaluate path effects requires a reference ergodic ground-motion model (GMM) to remove the average scaling and a non-ergodic GMM to identify regions with strong path effects.

In this study, we focus on the small magnitude earthquakes in the San Francisco region within 50km of the Hayward fault. From all the recordings available in the NCEDC in that region, only the recordings with a signal-to-noise ratio S/N > 3 are selected. The resulting dataset includes about 5,000 recordings from 346 events recorded at 151 stations, with magnitude 1.5 to 4 at rupture dis- tance Rrup < 100km. From this dataset, an ergodic GMM is developed, which includes the traditional magnitude, distance and depth scaling, and the source and site random effects. We also include a novel distance-dependent random effect on the source which removes the path effects that are sometimes mapped in the source random effect in traditional analysis. From the ergodic residu- als, a non-ergodic GMM is developed which captures the spatial variability of the source, site and path effects. The coordinate-specific source, site and paths effects show spatial correlation patterns which can be accurately modeled via Gaussian Processes (GP) that allow us to extrapolate them in space at unobserved source and site locations conditionally to observations and under physical constraints. As a result, the standard deviation of the residuals at high frequencies is reduced by a factor of 2 from the ergodic GMM compared to the non-ergodic GMM (1.1 to 0.52 at 15Hz). Going forward, the residuals of the ergodic GMM can be used as inputs to machine learning to develop non-ergodic path effects at high frequencies that can be compared to the results of the non-ergodic GMM based on GP.

Comparison of the Spatial Correlation of Non-Ergodic Terms in GMMs Utilizing Empirical and Simulation Data From Diverse Regions

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Recent studies, such as those by Sung et al. (2023) and Lavrentiadis et al. (2023), have developed non-ergodic GMMs, which incorporate the spatial distribution behavior of source, path, and site. These studies utilized the varying coefficient model (VCM) approach to account for the source, path, and site effects on ground-motion scaling for a specific site and source pair. The VCM considers the non-ergodic terms as spatially correlated random variables following assumed prior distributions, and it incorporates two hyperparameters derived from the posterior distribution: the correlation length and variance for each non-ergodic term. The hyperparameters aid in predicting the spatially correlated non-ergodic terms to adjust the ergodic model at a specific site. In recent studies, the hyperparameters have been estimated for six specific regions (California, France, Japan, Taiwan, Utah, and Cascadia) based on empirical data or simulation data. The non-ergodic terms include two site terms (one region site term that is spatially correlated and one uncorrelated site term), two path terms (one related to Q effects and one related to the 3-D velocity structure effects), and one source term. We compare the correlation lengths for the four spatially correlated terms for these six regions. Within the frequency range of 0.2-20 Hz, the correlation lengths from the VCM for the non-ergodic source, path, and site terms are in the ranges of 20-50 km, 15-45 km, and 10-30 km, respectively. A consistent result is that the correlation lengths for the source and site terms at frequencies higher than 10Hz are large (10s of km), which seems counterintuitive, but this may reflect regional kappa differences related to regional geology. In regions without enough data to estimate region-specific hyperparameters, the sets of hyperparameters from the six regions can be used in the forward prediction of the non-ergodic effects using the available region-specific ground-motion data.

Toward an Alternative Approach for Using VS Profiles in Estimating Seismic Site Response

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Two techniques dominate the assessment of seismic site response in engineering practice. First, ground motion models (GMMs) that use the slowness at the top 30 m (V_{S30}) as a proxy to capture the effects of the shallow sediments on the site amplification. Second, 1D site response analyses (1D SRAs) that use shear-wave velocity (V_S) profiles. It is expected that 1D SRAs lead to more accurate site response estimates at frequencies higher than a given site's fundamental frequency, as the entire V_S profile is used and provides additional information compared to V_{S30} alone. However, various studies have shown that 1D SRA-based site response estimates carry a significant bias and uncertainty. These observations raise the question of whether the information carried by V_S profiles adds additional value in 1D SRAs compared to V_{S30} in GMMs or whether alternative approaches for leveraging V_S profiles to estimate site response can be developed.

We investigate the ability of V_S profile-related parameters to contribute to the predictability of site response in the linear elastic range. A systematic evaluation using synthetic V_S profiles is conducted to examine the ability of V_S profile-related parameters to add to the predicting ability of V_{S30} alone in GMMs. V_S profile-related parameters considered in this study include (1) the maximum impedance contrast between consecutive soil layers, (2) the impedance contrast between the bedrock and the deepest soil layer, and (3) the V_S profile gradient. Preliminary results confirm that the investigated parameters have the potential to increase the predictive ability of site response models. In this presentation, I will show the trends observed for various site conditions, and preliminary results from an initial assessment using observations from borehole array sites.

Resonance vs Shape of Sedimentary Basins

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The dynamic behaviour of sedimentary basins is traditionally studied in the frame of 1D plane-parallel conditions, when the aspect ratio of the basin is low, or by means of 3D numerical models, trying to replicate the real case. The latter, however, require not always available parameters and rely on not always verifiable assumptions. Between the idealized 1D and the real 3D cases, an intermediate 2D idealized case can be conceived, whose properties constitute an important link to overcome the limitations of the 1D approaches and towards the understanding of the complexity of real 3D cases. This intermediate case was studied in the '80s by means of analytical approaches and is here more systematically explored, by exploiting the power of numerical methods. Thus, we study the relations between the modal frequencies of idealized 2D sedimentary filled basins and their geometrical properties, under different Vs gradients, to show what information, often unused, might be hidden in the resonance frequencies of basins. We show that when a basin geometry is not known, but its modal frequencies have been experimentally assessed, the proposed relations offer a quick estimate of its aspect ratio, maximum depth, and equivalent shear-wave velocity of the sedimentary filling. When the basin geometry is known, the proposed relations offer a prediction of the expected modal sequence, thus helping in the design of future field surveys to better characterize the basin fill. The proposed relations help understanding the main parameters governing the modal sequence in a basin and to quantify the role and the weight of each parameter. This also provides constraints on the information and the degree of accuracy effectively needed in the input parameters of site response analysis. The conceptual elements will be presented in a historical perspective.

Impact of Shallow Subsurface Stratigraphic Architecture on Shear-Wave Velocity Prediction: Examples From the Po Plain and Other Coastal Lowlands of Italy

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Detailed knowledge of shallow subsurface geology is essential to evaluate ground response analysis and seismic site characterization. However, for the investigation of the shallow velocity structure, stratigraphic architecture is often largely oversimplified. In this study, by adopting refined characterization of sediment cores, we portray a new modeling approach that can be applied to a wide range of coastal plains with no topographic relief, and used for reliable prediction of S-wave velocities at the scale of the whole sedimentary basin.

Within the uppermost 30 m, modern alluvial plains and coastal lowlands exhibit predictable facies architectures that reflect sedimentary evolution under global climate and sea-level changes. Following 25 years of research into the late Quaternary stratigraphy of the Po River plain, in Italy, we carried out the geophysical characterization of seven sedimentary units (lithofacies associations) that accumulated in distinct depositional environments (floodplain, swamp, fluvial channel, lagoon/bay, beach, shelf) or under particular conditions (paleosols). Individual lithofacies associations are typified by: (i) unique mechanical properties that cannot be captured by traditional engineering geology databases, (ii) distinctive (sheet-like, lenticular, or wedge-shaped) geometries, (iii) specific Vs values that can be estimated through Down-Hole measurements and calibration with high-resolution analysis of sediment cores. The thickness of unconsolidated Holocene deposits (and thus the position of the engineering bedrock) was observed to vary remarkably (10-55 m) from site to site, especially across the buried Adriatic paleovalleys, in a predictable manner. Using accurate three-dimensional models of facies architecture, we can predict the proportion of different lithologies along a stratigraphic column, and thus estimate shallow shear-wave velocity profiles at any point. The resulting Vs30 map enables precise soil classification that primarily reflects subsurface geology and that can be used effectively for seismic site effect evaluation and earthquake engineering design purposes.

Near-Surface Attenuation Estimated With Coda Waves: Insights From Numerical Simulations and Empirical Observations

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Site-specific seismic hazard assessments require appropriate characterizations and quantification of near-surface attenuation, which can be highly affected by local geologic structures—also known as site effects. Site effects are a complex function of both shallow and deep geological conditions, topography and other factors, which cannot be explicitly parameterized by commonly used site parameters like the time-average shear wave velocity for the top 30 m (Vs30). Recently, site-specific k0 has received increasing interest because of its ability to capture the attenuation properties of near-surface materials, but accurate characterization of this parameter has yet to be discovered. In this study, a site-specific k0 is partitioned into a specific-specific increment and a regional contribution characterized by coda waves. Coda waves, which are the backscattering waves of body waves, are expected to be less affected by the shallow soil deposits and more sensitive to the regional variations of hard rock attenuations at depth. Thus, recent studies attempted to measure the regional k0 from surface ground motions. However, the differences between the physics underlying direct body-wave attenuation (i.e., P-wave and S-wave) and coda-wave attenuation are still unclear. The limited understanding of the coda wave propagation mechanism in complex media suggests further investigation is needed. In this work, we firstly examine the applicability to measure regional k0 with coda waves. Using ground motions from the DesignSafe database, no correlations are observed between the S-wave and coda wave k0. One-dimensional simulations are introduced to further study the coda propagation mechanism and associated variability.

Site-Specific Response Spectra Estimation at Designated Seismic Stations of the Puerto Rico Strong Motion Program Seismic Network

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Site-specific response spectra were estimated at sites location of designated permanent seismic stations of the Puerto Rico Strong Motion Program Seismic Network (PRSMP-SN). Models of response spectrum are widely used in earthquake-resistant buildings design. However, they do not necessarily represent the behavior of a specific earthquake, and the soil amplification is poorly incorporated. Site-specific response spectra have the merit to overcome the two issues mentioned above. Designated sites of the PRSMP-SN were previously characterized by means of active-, and passive-MASW in order to estimate the V_{S30} shear-wave velocities, and the site transfer function estimation using ambient vibration measurements. Results of the 2D V_S-Z profiles of the studied sites and their site/soil classification according to NEHRP range from soil type D, and C for the majority of the sites. Shear-wave velocity range were between 260 to 300 m/s (Stiff-soil), to 350 to 680 m/s (Soft-rock). In terms of NEHERP V_{S30} the soil type classification the majority of the sites still on the category of soil type C. Results of the site-specific response spectra characteristics are discussed in terms of applications of engineering seismology.

How Well Can We Predict Broadband Site-Specific Ground Motion and Its Spatial Variability So Far? [Poster Session]

Poster Session • Wednesday 1 May

Conveners: Morteza Bastami, International Institute of Earthquake Engineering and Seismology (m.bastmi@iiees.ac.ir); Mohamad M. Hallal, University of California, Berkeley (mhallal@berkeley.edu); Chunyang Ji, North Carolina

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POSTER 120

Application of Conditional Dynamic Variational Autoencoder for Simulating Ground Motions in the Geysers Geothermal Field

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Accurate simulation of ground motions caused by induced seismicity is imperative for engineering operations to mitigate large events and for advancing our understanding of source physics through correlating with stress, strain and fluid flow monitoring. We focus on the Geysers geothermal field in northern California, whose induced seismicity activities have been linked to geothermal energy production. Physics-based simulations require a large computational cost and are susceptible to uncertainties in subsurface velocity models. Deep generative models are attractive alternatives that directly utilize observations. Based on the conditional dynamic variational autoencoder for ground motion simulation (CD-VAE-GMG) model developed for small natural earthquakes in the San Francisco Bay Area, we aim to generate region-specific waveforms associated with induced seismic events. We introduce a novel dynamic Variational Autoencoder design to ensure the statistical features of the waveform envelopes and spectra shapes to be consistent with observations in the time-frequency and time domains simultaneously.

Our model is trained to approximate the probability distribution of a vast dataset of ground motions in the Geysers geothermal field. It simulates three-component waveforms conditioned on earthquake magnitudes, epicentral distances, and earthquake depths. The training dataset comprises waveforms from over 30,000 earthquakes with magnitudes ranging from 0 to 4, recorded at 90 stations. Preliminary results demonstrate the effectiveness of the model. Generated seismic waveforms match the observed waveforms in both time and frequency domains, but some discrepancies remain in peak values and spectral shapes. We are improving the performance through data expansion, model tuning, and comprehensive validation. This study showcases the potential of machine learning techniques in simulating ground motion waveforms caused by the induced seismicity and enhancing their prediction. We further envision that our approach will become valuable for improving earthquake hazard assessment and gaining insights into seismic source physics.

POSTER 121

Lateral Variation in Coda Wave Attenuation in Sikkim Himalaya

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Spatial variations of coda wave attenuation (Q_c) have been investigated in the Sikkim Himalaya. We have used data from 2062 local earthquakes having an epicentral distance of 130 km that were recorded by a dense network of 27 broadband seismic stations across the entire Sikkim region between April 2019 and May 2022. Variations of Q_c with frequency suggest notable contrast across the region manifesting diverse tectonics beneath Sikkim Himalaya. A consistent high attenuation zone has been observed in central Sikkim, regions close to curvilinear trends of MCT, where seismicity is mostly concentrated. Northern Sikkim exhibits high Q values at all the frequencies where clear arrivals from Moho have been observed from receiver functions study for the seismic stations located in the north. The spatial distributions of Q_0 (Q_c) structure of the region is further investigated to examine the detailed attenuation characteristics across the region. It shows the differences in the attenuation characteristics across the region. A high attenuation pocket is evident in the central segment while northern Sikkim shows less attenuative medium. Our results reflect less complex crustal architecture below the northern part compared to the central portion of the Sikkim Himalaya.

POSTER 122

Inversion of Earthquake-HVSR in the Anchorage Basin, Alaska, for Delineation of Shallow Sedimentary Structures

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The Anchorage strong-motion network has been operational in and around Anchorage, Alaska, since 1995. The stations are primarily Kinemetrics force-balanced accelerometers with sampling rates of 200 Hz. Many seismological studies have been conducted using the recorded data collected from these stations. An earlier study utilized strong-motion records of 95 earthquakes of magnitude 4.5 and above between 2004 and 2019, including the November 30, 2018, MW7.1 Anchorage Earthquake, to compute the earthquake horizontal-to-vertical-spectral-ratio (e-HVSR) at 35 strong-motion stations across Anchorage. A total of 1,727 three-component recordings were used for the e-HVSR analysis. These records were processed, and the e-HVSR was calculated for each station over the 0.25–10 Hz frequency range. In this study, an inversion of the e-HVSR data from each strong-motion station was performed to obtain a 1-D layered earth soil profile for understanding the subsurface characteristics at individual sites. The inversion searches for models that satisfy least-squares fit criteria using a very fast simulated annealing algorithm and selected statistical tools, e.g., parameter correlation matrix and marginal posterior probability density function for quantitative assessments of each model. Where available, shear wave velocity data from the shallow boreholes were set a priori during the inversion analysis. The inversion results indicate the presence of higher-velocity (400–550 m/s) sediments at a relatively shallow (10–20 m) depth in the eastern part of the basin, at the foothills of the Chugach Mountains, in comparison to the western and northwestern parts of the Anchorage area. The inversion modeling of the e-HVSR results from the sites on the western and northwestern sides indicates sediments with lower shear wave velocities (250 –350 m/s) at 30-50 m depth. A detailed analysis of the 1-D inversion results and a comparison to the local geology is also presented.

POSTER 123

Measuring Shallow Seismic Attenuation in the Pacific Northwest of the United States Using Ambient Noise Seismology

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Owing to the impact on ground motion levels, seismic attenuation is one of the major components of seismic hazard assessment. Active tectonic regions tend to exhibit elevated attenuation and complex structures. This is notably evident in the Pacific Northwest of the United States, a region known for its combination of active volcanoes and active tectonics. We employ passive noise interferometry on hundreds of broadband seismic stations in the Pacific Northwest to measure seismic attenuation properties. The NoisePy package is utilized to calculate the single-station correlation functions from both permanent and temporary stations. Subsequently, we model the envelope of the cross-correlation coda waves by using the 2-D radiative transfer equation for scalar waves to estimate the intrinsic absorption parameters of Rayleigh waves. Through the best fit between observed and synthetic energy density functions of the envelopes of the coda, we derive the intrinsic absorption parameter of the medium. We analyze the data in multiple frequency bands, obtain the intrinsic absorption parameter, and transfer it into intrinsic attenuation factor Q. Finally, we explore the spatial variations in the observed attenuation parameters and discuss their values in the geodynamical context of the region.

POSTER 124

Relating Peak and Cumulative Ground Motions for Earthquakes in the San Francisco Bay Area

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We examine ~5000 ground motion records from 39 Mw3.5–6 earthquakes in the San Francisco (SF) Bay Area with the goal of understanding site conditions leading to amplification in either the form of sharp velocity pulses or longer duration resonant motion. Most estimates of seismic hazard are influenced by predicted peak ground velocity or acceleration (PGV or PGA). These quantities are, in general, affected by higher frequency motions (>1Hz), and thus may not be good indicators of the kind of shaking that threatens long period structures, such as tall buildings or bridges. Also, the peak motions do not inform us about the duration or total dynamic load to a structure, which may be weakened after several successive pulses of significant amplitude. This is important for structures around the SF Bay shoreline, where sites in very low velocity bay mud experience long duration ringing at ~1 Hz (Hirakawa and Aagaard, 2022). This type of resonant motion is likely the cause of the collapse of the Cypress Viaduct during the 1989 Loma Prieta earthquake (Rogers, 1991).

We compute PGV and cumulative absolute displacement (CAD) for the SF Bay Area ground motion records. CAD, the time integral of the absolute horizontal velocity, inherently increases with PGV since it involves integration of the largest velocity pulse but also incorporates additional motions. Sites that experience long duration ringing will have larger CAD than average. We consider each ground motion record in normalized PGV-CAD space and rotate the dataset into principal components. We refer to the first principal component as the "primary intensity" which accounts for the expected increase in CAD with PGV. We refer to the second principal component as the "excess shaking", which may be thought of as extra (or deficit) cumulative motion apart from what would be typical for a given PGV. We investigate site-specific trends in these two quantities and consider possible relations with subsurface geology. The results of this study will expand our definition of site response beyond changes to shaking amplitude, with direct application to the SF Bay Area.

POSTER 125

A Comparative Study Between the Resonance Frequency by Hvsr Analysis and Bedrock Depth in Western Busan, Korea

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Nakdong River is one of the major rivers in Korea that runs through the Busan metropolitan area. During the 1.6 km long bridge construction across the river, twenty-seven boreholes were drilled to measure the depth of the bedrock. This study determines the resonance frequencies at the borehole sites using the HVSR (Horizontal-to-vertical spectral ratio) technique and compares the results with direct measurements. Bedrock depths from the 27 borehole measurements vary from 38 to 70 meters. Although their variations are not serious along the 3.8 km long route, a relatively sharp decrease in the bedrock depth was noticed near the borehole NSB-5 (~38 meters). We collected ambient noise data at locations near 27 boreholes in 2022 and estimated resonant frequencies using the HVSR technique. Resonance frequencies from HVSR vary from 0.9 Hz to 1.3 Hz. A relatively high resonance frequency, 1.3 Hz, is estimated at NSB-5, which is consistent with the observations from the direct measurements from boreholes. Details of the boring logs indicate that the sedimentary layers consist of multiple lithologic layers, including reclaimed soil, silt sand, silt clay, and sand-mixed silt gravel. Since their impedance contrasts are not significant, it is not evident from the HVSR curves. This study demonstrated a significant correlation between the depth of bedrock identified in boreholes and the resonance frequency obtained through HVSR analysis using microtremor observations. HVSR analysis effectively reflected the bedrock depth at the microtremor observation sites.

POSTER 126

Preliminary Site Characterization for Earthquake Hazard Assessment Using Ambient Vibration Techniques in Haines Junction, Yukon

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In this paper, regional mapping of soil stiffness is carried out to improve the understanding of seismic hazards in southwest Yukon, Canada, where local amplification hazards are largely unknown. Ambient vibration (AV) measurements record microtremor seismic noise at broadband frequencies (0.1-128 Hz) and are used to calculate the horizontal-to-vertical spectral ratio and identify resonant frequencies at sites. *In situ* estimation of fundamental frequency f_0 is used to characterize sites and map local site amplification hazards.

We present preliminary site characterization using a combination of array and single station AV measurements from 23 sites in Haines Junction, Yukon. Fundamental frequencies ranging from 0.3-0.8 Hz are identified at the sites. The preliminary results suggest lateral spatial variation in fundamental frequencies, with higher frequencies identified north of Haines Junction and lower frequencies identified in south-central Haines Junction. We attribute these observations to the basin of the Dezadeash River. Identification of discrete layering in the shallow subsurface (~2.5-12 m depth) at some sites suggests the presence of an active permafrost layer. Lateral heterogeneity is found across some sites, potentially the result of either near-surface (active layer) or deeper (depth to bedrock) lateral variability.

POSTER 127

Influence of Buried Geometries on Ground Response Analysis: The Case of the Pescara Paleovalley System

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Detailed ground response analyses (GRAs) require a deep understanding of the geophysical properties and geometry of sediment bodies; however, GRAs have focused traditionally on vertical characterization, underestimating the importance of depositional architecture and the lateral variability of buried geometries. In this context, late Quaternary paleovalley systems represent a complex geological environment and a potential threat due to their unconsolidated infill, sharp contrast with adjacent substrates, and complex lenticular geometries, which have often been oversimplified in the attempt to model site-specific seismic effects. In this study, we employed a dense stratigraphic framework comprising continuous core stratigraphic descriptions, an extensive network of microtremor measurements, Down-Hole tests, and undisturbed samples for the estimation of shear modulus decay (G/G_0) and damping ratio (D%) to get robust, local data to perform GRA of the Pescara paleovalley system. Through the correlation of high-resolution stratigraphic data and microtremor measurements, we mapped resonance frequencies, highlighting rapid changes in the frequency range of interaction with common building types, and built the 3D geophysical depth model. The facies architecture was reconstructed through a cross-section transversal to the paleovalley axis and implemented into a 2D finite element model. GRA revealed higher seismic amplification (reaching a factor of 4) compared to simpler geological contexts, strongly linked to the buried paleovalley geometry, and peaked at frequencies between 0.9 and 1.3 Hz in the paleovalley center and up to 5 Hz towards the flanks. We computed the response spectra and compared them with those proposed by the Eurocode 8 guideline (EC8), which relies on soil category and Vs30. Remarkably, the strong amplifications observed show a significant underestimation of spectral accelerations compared to EC8. In this work, we modeled the seismic amplification due to the buried paleovalley body, highlighting the importance of integrating geophysical and subsurface geological data to achieve high-resolution GRA.

POSTER 128

Influence of Seasonal Frozen Soil on High-Frequency Attenuation (κ0)

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When estimating site effects in terms of amplification or attenuation of seismic waves, it is usually assumed that the seismic properties of the ground are constant over time. In recent years, several studies have shown that near-surface shear wave velocities can be subject to a variety of environmental parameters, such as temperature, precipitation or groundwater level, leading to a variation of shear wave velocity with time. Similar observations have been partly made for seismic attenuation, but studies investigating the influence of seasons on seismic attenuation are very limited.

Herein, the parameter κ0 is commonly utilized to describe the site-specific attenuation at high frequencies. We have calculated the difference in κ0 between surface and borehole station pairs of the KiK-net network in the northeastern corner of Hokkaido, Japan. We observe that Δκ0 is almost constant from May to November, but increases rapidly from late November to early January. In January and February, Δκ0 is about 0.05 s higher than in the summer (increased high-frequency attenuation), before returning to its original value between March and April. This observation can be explained by seasonally frozen soils of the upper few tens of centimeters, which add an additional layer of increased shear wave velocity to the geological 1-D velocity model below a station, thus increasing the high-frequency attenuation.

POSTER 129

Combining Simulated and Empirical Nonergodic Ground Motion Models for Southern California

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Partially nonergodic ground motion models (N-GMMs) have been developed from simulated data (e.g., Sung and Abrahamson, 2022) and from recorded ground motions (e.g., Parker and Baltay, 2022). Southern California is an example where both N-GMMs can be applied; the Parker and Baltay (2022) model is based on recorded ground motions from the greater Los Angeles region, and Moschetti et al. (2023) is developing similar factors for this region from Cybershake. These approaches have complementary benefits; for example, empirical data is limited at large magnitudes that are well-represented in the simulation data. Conversely, simulated data are limited by the accuracy of the three-dimensional velocity model while empirical data more accurately capture the effects of path and site. We repeat the analyses of Parker and Baltay (2022) using each of the four NGAWest2 ground motion models (ASK14, BSSA14, CB14, and CY14) as a common reference model for the empirical and simulated datasets. We use a maximum likelihood method, as an alternative to the empirical semivariogram approach of Parker and Baltay (2022), to compute the spatial correlation between site response terms as a function of period for each dataset. In addition, we explore using cross-variograms to estimate the spatial cross-correlation between the empirical N-GMM and simulation-based N-GMM as a function of period. Finally, we examine correlations between the simulation factors and surface geology and topography in Southern California. These results combine two sources of constraints on ground motion models and can be used to inform U.S. Geological Survey products such as the National Seismic Hazard Model and ShakeMap.

POSTER 130

Shear Wave Velocity Structure Beneath a Dense Seismic Array in the Presence of Local Noise Sources Using Matched Field Processing

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The presence of local sources in the ambient seismic wavefield causes bias in the estimation of surface wave dispersion via seismic interferometry (SI). Here we use Matched Field Processing (MFP) to capture local noise sources and then extract more accurate surface wave phase velocity dispersion curves from data recorded by a dense array of 2639 Fairfield Nodal Zland 1C nodes deployed near Sweetwater, TX. These short period instruments recorded continuously for 11 days, including signals from Vibroseis trucks at various locations.

MFP is an array processing method that conducts a grid search of correlations between a recorded wavefield and a synthetic wavefield generated by forward modeling. For each potential source location, an estimate of the phase match is computed between both wavefields over a certain frequency band, taking coherency of the wavefields across stations into account. The relative spatial phase differences between all sensors of the array patch can be expressed as a Cross Spectral Density Matrix (CSDM). A 3D energy spectrum matrix is obtained at each frequency and the peak of the energy spectrum matrix corresponds to the location of the dominant noise source. The velocity vector at the location of the noise source is extracted along the velocity axis as the velocity distribution for the current frequency. Velocity vectors that correspond to each frequency are then normalized and stitched together along the frequency axis to obtain the frequency-velocity energy spectrum, which is the dispersion energy map of the current data segment. Finally, we stack all the dispersion energy images from a single data segment to obtain a more stable dispersion energy map. This dispersion curve is then inverted using a Markov Chain Monte Carlo (MCMC) approach to retrieve the 1D shear wave velocity model beneath the patch of the array under consideration. Preliminary results show that MFP produces a more accurate dispersion curve in the 4-20 Hz frequency range than SI-based surface wave methods in the presence of local noise sources.

POSTER 131

Constraining Shear-Wave Velocity Profiles in Anchorage, Alaska, Through Inversion of Microtremor Horizontal-to-Vertical Spectral Ratios

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We modify shear-wave velocity (V_S) profiles, obtained from modeling of active-source multimethod site characterization data at 19 strong motion stations in the Anchorage, Alaska, region using microtremor horizontal-to-vertical-spectral-ratio (mHVSR) data. The acquisition sites were located throughout the City of Anchorage and northward through the Eagle River and Palmer-Wasilla areas. We deployed one 20-s-to-100-Hz three-component broadband seismometer for mHVSR data acquisition as part of our multimethod site characterization approach. We first calculate the mHVSR curves through standard processing techniques (time-series detrending, mean amplitude removal, bandpass filtering from 0.5 to 50 Hz, calculation of time-window averaged Fourier amplitude spectra, spectral smoothing). Then we model the mHVSR fundamental frequency (F_0) through inversion by an elitist genetic algorithm (EGA) technique. The initial V_S models at each site were developed from iterative least-squares joint inversion of active-source P- and S-wave refraction data complemented with Rayleigh and Love dispersion data, as previously described by Stephenson et al. (2022). However, these models were often limited to less than 50 m depth because of acquisition logistics, particularly at sites in urban areas, and these models commonly were not sufficiently deep to predict the observed mHVSR F_0. By adding a layer beneath the initial model depths and allowing up to 10% variability in the shallow layers defined by the active-source model, we extend the V_S profiles to greater depth through the EGA inversion of the mHVSR data. In addition, the mHVSR modeling generally corroborate the depths of shallow high V_S impedance boundaries in the initial active-source models. The new V_S profiles incorporating mHVSR modeling will be used in support of ground motion modeling and related earthquake hazards studies in the region.

POSTER 132

Seismic Site Characterization of Sikkim Himalaya Using HVSR

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The northeastern state of Sikkim lying in the central segment of the Himalaya orogen is a seismically active region which was plagued by the recent 2011 M_w6.9 earthquake. Analysis of local earthquakes recorded at the recently deployed seismic network of 27 broadband seismic stations revealed multiple seismically active domains with peculiar stress orientations. This makes it imperative to study the site characteristics crucial for determining the local site conditions in the face of prevalent seismic activity. In this study, we compute the horizontal-to-vertical spectral ratio (HVSR) of ambient noise for local site characterization using the resulting peak amplification (A_0) and resonant frequency (f_0). Since our network was operational during the COVID-19 pandemic, we have used the night time data during the lockdown period to ensure analysis of the most stationary part of noise. HVSR curves are observed to be varying distinctly with regional geology. Stations installed over the sedimentary basin exhibit high *A0*at low f_0, signifying the underlying thick deposits and sharp impedance contrast. Multiple dipping sheets of the Lesser Himalayan Duplex (LHD) could possibly be responsible for the double amplification peaks observed at stations installed over and around the LHD. The high elevation topography of Higher Himalaya experiences great wind speeds, which has the tendency to induce anomalously high A_0at low $f_0$evidenced by stations installed in northern Sikkim. We plan to further investigate how the sites respond during earthquakes, and also monitor if the HVSR trends vary temporally.

Illuminating Complex, Multiplet Earthquake Sequences at Kahramanmaras (Turkiye), Herat (Afghanistan), and Beyond

Oral Session • Thursday 2 May • 8:00 AM Pacific

Conveners: Aybige Akinci, National Institute of Geophysics and Volcanology (aybige.akinci@ingv.it); Pınar Büyükakpınar, GFZ Potsdam (pinar@gfz-potsdam.de); Gareth Funning, University of California, Riverside (gareth@ucr.edu); Alice-Agnes Gabriel, University of California, San Diego (algabriel@ucsd.edu); Mohammadreza Jamalreyhani, SUSTech, China (jamalreyhani@sustech.edu.cn); Edwin Nissen, University of Victoria (enissen@uvic.ca)

The October 2023 Herat, Afghanistan Earthquake Quadruplet - Aftershock Locations and Moment Tensors

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A series of four magnitude M_w=6.3 earthquakes struck the Herat province in northwestern Afghanistan in October 2023 causing widespread destruction and killing almost 1,500 people (information from the World Health Organization). All four main events have thrust mechanisms. Rupture likely occurred on blind thrust faults as no surface ruptures have been reported precluding a clear interpretation of fault dip direction(s). Fault segmentation, which could cause delayed rupture on adjacent segments, cannot be addressed due to the low resolution of existing earthquake locations as the events occurred far from seismic networks. The distance from the epicentral area to the closest permanent seismic stations in northeastern Iran is about 150 km and to the closest station in the east, the IRIS station in Kabul, about 650 km. To improve understanding of spatial relations and faulting styles, we use data from the Iranian seismic networks and from other stations at regional distances to locate the sequence and to obtain moment tensor solutions. Our preliminary results from locating over 100 earthquakes from 7 October to 20 November 2023 reveals a roughly 50x20 km distribution elongated in the west-northwest direction that coincides well with the uplift region from InSAR data (from LiCSAR). Moment tensors of the main events and 10 aftershocks (M_w 4.1-5.8) indicate predominantly thrust faulting on roughly east-west oriented faults. The shallow centroids of ~3-5 km for the main events suggest ruptures may have reached close to the surface perhaps explaining the localized strong destruction. Our results are consistent with rupture on a blind fault structure north of the right-lateral Herat (or Hari Rud) fault and south of the Siakhubulak fault. The Herat fault system is the dominant physiographic feature that connects the Arabia-Eurasia and India-Eurasia collision zones and, combined with sub-parallel thrust faults such as the one(s) active in 2023, accommodates any remaining relative plate motions.

Long-Term Seismicity of the East Anatolian Fault System and Its Relationship With the 2023 Mw 7.8 & 7.6 Kahramanmaraş (Se Türkiye) Earthquake Doublet

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The destructive 2023 M_w 7.8 & 7.6 Türkiye doublet (abbreviated as M1 & M2) breaks multiple fault segments along the East Anatolia Fault (EAF) system, forming one of the largest continental doublets ever recorded. To understand why the 2023 event developed to such a scale, we reconstructed a high-resolution long-term earthquake catalog ranging from 2020-2023 to better characterize the EAF fault behavior before and after the mainshocks. We adopt a deep learning-driven cataloging workflow called TED (Zhou et al. 2019, 2024), i.e. Training-based Earthquake Detection that applies Self-Attention RNN (SAR) for phase picking. We downloaded continuous broad-band data from AFAD and FDSN, forming a network of 64 stations that covers the whole EAF region. Our final catalog contains 38,424 events before the 2023 doublet and 85,520 aftershocks, which is a ~3 times increase of the AFAD catalog.

We find that seismicity before the 2023 doublet are low along the ruptured segment of EAF, except for the branch fault that nucleate M1 (abbreviated as nucleation branch thereafter). Similar quiescent feature was found along the Çardak-Sürgü Fault (CSF) that is responsible for M2. This pattern agrees with the fact that the ruptured segments are strongly locked during preseismic period. We specifically analyze the seismically active nucleation branch, and found that (1) microseismicity were dynamically triggered by the 2020 M_w 6.8 event, and (2) 3 seismic swarms were developed in 6 months before the mainshock. Both observations suggest that the nucleation branch was critically stressed before the earthquake. On the eastern end of EAF rupture, i.e. the western end of 2020 rupture, seismicity revealed a sharp change in fault dip. Moreover, preliminary results show that 4 repeater sequences of M_L 2.0-2.6 exist in the gap between the 2020 & 2023 rupture, which occur both before and after the 2023 doublet, indicating fault creep. Thus, long-term seismicity helps constrain the fault coupling condition of EAF, and provides insights on the nucleation and termination of the 2023 Türkiye doublet.

The Kahramanmaras (Turkey) Earthquake Multiplet Sequence Revealed by Deep Learning Computer Vision

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The February 6, 2023 Kahramanmaras (Turkey) earthquake multiplet involved two mainshocks ~9 hours apart on neighboring faults within the Arabia-Anatolia collision. The first M 7.8 event, the largest ever recorded on the East Anatolian Fault, and the subsequent M 7.6 event, collectively resulted in over 50,000 fatalities. Accurately detailing this earthquake multiplet sequence, including the interval between the two mainshocks as well as subsequent aftershocks, is important for advancing our understanding of seismogenic processes and regional tectonics, which in turn underpin earthquake science and hazard mitigation. Deep learning is becoming a powerful tool for seismological analysis, and our new algorithm, the Source Untangler Guided by Artificial intelligence image Recognition (SUGAR) (Tan et al., submitted), has proven to outperform skillful human analysts and popular AI and non-AI workflows in delineating complex earthquake sequences. SUGAR applies a 3D computer vision technique to the brightness video produced by the Source-Scanning Algorithm (Kao and Shan, 2004), guiding the phase association and making it possible to locate small events with poorly discernible waveforms, even when occurring concurrently. In this study, we retrain a SUGAR model with seismic stations in Turkey and apply it to the Kahramanmaras earthquake sequence from before the first mainshock to the end of April 2023. SUGAR's unusual ability at untangling complex signals is especially valuable in the early stage of the sequence, such as the ~9-hour interval between mainshocks. The SUGAR catalog has ~6 times as many events as the routine KOERI catalog. Results indicate that the first M 7.8 earthquake initiated on a secondary, west-dipping fault branch and propagated to the main subvertical East Anatolian Fault. The M 7.8 mainshock rupture terminated short of the 2020 M 6.8 Elazig earthquake, but remote aftershocks were triggered on the NE side of the 2020 rupture. The M 7.6 earthquake ruptured the Savrun-Cardak fault, but left a clear gap between it and the M 7.8 earthquake.

Surface Expression of the Narlı and East Anatolian Fault Rupture Intersection in the 2023 M7.8 Pazarcık, Türkiye Earthquake

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Field observations of surface rupture and displacement in multisegment or multifault earthquakes contribute to our understanding of how rupture initiation, propagation, and arrest are expressed at the earth's surface. The 2023 M7.8 Pazarcık earthquake in southeastern Türkiye represents a unique case of rupture initiation on the subsidiary Narlı fault, northward propagation, and triggering of bilateral East Anatolian fault (EAF) rupture. We evaluate this rupture sequence using field observations. In June 2023, we mapped parts of the M7.8 earthquake rupture north of the epicenter and recorded 68 measurements of left-laterally displaced cultural and natural features. We focused on a 30-km-long reach of the EAF that lacked previous field or remote observations of surface rupture and included the projected intersection with the northernmost Narlı fault. Field data show 10 km of previously unobserved EAF surface rupture northeast of Çiğli that is laterally continuous, locally distributed, and right stepping. Left-lateral EAF offset measurements range from

~1.8 to 6.8 m. Along a northeastern extension of the Narlı fault near Tetirlik, we observed 5 km of subtle and discontinuous rupture with 0.3–0.7 m of left-lateral displacement. We infer that EAF–Narlı fault interaction is expressed as 1) northeast-trending scarps along the eastern of two possible Narlı fault connections inferred from satellite observations, 2) a change in EAF displacement from ~2–5 m southwest to 6–7 m northeast of this intersection, and 3) a decrease in the lateral continuity of the EAF surface rupture at this projected intersection. This work highlights the importance of making systematic field-based rupture observations as it provides key data to constrain the kinematics of the M7.8 EAF rupture and provides benchmark field observations for comparison to remotely sensed displacement data.

Seismic Analysis of the 2023 Earthquake Sequence in Southeast Türkiye: Insights From Mainshocks and Aftershocks

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Two M_w 7.7 and 7.6 earthquakes struck southeast Türkiye on February 6, 2023. The series of earthquakes resulted in extensive destruction and tens of thousands of fatalities in Türkiye and Syria. Using complimentary source characterization methodologies and local, regional, and teleseismic data, we investigate both mainshocks and aftershocks. While the details of the fault network are resolved by centroid moment tensor inversion for 221 aftershocks ($M_w \geq 3.7$), back-projection analysis and finite source inversion for the mainshocks reveal coseismic slip, rupture length, and propagation mode along the main faults. Activating the nearby East Anatolian fault zone (EAFZ), the initial mainshock nucleated on a splay fault which is ~20 km off from the main fault zone. Along approximately 500 km, it ruptured bilaterally on many previously partially dormant fault segments, first toward the northeast and then to the south-southwest during 117 s. The east-west oriented Sürgü-Misis fault zone (SMFZ) was ruptured by the second mainshock, over ~115 km within 32 s with a slip of 7 m. The reconstruction of slip in the Bayesian bootstrap-based probabilistic joint inversion scheme exploits the model space and trade-off of extended source parameters for the two mainshocks. Source time functions are retrieved without pre-assumptions, and sub-shear rupture velocities are found. Interestingly, the stress drops retrieved from the extended source model were quite different between the mainshocks, with values of 5 and 11 MPa, respectively. The kinematic rupture is also used to calculate slip-induced stress changes which are compared with spatial aftershock distributions. We retroactively reconstruct rupture details using aftershocks with heterogeneous moment tensors including strike-slip, normal, and thrust events. This not only sheds new light on the geometry and behavior of large structures along the SMFZ but also maps the geometry of various segments along the main strand of the EAFZ. Our research provides valuable insights into the complex rupture evolution and fresh perspectives on the catastrophic earthquake sequence of 2023.

High-Resolution Fault Imaging From Fault Zone Guided Waves Recorded by Dense Arrays in the Aftershock Zone of the 2023 Kahramanmaras Earthquake Sequence in Southern Türkiye

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The 2023 Kahramanmaras earthquake sequence includes a M 7.8 earthquake initiated near Nurdağı in Gaziantep ruptured for more than 300 km along the East Anatolian Fault (EAF) in Southern Türkiye, and a M7.5 event near Ekinözü in Kahramanmaraş Province nine hours later. These events were followed by numerous aftershocks around both mainshock rupture zones. To better capture the ongoing aftershock sequence, we deployed up to 200 5-Hz Smartsolo nodal stations and 16 broadband/strong motion stations across nearly the entire rupture zone for more than three months. Our array also includes a one-month deployment of an ultra-dense fault zone profile across the Pazarcık segment of the EAF and the Sakçagöz-Narlı Fault (SNF) where the M7.8 mainshock initiated. In this study, we present clear evidence of seismic waves generated by fault zone structures and use them for high-resolution imaging of the low-velocity damage zone (LVDZ) across the EAF. We first select ~80 events within 20 km of the array center (C000), which is situated at the surface rupture of the M7.8 mainshock. We then rotate the two horizontal components to fault-parallel and fault-normal directions, and visually identify fault zone trapped waves (FZTWs) as long-period dispersive waves due to internal reflections within the LVDZ following the direct S waves at stations immediately surrounding the EAF. We find that FZTWs are recorded at more stations east of the array center rather than to the west, likely indicating an asymmetry in the LVDZ. Alternatively, it is related to the presence of quaternary basin with an estimated thickness of ~250 m based on the HVSR method. Our preliminary analysis shows that aftershocks directly beneath both two parallel faults can generate FZTWs recorded at stations along the Pazarcık segment of the EAF. Our next step is to quantify the degrees of FZTWs for events at different locations, and combine both FZTWs and time delays of direct P and S waves to better constrain the depth extent and geometry of the damage zone associated with the M7.8 mainshock.

Strong Ground Motion Characterization for the 6 February 2023 Mw 7.8 Pazarcık Earthquake in Kahramanmaraş, Türkiye

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The devastating 2023 Mw 7.8 Pazarcık earthquake, had a profound impact on south-central Türkiye and northwestern Syria, resulting in over 50,000 casualties and widespread damage. To better understand earthquake source properties and wave-propagation effects, we analyze strong ground-motion data recorded at ~230 stations. Our study involves determining regional distance-dependent attenuation using the Fourier acceleration amplitude spectrum (FAS) within the frequency 0.1 – 20 Hz. An apparent near-source saturation effect necessitates the incorporation of an additional finite-fault factor for distance scaling. We conduct uncertainty and sensitivity analyses, considering variable decay rates in the geometric spreading model. Significant duration of ground motions is modelled for two different measurements based on Arias intensity. We then construct a site amplification model incorporating both V_{S30}-scaling and peak ground acceleration (PGA)-scaling. Source parameters are then determined by fitting a theoretical Brune's ω^2 model with a reference Fourier source spectrum at 1.0 km. Our estimates result in a mean corner-frequency $_0$= 0.036 Hz, a Brune stress drop $\Delta\sigma$ = 4.79 MPa, and a reference rock site (V_{S30} = 800 m/s) κ_0 = 0.051 s. Analyzing near-source pulse-like waveforms, we demonstrate that the mismatch of peak ground velocity (PGV) between our model and near-fault observations is due to rupture directivity. Finally, we compare ground motions of the Mw 7.8 Pazarcık event to those of Mw 7.6 Elbistan and the 2020 Mw 6.7 Sivrice earthquakes. We find that the attenuation effects for the three events are identical in the frequency range ~0.2 – 6.0 Hz, with only minor differences in site responses above ~5.0 Hz. Source-spectra comparisons clearly indicate complex source properties for all three events. Our ground-motion analyses contribute to a better understanding and modeling of regional properties of attenuation, site response, and event-based source characteristics that are important for future region-specific seismic hazard assessment.

Conjugate Strike-Slip Faulting in the Truckee Basin of California, Northern Walker Lane

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The Walker Lane belt is a ~150 km wide zone of distributed and discontinuous transtensional faulting that roughly follows the California-Nevada border from Death Valley to Mohawk Valley, CA. This belt accommodates ~25% of the relative dextral transform motion between the North American and Pacific Plates. In the Northern Walker Lane, this dextral shear is accommodated across a series of normal-fault bound basins in conjunction with both northwest-striking right-lateral faults and conjugate northeast-striking left-lateral faults.

We present new lidar-based mapping in the Truckee Basin showing that the Polaris, Truckee, and Dog Valley are active conjugate strike-slip faults cutting a prominent sequence of glacial landforms and deposits emanating from the adjacent Sierra Nevada crest. Our paleoseismic trenching study of the ~25-km-long northeast-striking left-lateral Dog Valley fault provides evidence for one earthquake that occurred ~8.5–8.3 ka and a younger earthquake that postdates 8.3 ka. Three-dimensional trenches show that the most recent earthquake produced 115 cm of left-lateral slip. We present 29 new preliminary ^{10}Be and ^{36}Cl cosmogenic exposure ages of boulders from glacial moraines and outwash terraces in the Truckee basin. These ages provide limits on the late-Pleistocene (post-140 ka) slip rates of the ~35-km-long northwest-striking Polaris and Truckee faults. The age of a displaced glacial outwash channel shows that the Polaris fault has a right-lateral slip rate of $0.45^{+0.28}/_{-0.06}$ mm/a. Our mapping shows that the Truckee fault is a right-oblique slip fault and forms the northerly continuation of the West Tahoe fault. Glacial moraines displaced by the Truckee fault provide a right-lateral slip rate of $0.22^{+0.09}/_{-0.04}$ mm/a and a vertical slip rate of $0.12^{+0.09}/_{-0.06}$ mm/a. The sum of these two faults' dextral slip rates is less than half the maximum limit of ~3 mm/a of northwest-directed right-lateral shear measured by GPS across the basin. Taken together, these three conjugate faults raise questions in light of recent conjugate earthquake sequences in both the Walker Lane and abroad.

How Often Do Subduction Interfaces and Overriding Upper-Plate Faults Rupture in the Same Earthquake (Or Close Enough in Time to Be the Same Situation)?

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Many global cities such as Anchorage, Karachi (Pakistan), Guayaquil (Ecuador) and Wellington (New Zealand) are located in strain-partitioned environments. For these cities, the worst-case-scenario earthquake might be a joint rupture of the subduction zone and one or more upper-plate faults. For example, the worst-case-scenario earthquake for Wellington would be a joint rupture of the southern Hikurangi interface and the southern Wellington Fault: the first would pose a tsunami hazard, the second would rupture lifelines, and both would cause strong shaking. However, the likelihoods and characteristics of joint ruptures are not particularly well understood, as there are only a handful of well-known cases of them (among which are the 1964 M=9.2 Alaska, 1855 M=8.2 Wairarapa and 2016 M=7.8 Kaikoura earthquakes). In applications of physics-based earthquake simulators to New Zealand within the RNC national science challenge programme, joint subduction/upper-plate ruptures occur frequently (e.g., Shaw et al., 2022), but it is uncertain how much this behaviour is controlled by modelling assumptions and details of model setup. To ground-truth the earthquake simulators, we look at the largest recorded subduction earthquakes around the world and examine how many of them also involved slip on upper-plate faults, or were closely followed by large upper-plate aftershocks. We also examine potential interactions between subduction-interface and upper-plate seismicity in Hikurangi earthquake sequences in 1961 and 1990. Finally, we note that both cosesismic and early aftershock triggering of upper plate faults, as commonly seen in simulators, have significant consequencs for event response and emergency management systems stress testing.

2021 and 2022 North Coast California Earthquake Sequences Light Up Gorda Plate Faults Beneath the North American Plate

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The Mendocino Triple Junction (MTJ), north of 40N and west of 122W, is one of California's tectonically most active and complex regions. Two earthquake sequences in the MTJ region, beginning on 2021-12-20 (2021) and 2022-12-20 (2022), respectively, highlight the faults in the Gorda plate as it subducts beneath the North American plate. Upgrades to the instrumentation in the region in recent years allow a detailed exploration of the seismicity and finite faulting associated with these earthquakes, in order to better define the faults within the subducting Gorda plate, as well as their modes of rupture. The December 2021 sequence began with a doublet, separated by ~11 s in time and 30 km in space. Detailed analysis indicates that the first event was offshore (2021-OFF) on the Mendocino fault (MF) between the Pacific and Gorda plates. The second event was onshore (2021-ON) at a depth of 24 km within the subducting Gorda plate and was most likely triggered by the S-waves of 2021-OFF. Simultaneous finite source modeling of the two events indicates that they have about the same magnitude, M~6.1, despite the waveforms of 2021-OFF appearing smaller in recordings because it was more distant from all recording stations which are onshore. The source analysis shows that 2021-OFF ruptured eastward along the MF, and 2021-ON ruptured to the NE. The 2022 sequence began with a mainshock (2022-MS, M6.4) just off Cape Mendocino to the NW of 2021-ON, also on a fault within the Gorda plate. Its largest aftershock (2022-AS, M5.4) took place 11 days later about 40 km to the ESE of the main fault rupture. Finite source analysis of 2022-MS indicates that it ruptured NE, toward the towns in the area and caused damage exacerbated by 2022-AS.

Illuminating Complex, Multiplet Earthquake Sequences at Kahramanmaras (Turkiye), Herat (Afghanistan), and Beyond [Poster Session]

Poster Session • Thursday 2 May

Conveners: Aybige Akinci, National Institute of Geophysics and Volcanology (aybige.akinci@ingv.it); Pınar Büyükakpınar, GFZ Potsdam (pinar@gfz-potsdam.de); Gareth Funning, University of California, Riverside (gareth@ucr.edu); Alice-Agnes Gabriel, University of California, San Diego (algabriel@ucsd.edu); Mohammadreza Jamalreyhani, SUSTech, China (jamalreyhani@sustech.edu.cn); Edwin Nissen, University of Victoria (enissen@uvic.ca)

POSTER 67

Coulomb Stress Variation and Frictional Properties Control Postseismic Fault Slip and Late Aftershocks of the 2022 Zagros Earthquake Sequences: Deductions From Bayesian Inference and Insar Observations

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On 1 July 2022, a doublet of earthquakes both with magnitudes of Mw 6.0 occurred within two hours in the south-eastern part of the Zagros Mountains near the Persian Gulf in Iran. The earthquakes were relatively shallow and caused significant co- and postseismic surface deformation, which could be measured using ascending and descending InSAR scenes. We used these data to invert the geometry of the co-seismic slip and to simulate postseismic deformation mechanisms of the two mainshocks, repectively. A Bayesian inference approach confirmed that the two mainshocks occurred on two distinct faults with similar strike angles but different dip angles and fault depths. The maximum afterslip is concentrated in the shallow portion of the faults and reached approximately 0.45 m. We distinguish the temporal evolution of kinematic and stress-driven afterslip and infer significant variations in frictional properties, particularly between the Hormoz salt layer and its upper sedimentary cover. Friction is stronger above the salt layer and the relaxation time of the afterslip is shorter there. The model confirms and quantifies the decoupling role of the salt layer during and after earthquakes in the south-eastern foothills of the Zagro Mountains.

POSTER 68

Rupture History and Elastic Interaction of the 2022 Multiple Earthquakes in the Zagros Mountains, Iran

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Earthquake multiplets are defined as two or more consecutive earthquakes that occur within a short period of time and have a comparable magnitude and therefore differ from the typical mainshock-aftershock distribution. With in two hours on the 1st of July 2022, three earthquakes of *Mw* 5.8–6.0 hit the SE Fars Arc (FA), Iran. The FA is the 700-km-long, easternmost segment in the foreland of the Zagros continental collision zone, which is characterized by ~10 km thick sediments including extended evaporitic layers causing folding, thin and thick sheet sliding, syn- and anticline formations and extensive strain decoupling. This exceptional setting in the FA and the Zagros mountains also hosts frequent earthquake doublets.

Here we investigate the co-seismic deformation and elastic interaction between both the large mainshocks and 120 aftershocks. We use seismic and satellite deformation data with well-proven and newly developed earthquake parameter estimation tools. Our results indicate the activation of thrust faults within the lower sedimentary cover (<10 km) along with high aftershock activity at significantly larger depths (10 - 15 km). The two largest earthquakes of the triplet (both *Mw* ~ 6.0) ruptured the lower sediments at depths of 4–9 km, likely occurring on a south-dipping splay fault to the mapped Zagros Foredeep Fault beneath an anticline. The third, smaller, *Mw* 5.8 event occurred one minute before the second large event, and indicates either an early activation of deeper strata or a possible foreshock co-located on the mainshock faults. The comprehensive analysis of main- and aftershocks using available seismic and ground deformation data unravels the interaction of the July–December 2022 sequence with the sedimentary layers both above and below the evaporitic decoupling zone.

POSTER 69

Nodal Seismometer Array Recordings of Aftershocks of the 6 February 2023 Mw 7.8 and Mw 7.6 Kahramanmaraş, Turkiye Earthquake Sequence

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Aftershocks of the 6 February 2023 Mw 7.8 and 7.6 Kahramanmaraş, Türkiye Earthquake Sequence extended more than 550 km along the NE-SW-trending East Anatolian fault (EAF) and about 200 km along the E-W-trending Sürgü – Çardak fault (SCF) to its intersection with the EAF. Events from this sequence were recorded by the Türkish National Seismic Network (TNSN TU), which operates 321 stations (AFAD, 1990), and the Türkish National Strong Motion Network (TNSMN–TK), which operates 826 stations (AFAD, 1973) in Türkiye. Stations of these large networks are dispersed throughout the country, and the spacing between stations is highly variable, particularly within the aftershock area of the 2023 Kahramanmaraş sequence. To better evaluate aftershocks, causative faults, regional ground motions, and regional seismic velocities using more uniformly spaced stations, the U.S. Geological (USGS) and the Türkish Ministry of Interior Disaster and Emergency Management Authority (AFAD) recorded aftershocks from July 2023 until December 2023 using nodal seismometers. The nodal seismometers were deployed as (1) a two-dimensional grid of 3-component seismometers (> 400 km in longest dimension) and (2) three linear 3-component arrays across known or suspected causative faults. The 2-D nodal seismometer stations were spaced at ~30-km intervals, and stations of the linear arrays were spaced at either 0.5 or 1 km. A total of 126 nodal seismometers were deployed, and although many of them were retrieved by early December 2023, some of the nodal seismometers were left in the field to continue recording until about January 2024. The combined networks (TU, TK, and Nodal) are expected to provide data for developing an event catalog of unprecedented detail for the region, from which subsurface fault locations and connectivity can be better evaluated, regional ground motions can be better modeled, and regional P- and S-wave velocity models can be developed.

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High-Resolution Three-Month Aftershock Catalog using Nodal Stations of the 2023 Kahramanmaraş Earthquake Sequence in Southeastern Türkiye

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The Kahramanmaraş earthquake doublet on February 2023 in Southeastern Türkiye started with a Mw 7.8 earthquake at Sakçagöz-Narlı Fault rupturing the East Anatolian Fault (EAF) for more than 300 km. Nine hours later, a Mw 7.5 earthquake occurred near Ekinözü; this earthquake ruptured nearly 100 km along the adjacent Çardak fault. Both mainshocks have triggered a great number of aftershocks along the faults and surrounding areas in the complex Maras triple junction. To better map the ongoing aftershock sequence, we deployed approximately 200 5-Hz SmartSolo nodal stations and 16 broadband/strong motion seismic stations across the rupture zone focusing on major clusters and potential areas under threat, for more than three months starting in May 2023. These SmartSolo nodal stations are set with a sampling rate of 500 Hz to record higher quality waveforms from smaller aftershocks, as compared with a 100 Hz sampling rate from typical broadband stations. In this work, we start with the earthquake catalog with more than 15,000 events in the same period of nodal deployment from the Turkey Disaster and Management Authority (AFAD) catalog. The P and S arrivals are picked, using the PSIR method, in the nodal stations and used as templates for subsequent matched-filter detection (MFD). We also apply a deep-learning phase picker called EQTransformer and its association method to the continuous nodal records to help identify more events that were not listed in the AFAD catalog, which adds more template events for the MFD. Our preliminary results show that MFD can detect micro-earthquakes hidden in the noise with very small magnitudes. Waveform-based relocation methods are then applied to all detected events to build a more complete catalog. With a higher resolution catalog, fault and seismic structures, especially splay faults along the EAF and the adjacent faults can be identified and imaged for an improved understanding of potential seismic hazards in this region. Additionally, we expect to better decipher the physical mechanism of aftershocks and processes that drive the evolution of seismicity in Southeastern Türkiye.

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Investigating the Türkiye-Syria and Afghanistan 2023 Seismic Sequences

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We present our results for the strong earthquakes in Türkiye-Syria and Afghanistan that occurred in 2023. For the former, our analysis incorporates InSAR results derived from the SAOCOM-1, Sentinel-1 and ALOS-2 satellites. We applied both conventional interferometry and the Pixel Offset tracking technique to quantify surface deformations caused by the impactful earthquakes, resulting in substantial structural failures and multiple fatalities. Employing a combination of non-linear and linear inversions, we utilised high-resolution Synthetic Aperture Radar (SAR)-based datasets as input. This facilitated the creation of two meticulously segmented variable slip fault models for the M 7.8 and M 7.5 events, employing a multiscale sampling approach to fully harness the potential of the high-resolution radar data. This approach allowed for a detailed examination and definition of the specific characteristics of each segment of the extensive tectonic structures that triggered the events on the 6th of February 2023. Subsequently, this model was employed to examine the distribution of the intensity of ground motions in the affected region. In the context of the northwestern Afghanistan sequence, we processed Sentinel-1 SAR data from both Ascending and Descending orbits to estimate surface displacement using the InSAR technique. Through a sequential application of non-linear and linear optimization, we identified the causative faults for the sequence of three M 6.4 events occurring on 7, 11, and 15 October.

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Measuring Afterslip From the February 2023 Mw 7.8 Pazarcık Earthquake Using Optical Images and Radar Data

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The East Anatolian fault, a major plate boundary transform fault in southern Türkiye, has hosted many large earthquakes - most recently the 2020 Mw 6.8 Elazığ earthquake and the 2023 Mw 7.8 Pazarcık earthquake of the 6 February 2023 Kahramanmaraş earthquake doublet. Previous studies suggest a ~40 km long potentially locked section of the longer Pütürge fault segment. This region north of the 2023 rupture and south of the 2020 rupture did not exhibit surface rupture from either earthquake. Whether this area is at risk of an earthquake or if afterslip can fully account for missing displacement in the region remains an open question. We explore this question with remote sensing methods. Using Sentinel-2 and Planet optical images, we calculate coseismic displacement profiles across the northern Pazarcık rupture, which ruptured 45 km of the 95 km Pütürge segment. We investigate afterslip from the 2023 Pazarcık earthquake using Sentinel-1 interferograms in the region between the 2020 and 2023 ruptures. Our work aims to quantify surface displacement and distribution along the northern Pütürge section; image the Pütürge section to understand its seismic potential; and better constrain the interactions of multiple large earthquakes along a plate boundary fault.

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Decoding the Rupture Kinematics of the 2023 Mw 7.8 and Mw 7.5 Kahramanmaraş Earthquake Doublet: Insights From Comprehensive Seismic and Geodetic Analysis

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We investigate the rupture kinematics and slip distributions of the recent Mw 7.8 and Mw 7.5 earthquake doublet which struck the East Anatolian Fault (EAF), the Narlı Fault (NF), and the Sürgü Fault near Kahramanmaraş, Turkey, on Feb 6, 2023. Employing a comprehensive dataset that includes distant and local seismic data, high-rate GNSS recordings, InSAR, and SAR images, we apply joint finite fault inversion and slowness enhanced back-projection to unravel the intricacies of the rupture process. Back-projection and finite fault inversion consistently reveals an asymmetric bilateral rupture for the Mw 7.5 event: a supershear west branch and a subshear east branch, each approximately 65 km in length. The supershear branch is further validated through the identification of Mach cones and Mach waves. For the Mw 7.8 mainshock, our detailed examination uncovers a nuanced rupture process: initiation and propagation commence on the NF, with bilateral propagation occurring upon reaching the junction with the EAF. The rupture then extends 120 km to the northeast at 3.05 km/s and 200 km to the southwest at 3.11 km/s. Furthermore, the initiation of slip on the EAF before the arrival of the rupture from the NF suggests a remote triggering relationship between the main fault and the splay fault. To delve into this relationship and the dynamics of rupture triggering from the splay fault to the main fault, we employ dynamic stress calculations. Our study aspires to provide critical insights into the propagation of rupture on complex faults, contributing valuable knowledge applicable to large strike-slip fault systems globally.

Induced Earthquakes: Source Characteristics, Mechanisms, Stress Field Modeling and Hazards

Oral Session • Wednesday 1 May • 8:00 AM Pacific

Conveners: Asiye Aziz Zanjani, Southern Methodist University (aazizzanjani@smu.edu); Farzaneh Aziz Zanjani, University of Miami (fzanjani@earth.miami.edu); Nadine Igonin, University of Texas at Dallas(Nadine.Igonin@utdallas.edu)

Structural Controls on Induced Earthquake Sequence's Growth and Slip Behavior

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To examine how the fault structures within Oklahoma control induced earthquake behavior, we examine both 3D seismic data and seismogenic faults. We utilize the LArge-n Seismic Survey in Oklahoma (LASSO), a dense nodal array with >1800 sensors, to characterize multiple small (<1 km in length) seismogenic faults. The identified faults' orientations are then compared to the local stress field to determine how their behavior is affected by how well oriented they are in the stress field for failure. The seismogenic faults earthquakes temporal behavior indicates that optimally oriented are driven more often by event-event triggering, while non-optimally oriented faults are driven more often by fluid diffusion. These faults structural behavior mimics what is observed in faults characterized in nearby 3D seismic data and could either represent small isolated faults or small segments of larger complex immature faults. The immature fault structures indicated by both the seismogenic faults and 3D seismic not only affect seismogenic sequence development, but also the slip of larger events that occur on them. To confirm this, we compare slip distributions between low (Oklahoma) and high deformation regions (California). The low deformation regions have more prominent and well separated slip patches, which is a behavior indicative of immature faults. This behavior does not change if the event was induced or not. These observations suggest that the initial underlying stress distribution, strength and orientation of induced faults in low deformation regions are the primary controlling factors of the slip distribution, while the major driving forces of sequence development such as pore pressure perturbations or earthquake interactions play a secondary role.

Seismic Hazard Analysis for Hydraulic-Fracture Triggered Earthquakes in Oklahoma

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It has been well-publicized that Oklahoma experienced an unprecedented increase in seismicity starting about 2010 and continuing today. That seismicity peaked in 2015 when there were ~900 M3.0 or greater earthquakes that year, relative to a tectonic background rate of just 1-2 M3.0 or greater earthquakes per year prior to 2009. Many of those events are now understood to have been induced by wastewater disposal, some of which caused moderate but not widespread damage to the rural communities in which they occurred. While most public and regulatory attention has historically been focused on wastewater disposal into the Ordovician-age Arbuckle Group as a causal mechanism, in the last few years hydraulic fracturing (HF) triggers most of the induced seismicity in the state. We will report on our recent efforts to categorize HF-triggered seismicity, over the last decade, through statistical analysis. During the last decade and increasingly as the network has expanded and event detectability has improved through implementation of machine-learning, we find that almost 16% of HF completions are associated with the occurrence of an earthquake. Of those ~8,000 earthquakes associated with HF, ~1,000 were felt and reported to the USGS DYFI. We will discuss a couple of anomalous cases of larger than expected reported intensities, which include significant amplification of seismic waves due to local geology. One of those was a M3.2 HF-triggered earthquake that led to reports of light damage in southern Canadian County, OK. Our findings have important implications for mitigation of HF well completion seismicity as it is occurring and can guide best practices for future long-term geostorage and geothermal projects.

Undocumented Cases of Induced Seismicity in Oklahoma and Texas

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Identifying the causal factors behind elevated seismicity rates in areas with multiple overlapping oil and gas activities has always been a challenging issue. Often enough the dominant causal factor masks cases triggered by secondary operations. Using the framework presented in Grigoratos et al. (2020; 2022) our analysis hindcasts seismicity rates on spatial grid using either Hydraulic Fracturing (HF) or Salt Water Disposal (SWD) data as input and compares them against the null hypothesis of solely tectonic loading. In the end, each block is assigned a p-value, indicating the statistical confidence of its causal link with either HF or SWD operations. Here, we present results for the Eagle Ford (EF) play in Texas and parts of Oklahoma (OK). Our results confirm previous studies that linked most of the seismicity in the EF and OK with HF and SWD, respectively. That said, we also identified clusters of seismicity triggered by HF in OK that spatially overlap with areas affected by SWD, as well as clusters triggered by SWD in the EF that spatially overlap with areas affected by HF. Finally, we also found that at least one cluster of earthquakes in the western part of EF play, along the border with Mexico, is related only to SWD. Our analysis highlights that overlapping oil and gas activities might trigger seismicity at different depth intervals, without the latter necessarily being in hydraulic communication.

Regional Moment Tensors for Texas

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Easy access to digital waveform data from TexNet and other networks permits the determination of regional moment tensors, earthquake magnitude and seismic structure within Texas. Our catalog of over 175 moment tensors is dominated by events in the Delaware and Midland Basins of western Texas, being complete for Mw > 3.4, with some events having Mw as low as 2.9. Source depths vary between 3 and 12 km, with over half between 8 and 10 km. The Saint Louis University generic western US velocity model (WUS) fits waveforms well. Events in the Delaware Basin are characterized by normal faulting along a 60 km E-W trend, while events in the Midland Basin are aligned in an NE-SW direction with a mixture of normal and strike-slip mechanisms. A determination of regional ML and mLg for each event shows that high frequency ground motion out to several hundred km is similar to that of the stable continental interior of the central and eastern US rather than to that of the western US.

There has not been much success in determining moment tensors for the smaller number of events in the Eagle Ford Basin in the southeast of the state, lacking an appropriate velocity model. To address that need, ambient noise processing using the continuous waveform data of TexNet is being performed to augment the dispersion data set previously distributed by Herrmann et al (2021, SRL 92, pp. 3642-3656). The derived dispersion can be used to check the appropriateness of using the WUS velocity model in the west.

Cross-Examining Methods for Determining Source Mechanisms for Induced Earthquakes in the Permian Basin

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Establishing the causal link between induced earthquakes and oil and gas operations in the Permian Basin depends on accurately assessing the 3-D distribution of seismic sources and their mechanism. The local recordings of the Texas Seismological Network (TexNet), established in 2017, provide a unique opportunity to determine the source characteristics of induced earthquakes in Texas. As one of the main initiatives of the TexNet, the overarching goal of this study is to identify an optimal approach for the regular and automated determination of source mechanisms using TexNet real-time seismic data. In this study, we implemented waveform moment tensor inversion (MTI) using Gisola to analyze over 150 earthquakes in the Delaware and Midland sub-basins. Gisola utilizes an automated algorithm and conducts a 4-D spatio-temporal MT grid search to determine a preferred solution for the source. We then performed a comparative analysis among reported solutions from various sources (e.g., SLU, rCMT, scmtv, NEIC) to cross-examine the consistency in results. Despite general uniformity among different solutions for the source mechanism, the centroid depths derived from Gisola and scmtv consistently appear shallower than that of other solutions. Differences in solutions may be associated with the choice of frequency range used in the modeling, the resolution of centroid locations, the effect of the velocity model, and/or varying station geometry. We also derived focal mechanisms from the P-wave first-motion polarities using HASH for earthquakes that have sufficient azimuthal coverage. Among the 70 earthquakes examined for initial polarities, 58 yielded solutions with HASH, and 26 of those solutions were non-unique. This study underscores the robustness of Gisola in providing high-quality seismic solutions for a wide range of magnitudes (> 2.2) using TexNet data, offering a valuable contribution to the ongoing efforts to comprehend and address induced seismicity in the Permian Basin.

Spatiotemporal Evolution of Induced Earthquakes in the Southern Delaware Basin, Reeves-Pecos, West Texas

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Accurate source characteristics are crucial for assessing the evolution of induced seismicity associated with oil and gas operations and subsurface stress changes in space and time. This study examines the spatial and temporal patterns of seismogenic rupture on critically stressed faults in the Southern Delaware Basin (SDB), west Texas (Reeves and Pecos counties). Utilizing the Hypocentroidal Decomposition method (HD) (www.seismo.com/mloc), we conducted two nested inversions. First, we established a virtual point in space and time, known as Hypocentroid, using a core cluster of local events. We then determined the relative location of all events with respect to this Hypocentroid. The HD relocation improves relative spatial resolution by incorporating data calibration and weighting and mitigates the influence of the 1-D velocity model on earthquake location. We relocated over 6000 events post-2017 provided from the Texas Seismological Network (TexNet) catalog and 73 events from the TXAR catalog (2009-2017) (Frohlich et al., 2020). We supplemented the TXAR and TexNet catalogs by incorporating regional differential times from waveform cross-correlation and local single-station S-P differential times at hypocentral distances less than 10 km, respectively.

After relocation, the mean seismogenic depth of 1.5 km below sea level aligns with the depth of the shallow injection unit, the Bone Spring formation, and is consistent with smaller-scale studies in the region. The spatial correlation between pre- and post-2017 seismicity, along with temporal patterns, maps the expansion of active lineaments in length and number, particularly to the southeast of the study region, as injection activities have evolved. While deeper seismicity is notably absent, this study cannot rule out the involvement of basement faults due to temporal variability in data availability and reduced spatial resolution for deeper seismicity. Our results confirm a prominent influence of pressurization from shallow wastewater injection zones on shallow NW-trending strata-bound faults and the temporal migration of earthquakes along adjacent rupture zones.

Seismicity Triggering in the North Delaware Basin, West Texas, USA

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As part of the intraplate tectonic regime within the continental US, the seismicity rate in Texas is expected to be low. However, the seismicity rate in West Texas has steadily increased since 2009, and significantly accelerated since 2020. Notably, the Texas Seismological Network (TexNet) has reported 49 M≥4 earthquakes (all after 2020) and 3 M≥5 earthquakes (all after 2022). In the area of the North Delaware basin of Texas, the first M4+ earthquake (2020-02-18, 13:28:06) occurred in the area of Mentone, followed one month later by a main event (M4.9; 2020-03-26, 15:16:27). The seismogenic structure that hosts the Mentone cluster is a normal fault striking WSW-ENE, with the seismicity distributed around or above the basement. The presence of nearby long-term deep wastewater injection in the area strongly suggests that the seismicity is due to the oil and gas operations.

In contrast, ~11km to the southeast of the Mentone cluster, seismicity with its first M3+ earthquake on Jan 25th 2021, shows a complex, normal faulting system near the area of Coalson Draw. Since then, the Coalson Draw seismic zone has been very active, with two notable M5+ events (M5.4, 2022-11-16 21:32:44 & M5.2 2023-11-08 10:27:49). The seismicity is apparently spanning ~5 km in depth and stretching across the basin-basement interface at about 5 km depth. Following an increase of seismicity in September 2021 (6 M4+ events occurred between September 3rd and October 3rd, 2021), in October 2021 the injection volume has been reduced at approximately 20 km to the north of the Coalson Draw sequence, due to concerns of deep injection being the causal factor of seismicity in the area. Additionally, the hypocenter of the M4.9 Mentone event is closer (~11km) to the deep injection than the Coalson Draw sequence (~20km). These relations suggest that the Coalson Draw sequence might have been initiated by deep wastewater injection, and later the seismicity rate has accelerated (M3+ events) due to dynamic triggering mechanisms (i.e., earthquake-to-earthquake triggering), eventually resulting in the occurrence of the first M5+ event.

Potential Poroelastic Triggering of the 2020 M 5.0 Mentone Earthquake in the Delaware Basin, Texas, by Shallow Injection Wells

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The Delaware basin in Texas, one of the largest oil and gas production sites in the United States, has been impacted by widespread seismicity in recent years. The M 5.0 earthquake that occurred in March 2020 near the town of Mentone is one of the largest induced earthquakes recorded in this region. Characterizing the source parameters and triggering mechanism of this major event is imperative to assess and mitigate future hazard risk. A former study showed that this event may be attributed to the deep injection nearby. Interestingly, the earthquake is in proximity to shallow injection wells with much larger total injection volume. In this study, we investigate the role of these shallow injection wells in the triggering of the M 5.0 event despite their farther distance from the mainshock than the deep wells. We first perform source-parameter inversion and earthquake relocation to determine the precise orientation of the south-facing normal-fault plane where the mainshock occurred, followed by fully coupled poroelastic stress modeling of the change of Coulomb failure stress (CFS) on the fitted fault plane caused by shallow injection in the region. Results show that shallow wells included in our analysis caused close to 20 kPa of CFS change near the mainshock location, dominated by positive poroelastic stress change. Such perturbation surpasses the general triggering threshold of faults that are well aligned with the local stress field and suggests the nonnegligible role of these shallow wells in the triggering of the mainshock. We also discuss the complex effect of poroelastic stress perturbation in the subsurface and highlight the importance of detailed geomechanical evaluation of the reservoir when developing relevant operational and safety policies.

Using Converted Phases to Investigate Induced Seismicity in the Midland Basin, Texas

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Wastewater injection triggers seismic activities in the Midland basin, west Texas, where the seismic events as large as M5.2 have been recorded. Mitigation requires understanding the role of shallow (<1.5 km subsurface) versus deep (2.3-3.4 km subsurface) injection, and the determination of causal factors is complicated by the uncertainties of hypocentral depths (+/-3 km), which may be associated with the complicated basin geology and inadequate network coverage over time. Here, we use body wave conversions common for shallow earthquakes in sedimentary basins to constrain hypocentral depths. We first generate a series of synthetic seismograms to gain an intuitive understanding of the subsurface characteristics that lead to the converted phases, and investigate how the waveform is influenced by various source parameters and velocity models. Sonic logs show that the Silurian-Devonian+Ellenburger (SD+E) and the San Andres (SA) formations provide significant impedance contrasts between layers to generate converted body waves (sP). These sP phases are potentially identifiable to earthquake analysts with epicentral distance less than 10 km. The clarity of the converted phases depends on radiation pattern, focal depth, and geology along the propagation paths. Changes to quality factors (*Qp* and *Qs*) and density did not produce any notable changes to shape and signal-to-noise of the synthetic sP. Synthetic tests indicate that the relative timings of converted phases are directly controlled by earthquake depths, and the amplitude of converted phases is strongly tied to the amplitude of the S-wave. Events located in the basement will yield two main converted phases, one from the SD+E boundary and one from the SA. The velocity contrast at the top of the SD+E yields an identifiable converted phase whose S-sP time could be incorporated into earthquake location algorithms. Converted phases have the greatest clarity (signal-to-noise) at depths greater than 6 km and operationally should be picked on data between 2-10 km event station distances. Lastly, we provide comparisons between the synthetic waveforms and real data.

Fault Reactivation During Induced Seismicity Sequences in Southern Kansas

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Using machine learning enhanced catalogs, it is possible to study the evolution of earthquake sequences in great detail owing to the significant decrease in magnitude of completeness compared to routine catalogs. We use the enhanced catalog of Park et al. (The Seismic Record, 2022) for Oklahoma and Southern Kansas to examine the spatial and temporal evolution of seismicity on individual faults in southern Kansas. In the Park et al. study it was found that individual faults commonly activate multiple times. To better understand the nature of reactivation we refine the hypocentral locations using the slope of the cross spectrum to measure sub-sample differences in travel time between highly correlated events. We obtain precise relative locations for earthquakes occurring along individual fault structures with an accuracy of 10-20 m. Along one isolated, 2.5 km-long fault we find approximately 10% of the events are "true" repeaters (>50% overlap in rupture area). Interevent times vary widely, between a few hours and several months with no clear trend with magnitude. Repeating earthquakes concentrate along the central portion of the fault indicating that the same portion of the fault slipped more than once during the sequence. Of note, the largest repeaters in the sequence, ML 3.2 and 3.1 occurred shortly after the fault became seismically active and just 3 days apart. This raises the question of the re-failure mechanism. Further investigations will be needed to determine the role of aseismic slip (potentially revealed by small repeaters), stress interaction and/or progressive weakening from rising pore pressure as the re-triggering mechanism.

Detailed Analysis of Microseismic Activity Associated with Shutdowns of the San Emidio Geothermal Plant, Nevada

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We are analyzing dense seismic array data encompassing shutdowns of the San Emidio geothermal plant in Nevada in 2016 and 2022. In 2016, an array of ~1,300 vertical-component seismographs operated by Microseismic Inc. recorded for about a week. In 2022, an array of 450 three-component seismographs was deployed as part of the WHOLESCALE project, covering most of the northern ~2/3 of the 2016 array footprint at twice the instrument spacing, and recorded for about a month. The data are being analyzed with two workflows to detect and locate the microseismic events. The first generates a microseismic event catalog directly from the raw continuous seismic data. The second produces high-precision event locations via a sequence of repicking arrivals, waveform cross-correlation, and double-difference relocation. Analysis of the 2022 data set reveals intense seismic activity commencing soon after shutdown and returning to the previous background rate shortly after restart. The events fall into several main clusters that include some linear features. Preliminary results for the 2016 data set show a similar pattern of heightened activity during the shutdown, revealing an order of magnitude more events than a previous catalog estimated using a back-projection approach. As the catalog size allows, statistic-physics models analyzing space-time connections as well as magnitude clustering are explored.

The work presented herein has been funded in part by the Office of Energy Efficiency and Renewable Energy (EERE), U.S. Department of Energy, under Award Numbers DE-EE0007698 and DE-EE0009032. The seismic instruments deployed in 2022 were provided by the Incorporated Research Institutions for Seismology (now the EarthScope Consortium) through the PASSCAL Instrument Center at New Mexico Tech. Data collected will be available through the EarthScope Data Management Center. The facilities of the EarthScope Consortium are supported by the National Science Foundation's Seismological Facility for the Advancement of Geoscience (SAGE) Award under Cooperative Support Agreement EAR-1724509.

Source Characteristics of Microseismicity Occurring During Operational Shut-in Periods at the Coso Geothermal Field, California

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Throughout its 30+ years of energy production, the Coso Geothermal Field (CGF) in California has regularly experienced both tectonic and induced microseismicity. While distinguishing between these two types of earthquakes can be difficult, knowledge of the interplay between operational parameters and the reservoir's seismic response can shed light on key factors affecting the stress field and the reservoir's productivity.

In this study, we examine daily production and microseismicity data from the CGF between 1996 and 2010 to gain insight into the evolution of its stress field and how it has been affected by long-term production. Using 27 seismic stations from a local network, we analyse the source characteristics of 60,000+ earthquakes with moment magnitudes between -1 and 3.3. We find that most of the seismicity occurs towards the southern and eastern sections of the field, coinciding with the regions of the CGF where most of the fluids are reinjected. Additionally, these regions with higher seismicity rates tend to experience an abrupt increase in seismicity rates during the yearly power plant maintenance periods and wellbore shut-ins. Increased seismicity during shut-in periods has been observed previously at other geothermal fields and spatially linked to production wellbores. Through waveform cross-correlation and seismic event relocation, we identify distinct clusters of microseismicity re-occurring during these shut-ins. These observations may suggest that certain fracture and fault sections respond quicker to changes in pore pressure and poroelastic stresses within the geothermal system. Better understanding of these relationships can de-risk geothermal operations and optimize productivity of the field.

Double-Pair Double-Difference Relocation for Dense Network Improves Depth Precision of Induced Seismicity, Leading to a Detailed 3D Fault Geometry Model

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Earthquake locations with well-constrained uncertainties allow for interpreting fault systems and fault activation mechanisms for large datasets. Improved precision and reduced uncertainty of relative locations can aid in understanding fault plane geometry and provide images of fault activation from induced seismicity. Double-pair double-difference relocation is an adaptation of event-pair relocation that incorporates station-pair differential travel times, which is particularly useful for dense networks. The additional information from station pairs limits the impact of velocity model uncertainties, reducing the impact of velocity model errors in locations. For reservoir applications with induced seismicity, this benefit is pronounced at depths where large velocity contrasts due to reservoir layers occur. In such areas, source locations can be poor from the traditional event-pair relocation method. We present double-pair double-difference relocation results for 4,000 induced events from monitoring near Fox Creek, Alberta. Because of highly correlated waveforms with a 0.9 cross-correlation coefficient cut-off, including station-pair information increases data from 2.5 million cross-correlation differential times to 62.8 million data points. The relative uncertainties in the double-pair relocated catalog are zero-mean and 1-2 m for all three spatial parameters, which improves upon the event-pair relocations with relative uncertainties of 3 m in X and Y and 4 m in depth and nonzero means in the range of 50 m in Y and 100 m in Z due to directional anisotropy. Double-pair relocations lead to spatial clustering of events at discrete depths, which is consistent with the geology of the stimulated zone, comprising thin layers of stronger carbonates embedded within weaker shales. Using double-pair double-difference, we provide a precise fault map, including 3D least-squares planar fits for earthquake clusters. The fault map confirms prior studies about existing faulting in the region, particularly that the study area is part of a larger structural corridor, likely a flower structure exhibiting Riedel shear behavior.

Multi-Sensor Microseismic Monitoring of the Quest CCS site, Alberta, Canada

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Nowadays, Carbon Capture and Storage appears as one of the solutions to reduce the amount of CO_2 in the atmosphere. At the Quest CCS site in Alberta, Canada, injection of CO_2 started in 2015 with one million tonnes per year and ongoing until 2040. Microseismic monitoring has been part of the MMV plan since the beginning of the project, aiming to mitigate the potential risks associated with the injection. The closer area around Quest has been seismically quiet before injection operation started. A string of eight 3-component geophones was installed in a deep monitoring well. In addition, 153 surface nodes arranged in mini-arrays were temporarily deployed and a DAS cable installed in one of the injection wells was interrogated during a period of six months.

More than 600 microseismic events of magnitude ranging from -2 to 0.8 were detected and located within the area of review. All events have been located in the Precambrian basement below the reservoir causing no containment threat. This rich dataset allows for the comparison of the different monitoring technologies against each other both in terms of detectability and locatability of events. We demonstrate how signal processing and array processing techniques can significantly lower the event detection threshold. Event location uncertainties can be reduced by combining various data.

Advanced InSAR Analysis of Groningen's Subsurface Deformation: Enhancing Understanding of Reservoir Rheology and Induced Seismicity Modeling

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In the context of the increasing incidence of induced seismicity linked to hydrocarbon extraction, our study presents a comprehensive analysis of subsurface deformation at the Groningen gas field in the Netherlands, a notable example of seismic activity associated with gas production. Employing a multidisciplinary approach, we integrate InSAR data (RADARSAT2, TerraSAR-X, Sentinel-1), GNSS, and optical leveling to investigate the reservoir's time-dependent deformation. We leverage Independent Component Analysis (ICA) to distinguish deformation sources, offering insights into the intricate interplay of subsurface operations. We observed pronounced decadal subsidence across the Groningen field, with spatial variations in subsidence rates highlighting local compressibility differences. Notably, ICA uncovered significant seasonal fluctuations in the Norg area, with a 20 mm amplitude over a 5x5 km region, correlating with gas storage cycles and revealing a previously obscured deformation signal. Through comparative analysis of long-term subsidence and Norg's seasonal deformation against various model predictions, including linear poroelastic and rate-type compaction models (RTiCM), we identified evidence of inelastic compaction in the reservoir. This insight, manifested as a time-dependent increase in apparent compressibility (Cm), is pivotal for advancing seismicity forecast models. Our results contribute significantly to understanding the hydromechanical processes governing induced seismicity and highlight the need for integrated geomechanical modeling in managing seismic risks in Groningen and similar settings.

Induced Earthquakes: Source Characteristics, Mechanisms, Stress Field Modeling and Hazards [Poster Session]

Poster Session • Wednesday 1 May

Conveners: Asiye Aziz Zanjani, Southern Methodist University (aazizzanjani@smu.edu); Farzaneh Aziz Zanjani, University of Miami (fzanjani@earth.miami.edu); Nadine Igonin, University of Texas at Dallas(Nadine.Igonin@utdallas.edu)

POSTER 96

The Critical State of Stress Preceding the Prague m5.7 Earthquake

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Here we examine induced seismicity, a consequence of contemporary oil and gas extraction methods. We focus on understanding the role of large earthquakes in triggering subsequent seismic activities via transient dynamic stressing. Central to our investigation is Prague, Oklahoma, a region characterized by natural, induced, and dynamically triggered seismicity. We analyze approximately 1.5 years of data (2010 - 2012) gathered from EarthScope's USArray Transportable Array (TA), supported by an advanced local earthquake catalog. We investigate 254 teleseismic earthquakes (magnitude ≥ 6), and identify cases of increased seismic activity in Prague, Oklahoma, integrating a robust statistical approach. Notably, our findings indicate evidence of heightened triggered seismicity preceding the 2011 Mw 5.7 Prague earthquake, implying a state of critical stress prior to the event. This research highlights the complex interactions of static, induced, and transient stresses, offering vital insights for understanding and potentially mitigating induced seismicity.

POSTER 97

A 3-Dimensional P-Wave Tomography Model of the Pecos, Texas Region of the Delaware Basin

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With increasing earthquakes in the Delaware Basin since 2009, earthquake studies, including accurate hypocenters, are critically needed in the Delaware Basin to identify the structures producing earthquakes, and to determine if they are related to unconventional petroleum development and production. In 2018, with funding from the Texas Seismological Network (TexNet), the University of Texas at El Paso deployed and maintained a network of 25 Magseis Fairfield Z-Land Generation 2 5-Hz seismic nodes in the Pecos, Texas region of the Delaware Basin, known as The Pecos Array. The network was deployed from November 2018 until the beginning of January 2020, with an additional two months of data recorded in September and October 2020. The network collected continuous 3-component data with a 1000-Hz sampling rate. The spacing of the nodes varied from ~2 km in town to ~10 km farther away from the city center. The Pecos Array was used to conduct a local 3-D P-wave tomography study in the Pecos, Texas region using the SIMULPS software. Previous tomography studies have been conducted to derive a P-wave velocity model of the entire Permian Basin, but these studies covered a broader area, and their best velocity results were in the upper 35 km of the crust. With our denser array, localized earthquakes, and increased ray coverage in the Pecos, Texas area, we have created a detailed 3-D velocity model for the top 8 km of this region. We observe velocity values that are consistent with reported geologies in the basin, and slower velocities on faults compared to areas without faults. We found that our new model is ~25% slower between depths 2–6 km compared to the DB1D regional velocity model that TexNet uses to locate their public catalog.

POSTER 98

Pore Pressure Effect on Coulomb Stress Change and Triggering of Earthquakes in Raton Basin, Colorado-New Mexico Region

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The Raton Basin, located in southern Colorado and northern New Mexico, is an actively producing hydrocarbon basin that has undergone increased seismicity since 2001, which is attributed to anthropogenic perturbations resulting from wastewater injection. To better understand how changes in pore pressure and shear stress along faults give rise to earthquake sequences, we investigate the spatio-temporal evolution of static Coulomb stress changes associated with nine seismic events of magnitude Mw>4 that occurred in the Raton Basin between 2001 and 2011. Examining the distribution of stress provides insights into whether subsequent earthquake events in the region are triggered or delayed. Wastewater injection operations in the region have raised pore pressures in nearby fault zones, increasing the likelihood of inducing slip or triggering earthquakes on critically stressed faults. Pore pressure effect cannot be neglected, and we further examine how it affects Coulomb stress. Our analysis reveals that the 2011 Mw 5.3 earthquake, the largest magnitude event occurred in the basin, was likely triggered by cumulative static stress changes and pore pressure increases resulting from the prior seismicity from 2001 to 2005. We find notable differences of approximately 0.1 MPa in our models of stress change when including versus excluding the effects of pore pressure. This is significantly higher than the 0.01 MPa change typically considered sufficient to trigger seismicity. Our results show that pore pressure can significantly affect modeled Coulomb stress changes over time. Careful monitoring of pore pressure changes, combined with modeling of stress interactions across regional fault networks, is critical for understanding induced seismicity hazards in regions undergoing continued wastewater injection. Incorporating pore pressure data into stress change models enhances the insights into earthquake triggering and aftershock forecasting.

POSTER 99

The Minimal Effect of Solid-Earth Tides on Earthquake Rate in Oklahoma and Kansas

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Natural stress oscillations from Earth's tides provide short-timescale, semi-repeatable tests of fault strength. Given that induced earthquakes occur along critically stressed faults due to high fluid pressures, it is possible that there would be a correlation between the small stress changes imposed by Earth tides and induced earthquake rates. We investigate this using a machine-learning-built earthquake catalog spanning 2010-2020 (Park et al., 2022) that contains ~300,000 events in northern Oklahoma and southern Kansas and numerical modeling of the solid-earth tides. We use Schuster's p-value to test whether there is a statistically significant correlation between the semidiurnal tidal phase and the earthquake rate. Schuster's test assumes that each earthquake is independent; therefore, we declustered the earthquake catalog using three approaches (Reasenberg, nearest-neighbor distance, and phase bin method). For all three declustered catalogs, we found that the ~3 kPa volumetric stress change from solid Earth tides does not significantly (p-value>0.05) affect the earthquake rate when the full study region and ten year time period were considered. We tested the effect of the tides on various space discretization and time windows of the earthquake catalog and generally observed a minimal effect of solid Earth tides on the earthquake rate, often less than that expected by random chance (5 %). Preliminary results for the spatial variations in tidal triggering from 2015-2017 reveal 6 % (3 out of 47) of the 20x20 km cells are significantly correlated to the solid Earth tides. Two of the three cells are in close proximity to regions with high rates of wastewater injection. Of particular interest is the region near Cushing, Oklahoma which has a p-value of 0.002 and an elevated earthquake rate from -120 to 90 phase angle. This area is in close proximity, ~15 km, to the largest total volume of wastewater injection, ~500 M barrels injected by 2017.

POSTER 100

Hindcasting the 1993 - 2023 Wirdum Induced Earthquake Sequence

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On October 8th 2022, a ML 3.1 earthquake struck the village of Wirdum, 20 km from the city of Groningen in the Netherlands. The earthquake could be linked to a 4.3 km fault cross-cutting a gas reservoir, the Wirdum fault. The Wirdum fault segment experienced over 30 prior earthquakes since its reactivation due to gas production, including a ML 2.5 (2019) and a ML 2.7 (2015). Current hazard models lack the capability of both hindcasting a sequence of induced earthquakes over decades and studying the source and surface processes. For this a physics-based prediction framework is needed. Using high-quality data of the Groningen gas field, we re-interpreted the fault geometry. Constrained by well-log data we load the realistic fault geometry with heterogeneous pre- and post-production stresses using a semi-analytical 2.5D poroelastic stress solution (PANTHER; Buijze, 2024). Based on extensive laboratory experiments we use heterogeneous friction and elastic parameters to account for variable along-strike on-fault reservoir offset and bi-material regions, embedded in a detailed geological model. We derive the critical stress levels at which we simulate the three ML 2.5+ earthquakes of the Wirdum sequence through data-driven 3D dynamic rupture modelling (SeisSol). Results show predicted critical levels of on-fault stresses similar to observed reservoir pressure at times of each earthquake. Each earthquake nucleates spontaneously through stress loading. Simulated hypocentres are controlled most by variations in fault dip (its first M1's), although other fault geometry aspects are important as well. Rupture arrest is dominantly controlled by on-fault stress heterogeneity resulting from along-strike kilometre-scale undulations of the fault geometry. Calculated first arrivals for each earthquake largely agree with observed seismograms. This physics-based hindcasting framework for induced seismicity will be used to forecast future earthquakes on the Wirdum fault. We will build forth on this for seismic hazard assessment and Mmax estimates in Groningen and towards a successful contribution of sustainable subsurface solutions.

POSTER 101

Quake-Dfn, A Software for Simulating Sequences of Induced Earthquakes in a Discrete Fault Network

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We present an earthquake simulator, Quake-DFN, which allows simulating sequences of earthquakes in a 3-D Discrete Fault Network governed by rate and state friction. The simulator is quasi-dynamic with inertial effects being approximated with radiation damping and a lumped mass. The lumped mass term allows accounting for inertial overshoot and, in addition, makes the computation more effective. Quake-DFN is validated against three benchmark problems: (i) the rupture of planar fault with uniform prestress (SEAS BP5-QD), (ii) the propagation of a rupture across a step-over separating two parallel planar faults (RSQSim and FaultMod), and (iii) a branch fault system with a secondary fault splaying from a main fault (FaultMod). Examples of injection-induced earthquake simulations are shown for three different fault geometries: (i) a planar fault with a wide range of initial stresses, (ii) a branching fault system with varying fault angles and principal stress orientations, and (iii) a fault network similar to the one that was activated during the 2011 Prague earthquake sequence in Oklahoma. The simulations produce realistic earthquake sequences. The time and magnitude of the induced earthquakes observed in these simulations depend on the difference between the initial friction and the residual friction μ_i - μ_f, the value of which quantifies the potential for run-away ruptures (ruptures that can extend beyond the zone of stress perturbation due to the injection). The discrete fault simulations show that our simulator correctly accounts for the effect of fault geometry and regional stress tensor orientation and shape. These examples show that Quake-DFN can be used to simulate earthquake sequences, most importantly magnitudes, possibly induced or triggered by a fluid injection near a known fault system.

POSTER 102

Crustal Rheological Layering Revealed in Multiscale Signals of Natural and Anthropogenic Processes at Pawnee, Oklahoma

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Oklahoma has experienced a significant increase and decrease in human-induced earthquakes in the past decade. The Mw5.8 Pawnee earthquake in 2016 is the largest recorded event linked to wastewater injection, rupturing a previously unmapped Sooner Lake Fault (SLF). Two months after the event, eight continuous Global Navigation Satellite Systems (GNSS) stations were deployed around the SLF, adding to the growing monitoring networks in the state. Here, we use multi-year geophysical observations from the Pawnee region to estimate the spatiotemporal evolution of seismicity and strain and probe the rheological properties of intraplate faults and crustal layers. We process the GNSS position time series to reveal transient signals due to crustal processes from late 2016 to 2022. The largest rapid deformation signals coincide with an M3.9 event within earthquake swarms in 2019. Interestingly, the GNSS stations farthest from the faults primarily exhibit subsidence, attributable to poroelastic deformation due to changes in injection activities into shallower rock formations. In contrast, near-fault stations show larger horizontal movements and uplift, suggesting an origin of faulting processes. Over the recorded post-seismic period, seasonal signals predominate the vertical GNSS components, whereas the horizontal components show similar steady trends, with intrastation differences in average rates below ~1 mm/yr. The lack of spatially localized, transient geodetic strain suggests that postseismic fault slip is either persistently weak over years or short-lived within two months of the Pawnee event. We further estimate decadal GNSS secular rates over a larger region and find differential movements of ~1 mm/yr between the Pawnee array and nearby stations, which may be explained by the viscoelastic flow of the lower crust. We derive updated source models of the Pawnee mainshock and swarm events to estimate stress changes and assess the contributions of aseismic slip and poroelastic and viscoelastic deformation.

POSTER 104

Fluid-Induced Aseismic Slip May Explain the Non-Self-Similar Source Scaling of the Induced Earthquake Sequence Near the Dallas-Fort Worth Airport, Texas

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Numerous studies have reported the occurrence of aseismic slip or slow slip events along faults induced by fluid injection. However, the underlying physical mechanism and its impact on induced seismicity remain unclear. In this study, we develop a numerical model that incorporates fluid injection on a fault governed by rate-and-state friction to simulate the coupled processes of pore-pressure diffusion, aseismic slip, and dynamic rupture. We establish a field-scale model to emulate the source characteristics of induced seismicity near the Dallas-Fort Worth Airport (DFWA), Texas, where events with lower stress drops have been observed. Our numerical calculations reveal that the diffusion of fluid pressure modifies fault criticality and induces aseismic slip with lower stress drop values (<1 MPa), which further influence the timing and source properties of subsequent seismic ruptures. We observe that the level of pore-pressure perturbation exhibits a positive correlation with aseismic stress drops but a reversed trend with seismic stress drops. Simulations encompassing diverse injection operations and fault frictional parameters generate a wide spectrum of slip modes, with the scaling relationship of moment (M_0) with ruptured radius (r_0) following an unusual trend, M_0- $r_0^{4.4}$, similar to M_0- $r_0^{4.7}$ observed in the DFWA sequence. Based on the consistent scaling, we hypothesize that the lower-stress-drop events in the DFWA may imply less dynamic ruptures in the transition from aseismic to seismic slip, located in the middle of the broad slip spectrum, as illustrated in our simulations.

POSTER 105

DC or Non-DC? Exploring Uncertainties and Resolution Limitations for Source Mechanism Studies in a Complex EGS Environment

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The causal connection between high-pressure fluid injections and induced seismicity is well known. The source processes of individual microseismic events and their interaction as an ensemble are less well understood and may depend on the geological preconditions and the injection design. Two endmembers of plausible acting mechanisms are pure shear, represented by a double-couple (DC), and pure tensile opening, represented by non-DC components of the moment tensor. Between the two endmembers, there are mixed-mode events and the mixed occurrence of both shear-dominated and tensile-dominated events. Differentiating between these mechanisms and resolving the non-DC component can be challenging in many EGS. Surface monitoring might provide good azimuthal coverage but cannot record relatively small-magnitude events at depth. Borehole monitoring, while closer to the source area, may suffer from the reduced azimuthal coverage required to reliably resolve differences in the source mechanism. Most EGS projects suffer from these inherent difficulties in resolving the source mechanisms of the predominantly small-magnitude events, thereby introducing significant uncertainties in inversion results. Our limited knowledge of the velocity structure of the subsurface may also bias the result, eventually hindering the reliable resolution of non-DC and DC components. Understanding these limitations is key for following interpretations of acting larger scale processes, such as the development of a rather simple hydraulic fracture or the activation of a complex fracture network mainly driven by slip along preexisting faults and fractures.

We systematically explore these uncertainties and shed light on using full-probabilistic inversion schemes relying on first-motion polarities, amplitude ratios, spectra, and full-waveforms using real and synthetic data related to the Utah FORGE, a large-scale experimental EGS.

POSTER 106

Wastewater Disposal and Hydraulic Fracturing Interaction Propagating Seismicity in Oklahoma

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Wastewater injection and hydraulic fracturing processes have independently been attributed to induced seismicity in Oklahoma. When the two processes occur concurrently in close spatial proximity, an interaction of the perturbed stress can accelerate slip, inducing seismicity on a fault. We analyze a sequence in eastern Oklahoma, near the town of Quinton, where an earthquake sequence occurred over a several year timespans in 2019-2022, adjacent to hydraulically-fractured well completions and a large volume injection well. We use this insight to better understand the interaction between wastewater injection and hydraulic fracturing processes and evaluate their respective roles in inducing earthquakes. We analyze the frequency content of the broadband seismograms to detect possible fluid movement on the seismogenic faults by analyzing waveforms recorded at the same station to discount the influence of the ray path and site conditions. Analysis of the energy frequency spectrum (i.e., frequency index) indicates a temporal variation of frequencies that has increasingly low frequency events correlated with times of active wastewater injection. The increasing low frequency content events coincides with an increased rate of seismicity. Upon the cessation of injection, the low frequency content in events decreases over time as the seismicity rate decreases. Constrained earthquake focal depths from a relocated catalog indicate that the low frequency earthquakes occur only within the sedimentary formations along with the high frequency dominated earthquakes, even though the later extends into the basement. We postulate the hydraulic fracturing process reactivates faults that are hydraulically connected to the wastewater injection well that subsequently allow fluid propagation into the seismogenic faults, as observed from the spatiotemporal distribution of the earthquakes. We conducted lab experiments for different earthquake excitation scenario for faults saturated with fluid and compare to semi-saturated faults. We will present an updated analysis of simulation of earthquake excitation on faults with variable fluid content.

POSTER 107

Centroid Full Moment Tensor Analysis Reveals Geological and Injection Related Constraints of Induced Seismicity at the Experimental Otaniemi EGS Site, Helsinki Region, Finland

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In 2018 and 2020 two ~6 km deep geothermal wells in Otaniemi, Helsinki region, Finland were stimulated to develop an experimental enhanced geothermal system. The stimulations activated pre-existing fracture networks and induced thousands of small earthquakes. We present the results of centroid full moment tensor (MT) analysis using the probabilistic seismic source analysis framework Grond and fitting P- and S-waves in the time domain from ~30 stations within 9-km of the drill site. Although the Precambrian shield setting permits using a half space velocity model, channel-wise time shift and amplitude corrections are used to account for small scale crustal variations. The competent medium with low attenuation combined with carefully defined corrections allow the resolution of good MT solutions that reflect the complexities of the source process and source volume.

MT solutions of 301 M_w0.3-2.0 induced events have uniform reverse mechanisms, which is in apparent conflict with the reported regional strike-slip stress field. The average DC component is 80 % and spatially separated DC component clusters reveal small differences in local fracture orientations. The average non-DC component is 20 %, but the non-DC components display clear spatial patterns. In non-DC components a difference is observed between the 2018 and 2020 MT solutions, the 2018 solutions having an average compressive component and the 2020 solutions having an average opening component. Within the 283 events of the 2018 induced seismicity the CLVD component trends towards negative values with increasing distance from injection well. The ISO component over the full set of 301 events shows clear spatial variation that seems not to be related to the positioning relative to the injection wells, but is potentially geologically controlled. We discuss the potential causes of the difference in non-DC components between the two injections including different pre-existing medium and fluid properties in the injection locations, and pore pressure changes following the first stimulation.

POSTER 108

Inferring Maximum Magnitudes From the Ordered Sequence of Large Earthquakes

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The largest magnitude earthquake in a sequence is often used as a proxy for hazard estimates, as consequences are often predominately from this single event. In this paper, the statistical concept of order statistics is adapted to infer the maximum magnitude (M_{MAX}) of an earthquake catalogue. A suite tools developed here can discern M_{MAX}influences through hypothesis testing, quantify M_{MAX}though maximum likelihood estimation, or select the best M_{MAX}prediction amongst several models. The efficacy of these tools is benchmarked against synthetic and real-data tests, demonstrating their utility. Ultimately, thirteen cases of induced seismicity spanning wastewater disposal, hydraulic fracturing, enhanced geothermal systems are tested for volume-based M_{MAX}. I find that there is no evidence of volume-based processes influencing any of these cases. To the contrary, all these cases are adequately explained by an unbounded magnitude distribution. These implications towards mitigating induced seismicity and inferring source processes are discussed. Overall, this suite of tools will be important for better understanding earthquakes and managing their risks.

POSTER 109

Constraining the Non-Double-Couple Components of Local Events Recorded by Dense Nodal Array

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Traditional seismic source assumptions (i.e., double-couple model) may not fully describe small-moderate magnitude events with non-negligible explosive or non-linear features (i.e., non-double-couple components, non-DC). However, in local distances, constraining these non-DC components is challenged by complex 3D velocity structures that restrain the successful simulation of seismograms. Alternatively, using polarities and amplitudes to resolve full moment tensors presents significant potential with the recent boost of the dense nodal array. This study introduces an algorithm combining different far-field observations (i.e., direct P-wave polarities, amplitudes, and S/P amplitude ratios) to characterize and visualize the non-DC components of small earthquakes. The optimal moment tensor and associated uncertainties are determined through a grid search over 6-D moment tensor space, and then projected onto lune plot for virtualization (Tape & Tape 2012). The efficiency and accuracy are tested with both synthetic data and field observations near a hydraulic-fracturing well (ToC2ME) in Western Canada. The reliability of our metric is quantified via the angular difference ω (i.e., range from 0 to 180) between two moment tensors. The range of possible solutions and mismatches increases from ω=1.6 at noise free to ω=15 when 10-times field noises are added. In addition, our metric shows strong resistance to structure heterogeneity under such dense array coverage: the optimal solutions can still be resolved with perturbations on station-based layered-velocity models as high as 40%. Our inversions for 167 M>1 events within ToC2ME agree with Zhang et al., 2019, with 93% of events displaying ω<20. Furthermore, when compared with the known hydraulic-fracturing operations, our reassessed non-DC components exhibit more interpretable physical processes. Our proposed moment tensor inversion algorithm for dense arrays could serve for many other anthropogenetic involved local-scale settings, especially where uncertainty evaluation and virtualization for non-DC couple components are needed.

POSTER 110

Unraveling the Subsurface Mosaic: Implications of Tectonic Structures and Fault Orientations on Induced Seismicity

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Pre-existing geological frameworks like tectonic structures, fault orientations, and pore pressure diffusion, contribute to an intricate relationship with induced earthquakes. This study seeks to develop a holistic understanding on the influence of geologic factors on induced seismic events, by employing 3D fault imaging and InSAR modeling methodologies. The aim is to create a detailed spatial map showing the distribution and orientation of tectonic structures and faults in the Olkaria Geothermal Complex in Kenya, an area susceptible to induced seismicity from Geothermal Power Production. The study aims to uncover patterns and correlations contributing to a comprehensive understanding of the dynamic processes at play beneath the Earth's surface by exploring the interplay between these geological features and induced seismicity. The research anticipates an outcome of a refined spatial representation of tectonic elements and valuable insights into the role of fault orientations in influencing the occurrence and magnitude of induced seismic events. This research approach underscores its potential to advance our comprehension of induced seismicity, informing strategies on responsible resource exploitation in regions impacted by human activities like enhanced geothermal systems, oil and gas production, fluid injection in mining, and carbon capture.

POSTER 111

On Delayed Triggering of Earthquakes by Anthropogenic Activities

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It is common to observe relatively large earthquakes that occurred after completion of anthropogenic activities. Such delayed triggering poses a significant challenge in hazard assessment, yet its mechanism remains elusive. Here we focus on the Weiyuan shale gas field, Sichuan Basin, where the largest earthquake (Mw 5.0) occurred 3 months after the shut-in of nearby fracking wells. We first construct a high-resolution earthquake catalog, illustrating that the source fault of the 2019 Mw 5.0 earthquake was activated one year ahead. After frackings were completed nearby, the rate of seismicity decreases until the mainshock occurrence. To explore the mechanism of 3-month delay, we then develop a fault model in 2D antiplane shear governed by rate-and-state friction, coupled to pore pressure diffusion. We take into account three past injections at different wells, and inject fluids in three stages into the velocity strengthening (VS) part of the fault. A velocity weakening (VW), seismogenic patch is placed some distance away from the injector. We observe that after injection stops, aseismic slip is able to propagate further from the VS part of the fault into the VW patch, making it more susceptible to earthquake nucleation. Even though the first and second injections failed to rupture the fault, they both contributed to bringing the fault closer to failure. Eventually, the additional stress perturbation from post-injection aseismic slip due to the third injection triggered an earthquake, which occurred about 3 months after injection stopped.

This type of delayed earthquake triggering due to post-injection aseismic slip from multi-stage injection has not been explored before, and we believe it is highly plausible that such an effect is not unique to our study region. It may be a viable mechanism to explain other induced earthquakes that occur sometime after well shut-in. Apart from pore pressure diffusion and poroelastic effects, post-injection aseismic slip should also be taken into account when assessing the hazard of earthquakes trailing well stimulation completion.

POSTER 112

Source Mechanisms Inversion of Induced “Seismicity” During Laboratory Hydraulic Fracturing

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This paper presents a laboratory study focused on hydraulic fracturing within a shale specimen. During the study, in-situ acoustic emissions were monitored using a 24-sensor array, with four sensors placed on each of the sample block's surfaces. The large shale specimen featured a pre-existing natural fracture spanning the entire sample. To replicate authentic subsurface stress conditions, a true tri-axial compression system applied confining stress. Fluid was introduced through a central borehole within the specimen until a hydraulic fracture developed along a pre-cut notch situated at the borehole's edge. This newly formed hydraulic fracture was oriented perpendicular to the pre-existing natural fracture.

We employ a quantitative analysis approach to study hydrofracturing processes, focusing on the localization and source mechanism inversion of induced labquakes recorded by the 24-sensor array. Utilizing waveform-based inversion techniques, our study reveals key insights into the hydraulic fracture growth and the activation of natural fractures that trigger these recorded labquakes. This research offers a comprehensive understanding of the dynamics involved in hydraulic fracturing processes.

POSTER 113

How Induced Earthquakes Response to Pre-Existing Fractures and Hydraulic Fracturing Operations? a Case Study in South China

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Hydraulic fracturing in shale gas production can induce damaging earthquakes, making it crucial to understand and mitigate the induced seismicity. The Cen'gong shale gas block in South China offers extensive data—3D seismic, geological structure, microseismic data, and detailed stimulation operations—allowing a comprehensive investigation into induced earthquakes by hydraulic fracturing. Using a dense temporary seismic array and deep-learning workflows, we build a high-precision earthquake catalog and determine their focal mechanisms. Pre-existing fractures are identified through the Ant Tracking attribute derived from the 3D seismic data. We analyze the distribution, frequency, magnitude, and focal mechanisms of induced earthquakes, compare them spatially with the distribution of the pre-existing fractures, and track their temporal changes during and after hydraulic fracturing. Most induced earthquakes occurred along pre-existing fractures, exhibiting larger magnitudes and persisting post-stimulation. Focal mechanisms remain consistent throughout and after the stimulations. Abrupt drops in injection pressure often coincide with significant earthquakes. Our observations reveal that induced earthquakes initiated from the far side of the fractures, and then linearly migrated along the pre-existing fractures. This directional migration pattern is explained by differential stresses along the fractures. Our analysis suggests that both pre-existing fractures and stimulation operations significantly influence induced earthquake occurrences. Therefore, enhancing our comprehension of pre-existing fractures and optimizing stimulation operations can migrate earthquake hazards in shale gas production.

Integrative Assessment of Soil-Structure Interaction and Local Site Effects in Seismic Hazard Analysis [Poster Session]

Poster Session • Friday 3 May

Conveners: Swasti Saxena, Pacific Northwest National Laboratory (swasti.saxena@pnnl.gov); Mohammad Yazdi, Mott MacDonald (mohammad.yazdi@mottmac.com); Peiman Zogh, University of Nevada, Reno (pzogh@unr.edu)

POSTER 136

Assessment and Results From New Bayesian SPAC Analysis for 1D Velocity Profiles Compared to Traditional MASW in Puerto Rico

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In March of 2022, a collaborative research initiative between the United States Geological Survey and the University of Puerto Rico at Mayagüez led to the acquisition and processing of average shear wave measurements to a depth of 30 meters (Vs30) at 22 seismic stations across Puerto Rico employing, in part, conventional Multichannel Analysis of Surface Waves (MASW) methodologies. However, estimation of velocity profiles using the MASW technique is a nonlinear process, and rigorous estimation of uncertainty in Vs profiles and Vs30, while crucial for proper physical interpretation, is a challenging problem. The uncertainty in MASW Vs profiles can stem from both theoretical challenges (e.g., higher modes, topography, near and far field effects, insufficient source energy, unknown model parameterization) as well as measurement errors (e.g., noisy geophone recordings). Here, we present a new phase of the investigation wherein select MASW-analyzed sites in Puerto Rico will undergo reevaluation using a Bayesian Spatial Autocorrelation (SPAC) method using microtremor array data collected with temporary small-aperture nodal arrays. Having both MASW and SPAC datasets will provide the opportunity for a comparative analysis between the two methodologies for ocean island environments. The Bayesian SPAC methodology we use provides a rigorous estimation of uncertainty in Vs and Vs30 when compared to the MASW models we developed through a least-squares iterative modeling approach. Based on preliminary SPAC results, the study will be expanded to include new sites not necessarily suitable for traditional active-source multimethod data collection. The additional site selections will be guided by the seismic resilience needs articulated by local communities throughout Puerto Rico. This expansion is conceived as part of a collective impact earthquake science initiative, aligning research endeavors with the practical requirements of the community.

POSTER 137

Seismic Response in Pyramids of the Chichén Itzá Area, México

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We analyzed the seismic response of three archaeological structures in the Chichén Itzá area, Yucatán, Mexico, to provide elements that track their preservation. We measured ambient seismic noise with broad-band seismographs for three days, and we used the HVSR method and transfer functions to quantify vibration frequencies. The results show that the site frequency is 1.3 Hz. However, in the pyramids under study, especially the Kukulkan Pyramid, also called The Castle, the fundamental frequency is 5.1 Hz with a relative amplification of around 6. Our results show that the pyramids behave like soft soil on a rigid layer. In the case of the Kukulkan Pyramid, the noise recording at its base allows us to observe an effect of kinematic interaction due to the difference in rigidity between the subsoil and the structure. We did not observe any directional effect on HVSR curves due to the internal anisotropy of the pyramids. The estimated internal shear velocity is 255 m/s (considering the seismic response is of topographic origin). This velocity corresponds to non-compact materials resting on competent substratum with velocities larger than 1000 m/s, materials that are susceptible to stress changes that may eventually lead to structural deterioration. The findings of this study suggest that continuous monitoring and instrumentation of the lower levels is needed to evaluate the influence of sub-structures during the pre-construction stages and to determine whether there are other effects due to the karstic nature of the subsoil.

POSTER 138

Site Response Analysis and Its Significance at Nonlinear Sites

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This study presents a case history of one-dimensional time-domain nonlinear site response analysis for a major infrastructure project in the San José area, California, USA. The subsurface material of the study site consists of Holocene alluvial deposits with interbedded and crosscut clays and silts, sands, and gravels. Two levels of design earthquakes were considered herein associated with the return periods of 225 and 975 years. For each design level, site response analyses were performed to propagate a suite of eleven pairs of horizontal input ground motions at the reference soil horizon (a depth of about 75 m; V_{S30} of about 490 m/s) through a site-specific ground model. Also, a series of sensitivity evaluations were also conducted for verifying and enhancing understanding of dynamic response of the study site. The site response analysis results show the site exhibits high nonlinearity, deamplifying short-to-intermediate period content (0.01 to 1 s) while amplifying long period content. A comparison of surface response spectra from the site response analysis versus ground motion models and probabilistic seismic hazard analysis (PSHA) is presented herein highlighting the design implications of conducting site response analyses at soft sites, where high nonlinearity is anticipated.

POSTER 139

Ambient Vibration Testing of Canada's Tallest Wood Frame Building

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The objective of this research is to study the dynamic characteristics of the relatively new and increasingly popular class of tall wood frame buildings to better understand their natural mode frequencies and shapes. This study quantifies the dynamic characteristics of the tallest wood frame building in Canada, the 18-storey Brock Commons building, located in Vancouver, British Columbia. Identification of the modal characteristics of the building can contribute to understanding the dynamic behaviour of tall wood buildings in general, especially to better model and predict their behaviour under seismic loading by parameterization of numerical models. *In situ* ambient vibration tests were conducted on the structure and the enhanced frequency domain decomposition technique was employed to carry out a complete operational

modal analysis of the building. Translational modes in *x*- and *y*-directions as well as torsional and rocking modes are identified, ranging in frequency from 0.940-9.232 Hz. Results show the fundamental period of 1.064 s is lower than the period predicted by a finite element model (2.0 s), suggesting the building is less flexible than estimated. The identification of rocking modes similar to the natural frequency of the surrounding soil suggest that soil-structure interaction contributes to these modes; however, a soil-specific study is required to further explore these effects.

POSTER 140

Wind Turbines as a Metamaterial-Like Urban Layer: An Experimental Investigation Using a Dense Seismic Array and Complementary Sensing Technologies

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A fundamental difficulty in earthquake engineering is the deflection and control of the impacts of the complex urban seismic wavefield on the built environment. The interactions between the soil and the structures, as well as between the structures, have a significant impact on the lateral variety of ground motion with respect to earthquake damage. Here we report on a study investigating the hypothesis that flexural and compressional resonances of a large number of structures—in this case wind turbines in a wind farm—strongly influence the propagation of the seismic wavefield. A large-scale geophysical experiment demonstrates that surface waves are strongly damped in several distinct frequency bands when interacting at the resonances of a set of wind turbines. The ground-anchored arrangement of these turbines produces unusual amplitude and phase patterns in the observed seismic wavefield as well as differences in the intensity ratio between stations inside and outside the wind farm and in surface wave polarization. Additional geophysical equipment (e.g. an optical fiber, rotational and barometric sensors) was used to provide essential explanatory and complementary measurements. A numerical model of the turbine also confirms the mechanical resonances that are responsible for the strong coupling between the wind turbines and the seismic wavefield observed in certain frequency ranges of engineering interest.

POSTER 141

Site-City Interaction in the Valley of Mexico: 3D Simulations and Observations

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We investigate the built environment's impact on ground motion in Mexico City. Our research is based on robust velocity and city models, the details of which are thoroughly discussed, and numerical simulations. In our velocity model, we incorporated over two hundred one-dimensional profiles obtained from a noise tomography of the southern part of Mexico City. Additionally, we integrated more than one hundred geotechnical profiles into a regional velocity model. The shear beams, representing the utilized buildings, are the first comprehensive digital model of the Mexico City metropolitan area. The building inventory was compiled by merging LIDAR information from the Valley of Mexico, data from the current building inventory published by the government of Mexico City, and data available from the metropolitan area of the State of Mexico. Regarding system modeling, we conducted finite element simulations using data from a local earthquake and the M7.1 2017 Puebla-Morelos earthquake. Preliminary analyses, valid up to 1Hz, reveal an increment in ground motion duration attributable to the presence of buildings. Also, we observe a velocity reduction at ground level in areas with high building density, along with the formation of waveguides channeling energy in several areas of the lake zone due to arrays of structures. We compared our simulations with the reported damage during the Puebla-Morelos event. Our findings indicate that the observed damage levels are better explained when considering the city than in simulations that ignore the city.

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POSTER 142

Seismic Response of Nenana Sedimentary Basin, Central Alaska

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Nenana basin in central Alaska is a long (90 km), narrow (12 km), and deep (7 km) sedimentary basin aligned with an active fault zone producing Mw >= 6 earthquakes. From 2015 to 2019, 13 broadband seismic stations were deployed in the region as part of the Fault Locations and Alaska Tectonics from Seismicity project. These stations recorded a wide range of earthquakes, including Mw 3–4 directly below the basin as well as several regional earthquakes Mw > 6. These 43 local and regional earthquakes, in addition to five teleseismic events and continuously recorded ambient noise, provide a data set that we use to quantify the response of Nenana basin to the seismic wavefield. We calculate spectral ratios between each station and a bedrock reference station for 48 earthquakes. We find amplification of 11–14 dB (amplification ratio 3.5–5.0) for low frequencies (0.1–0.5 Hz), and 8–15 dB (amplification ratio 2.5–5.6) for high frequencies (0.5–4.0 Hz) on the vertical component. At low frequencies, amplification of the earthquake wavefield agrees well with amplification of seismic noise, with both data sets exhibiting stronger amplification on the horizontal components, in comparison with the vertical component. Furthermore, stations overlying the deeper part of the basin exhibit stronger amplification, whereas stations at the margin of the basin exhibit minimal low-frequency amplification. At higher frequencies, amplification occurs at both deeper basin stations and also marginal basin stations. Our study establishes a catalog of diverse events for future theoretical and numerical studies that can use Nenana basin to better understand the complex influence of sedimentary basins on the seismic wavefield.

POSTER 143

State of the Art in Seismic Metamaterials

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Studies on structured soils, including seismic metamaterials, have shown the existence of complex wave phenomena within and around the structured zone. The aim is to assess areas where seismic or vibratory energy is concentrated, and to decide whether it would be worthwhile to exploit them by judiciously placing piezoelectric energy sensors. The article presents what is already being done with vibration sensors implanted in civil engineering structures and shows the potential interest of seismic metamaterials in this context. The modification of the surface signal by both structured soil and surface resonators meets the challenges of Civil Engineering through the effects of soil-structure interaction. Seismic metamaterials can therefore not only be considered for building protection, lensing and minimizing the effects of potentially deleterious Rayleigh waves, but also have potential applications in energy harvesting using ambient seismic noise.

Learning Across Geological, Geophysical & Model-Derived Observations to Constrain Earthquake Behavior

Oral Session • Wednesday 1 May • 8:00 AM Pacific

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Strain Accommodation Along the Northeast Altyn Tagh Fault System and the Potential for a Future Large-Magnitude, Multi-Fault Rupture

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Large continental strike-slip fault systems typically comprise a principal displacement zone and subordinate splay faults, exhibiting complex geometry and variations in fault distribution. Understanding the architecture, interconnections, and synchronous rupture patterns of these faults is crucial for comprehending their tectonic evolution, strain distribution, and earthquake behavior. Here we provide a comprehensive analysis of Quaternary deformation, interconnection, and late Holocene ruptures along the EW-trending Nanjieshan Fault (NJSF), a major branch fault of the Altyn Tagh Fault (ATF) system. The calculated strike-slip rate of the master NJSF is ~0.5 mm/a since ~45 ka, consistent with the low slip rates observed on other faults NW of the ATF. Moreover, the NJSF may have experienced an exceptionally high slip rate since the late Pleistocene, implying a potential change in fault strain distribution along the northern ATF. New trench data across the NJSF reveals three surface-rupturing events in the last 2500 years. Significantly, these millennium-scale events coincide temporally with the last two major earthquakes documented on the principal ATF, suggesting quasi-simultaneous rupture behavior. We conclude that accurate evaluation of paleoearthquake magnitudes and potential rupture behavior on major continental strike-slip fault systems should include field studies of both the principal fault and subordinate branching faults.

Partitioning of Oblique Convergence During Simultaneous Rupture of a Megathrust and Splay Fault: Observations From the Western Nepal Fault System

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The subaerial megathrust system of the Himalaya provides opportunities for examining subduction zone - splay fault behavior using methods that are difficult for the typical submarine subduction zone environments. Some major historic megathrust ruptures (e.g., the 1964 Good Friday earthquake in Alaska) have produced simultaneous displacement on sub-parallel splay faults, but how common is this splay-fault behavior and what role does it play in slip partitioning in subduction zones undergoing oblique convergence? In the Himalayan orogen, we examine the Western Nepal fault system, a generally NW-trending series of faults that cut obliquely across the structural grain of the Himalayan orogen and is interpreted to intersect with the Main Himalayan Thrust (MHT) at depth. Paleoseismic investigations along most of the fault system reveal youthful surface ruptures, and while several sites have limited temporal resolution, several of these sites specifically constrain the occurrence of a surface-rupturing earthquake within the past 700 years. This timing overlaps with the Great 1505 Himalayan earthquake, the only historic rupture of the MHT interpreted to have ruptured beneath the WNFS. The trace of the WNFS across topography illustrates a typically moderate to steep N to NE dip and landforms offset across the fault define long-term right-lateral and extensional motion, with relative proportions of lateral vs. extensional slip increasing to the NW along the fault system. Based on the lack of documented large historic earthquakes in the area of the WNFS, we propose that the WNFS ruptured simultaneously with the rupture of the megathrust in the 1505 earthquake, or as several smaller earthquakes that are below the current limit of detection from pre-instrumental records. The slip-partitioning across the Himalaya of western Nepal is accommodated by earthquakes occurring on faults bounding a sliver of the orogenic wedge, and the potential for simultaneous ruptures of these faults (MHT and WNFS) presents a new scenario for seismic hazard assessment of the region.

Architecture of an Active Tsunamigenic Splay Fault: Outcrop to Micro-Scale Structure of the Patton Bay Fault, Montague Island, Alaska

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In the 1964 M_w 9.2 megathrust earthquake in south-central Alaska, the Patton Bay splay fault hosted coseismic rupture both offshore and on Montague Island with up to 10m of throw along the surface. The offshore expression of this fault has been proposed to be a source of the subsequent local tsunami. Tsunami-genesis can be influenced by surface rupture of shallow, megathrust-related splay faults and how they transfer seismic slip from a megathrust rupture path to the surface. The 1964 rupture came to the surface along the Strike Creek strand of the PBF fault, but the locus of major long-term displacement is the nearby Deception Creek strand, which is well-exposed on an intertidal wave-cut platform. This unique on-land exposure of an active megathrust splay fault presents the opportunity to investigate the fault zone architecture and mechanical properties from host rock to fault core. Macro- and microstructural observations are being used to determine the fault zone and fault rock properties that reflect earthquake processes. Microstructural analysis includes identifying potential cataclasite formation, fluidized fault rocks, foliated fault gouge, shear sense, and mineralogical or geochemical signatures of frictional heating, each potentially a signature of past seismicity. We identified field-scale structural zones including hanging wall and footwall damage zones and a fault core. The fault zone is ~150-m wide, with damage zones made up of highly fractured bedrock, disrupted bedding, cataclasite-rich patches, and a nearly continuous gouge-rich fault core ~8-m wide. The damage zones have varying degrees of disrupted and intensely fractured bedding and local cataclasite formation. This exposed fault exhibits structural variations consistent with a mature brittle fault with a single principal slip zone that is surrounded by a fractured damage zone. These structural characteristics have been described in other seismogenic splay fault studies and support the conclusion that Deception Creek fault is the primary strand of the Patton Bay Fault on Montague Island and has historically ruptured in great earthquakes.

Paleoseismic Investigations of Quaternary Active Faults in the Forearc and Backarc of the Central Pacific Northwest, u.s.a.

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Oblique northeast-directed subduction of the Juan de Fuca plate and northward impingement of the Sierra Nevada block drive clockwise rotation of the PNW region relative to stable North America. Our work has yielded new observations of surficial deformation across the central Cascade Arc in Oregon (OR) where the rates and timing of faulting during the past 100,000 years are largely unconstrained. We combine lidar and field-based mapping to identify Quaternary active structures, characterize their slip rates, and where possible, constrain the timing of prehistoric surface rupturing earthquakes. In eastern OR, on the Strawberry Mountain fault, we document extensional faulting in a region broadly inferred to be compressional - related to Yakima Fold and Thrust deformation. Here, we document 2 post-LGM earthquakes and calculate a slip rate of 0.18 ± 0.02 mm/yr since the late Pleistocene.

The central Cascade volcanic Range is defined by a lower relief ancestral Eocene to Miocene arc forming the western foothills and is offset relative to the active high Cascades arc, a result of ~ 1°/My clockwise rotation for the last 16 My. The westward escape of the forearc creates a space problem, earlier research shows that the arc creates new crust on the trailing edge, and we document structural accommodation of tectonic extension by normal faulting. We observe numerous N-S trending extensional faults through both the high and ancestral arc. On the Mt Hood fault zone we map glacial moraines from the most recent glaciation, 21.2 ka ± 3 based on our new He^3 surface exposure ages, offset by 2.7 m high scarps. A trench across an uphill facing scarp revealed 2 post-LGM surface rupturing earthquakes, and 2.3 m of total vertical separation. In the OR Coast Range on the Gales Creek Fault, we map right laterally deflected drainages, aligned springs, and side-hill benches. A paleoseismic trench here revealed evidence of three surface rupturing earthquakes in the last ~8,800 yr. We speculate that the earthquake timing may be linked to large on-shore stress changes in the crust immediately following a megathrust subduction zone earthquake.

Coseismic Temperature Proxies and their Applications to Understanding Earthquake Rupture and Seismic Hazard

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During an earthquake, frictional resistance along a fault can lead to the generation of high temperatures. The temperature rise that occurs provides clues into an earthquake's size and rupture dynamics as temperature is dependent on various earthquake properties like displacement and frictional energy. Numerous thermal proxies have been developed to evaluate coseismic temperature rise including but not limited to biomarkers, pseudotachylyte, vitrinite reflection, and calcite decomposition.

Here, we present results of work integrating these proxies and what they can teach us about earthquakes with a particular focus on biomarkers, which are organic molecules present in some rocks that are progressively altered with increasing temperature and duration of heating. These proxies provide a means of constraining the displacement during an earthquake along bedrock faults where traditional paleoseismic techniques cannot be applied. They also enable quantification of the frictional energy dissipated during slip and therefore, insight into the earthquake energy budget. We also present recent and ongoing work on faults in California and New Zealand, which couples biomarker thermal maturity with K/Ar dating to assess when these faults last experienced the high temperatures associated with earthquake slip, and hence when they were last active.

Inter-Seismic Slip in Caldera Collapse Earthquake Cycles

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In most tectonic settings, multiple complete characteristic earthquake cycles have not been observed and loading histories can be complicated, which limits the extent to which field-scale fault frictional behavior can be resolved. Empirical rate-and-state dependent friction formulations based on small-scale lab experiments are a standard starting point, and there is experimental and observational evidence for the importance of processes such as dynamic weakening. However, the relevant physical mechanisms and potentially heterogeneous parameters controlling friction are generally not well constrained. In this work, we approach field-scale fault mechanics by studying caldera collapse at basaltic volcanoes, which has been observed to occur via sequences of multiple discrete ring fault earthquakes. We focus specifically on the well-monitored 2018 eruption of Kīlauea Volcano, which exhibited large amounts of both co- and inter-seismic slip. We use 2D axisymmetric earthquake cycle simulations, with fully dynamic elasticity and compressible viscous fluid flow, which show that standard rate-and-state friction formulations cannot readily produce the amount of co- and inter-seismic slip observed. We investigate whether adding dynamic weakening and asperities to primarily velocity-strengthening faults can better explain seismic and geodetic data. Additionally, we explore what depth-dependent fault properties and physical weakening mechanisms (e.g., thermal pressurization or shear heating) are most consistent with observations. These findings have implications for understanding fault mechanics in general, fault properties in volcanic and geothermal settings, and the dynamics of collapse eruptions.

The Influence of Preexisting Geologic Structures on Coseismic Surface Deformation During the 2019 M7.1 Ridgecrest, California, Earthquake

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We investigate how preexisting structures influenced the 2019 M7.1 Ridgecrest, California earthquake rupture at the tens-of-kilometers and meter scales by combining field and remote sensing observations, laboratory analysis, and mechanical modeling. At the longest scales, the fault geometry appears to be inherited from the surrounding late Jurassic Independence dike swarm (IDS), mapped with satellite imagery and airborne lidar data. In the field, we observe multiple fracture sets surrounding the dikes, including dike-parallel fractures that add to the pervasive structural fabric that existed prior to fault initiation. Based on the common geometries and observed deformation, we conclude that the Ridgecrest source faults likely evolved through reactivation of IDS structures. Consequently, we show through a series of finite-element models that the inherited fault geometry strongly controlled the coseismic slip distribution, producing elevated slip (~3-4 m compared to <~1 m elsewhere) within a ~12-km-long section of the rupture oriented ~20 degrees more northerly than elsewhere. Part of this maximum slip zone lies within the China Lake Playa where the rupture localized into knife-edge echelon segments separated by meter-scale left steps. We explore surface rupture processes at this length scale using discrete element models, which suggest that the development of such a narrow deformation zone is encouraged by loosely packed granular material that produces minimal dilation during shear. We analyze samples collected from the surface rupture using scanning electron microscopy techniques and find that a sequence of evaporite minerals coat the rupture surface, including halite that flows ductilely around broken clasts of carbonate mud. These observations suggest that the 2019 surface rupture may have reoccupied preexisting fractures, perhaps formed during a previous surface-rupturing earthquake. Over the range of scales considered, combining field, laboratory, and modeling methods illustrates the importance of preexisting structures in controlling where and how earthquake deformation accrues.

Bayesian Dynamic Source Inversion of the 2004 Parkfield Earthquake: Insights From Linked 3D Dynamic Rupture and Afterslip Modeling Constrained by Gps and Strong Motions

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The 2004 Mw 6.0 Parkfield earthquake is one of the best-observed events ever. Since then, computational capabilities and methods have tremendously advanced, enabling the illumination of the source process with unprecedented detail. We present a 3D Bayesian dynamic rupture finite-fault inversion of the 2004 Parkfield earthquake where the model parameters consist of the spatially variable prestress and friction parameters. We use a fast-velocity-weakening rate-and-state friction law to simulate the coseismic and postseismic rupture phases in the same modeling framework. Strong motion and GPS data, including three months of postseismic displacements, constrain the inversion. We use a parallel tempering Markov chain Monte Carlo approach to tackle the non-linear high-dimensional inversion problem.

The Bayesian approach provides an ensemble of models fitting the data from which we infer the mean and variability of various kinematic and dynamic parameters. We provide estimates of stress drop, fracture energy, and radiation efficiency, which are constrained by the data and the underlying physics. The coseismic rupture transitions from pulse-like to crack-like as it propagates towards the creeping section of the San Andreas fault. The pulse-like phase generates most of the seismic radiation while the crack-like rupture dominates the coseismic GPS recordings. We observe different rupture arrest mechanisms imprinting on the subsequent afterslip evolution. Afterslip concentrates within two major patches above the coseismic rupture zone separated by a barrier that also delays the coseismic rupture. Parts of the fault that already slipped coseismically continue to host afterslip. We find a gradual increase in afterslip rise time and identify different modes of afterslip. Our results provide new insights into earthquake rupture complexity and the transition from the coseismic to the postseismic phase.

Multi-Cycle Evolution of Seismicity and Fault Zone for a Fault Network

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Seismic activity exists in a variety of scales from small tremors to large earthquakes resulting in severe economic and societal impacts. It is crucial to understand the mechanism behind the rupture of complex fault systems and how it evolves with time to better inform the seismic hazard models. Here, we model sequences of earthquakes and aseismic slip for a fault network having a primary fault and multiple secondary faults with different size and orientations. We incorporate Drucker-Prager plasticity with pressure dependent yield criterion to capture the off-fault bulk response. The friction is modelled by a rate and state dependent friction law. We assume 2D plane strain deformation and utilize an in-house hybrid numerical scheme, FEBE, combing finite element (FEM) and spectral boundary integral (SBI) methods to resolve both fast dynamic events and slow interseismic deformation.

The simulation results show emergence of complex seismicity including spatiotemporal clustering, foreshocks, and aftershocks. We observe co-seismic activation of the secondary faults during the rupture propagation on the primary fault as well as the migration of aseismic slip between the nearby secondary faults. Foreshocks happen on the secondary faults when the length of the secondary faults is greater than the nucleation length. The initial phase of the seismic cycle exhibits partial ruptures on the primary fault with more distributed seismicity on the secondary faults. Later, the seismicity tends to become more concentrated on the primary fault with full fault spanning rupture. The evolution of off-fault plasticity for the fault network shows more plastic deformation near the ends of the secondary faults that experiences activation. This plastic strain is indicative of off-fault damage and demonstrate the possible non-equilibrium evolution of seismicity and fault zone hosing a network of faults. Our findings may enlighten the understanding of the seismic source mechanics for complex fault zones and the long-term evolution of the fault zone with multi-cycle earthquakes.

Bayesian Inference of Rheological Parameters From Observations Before and After the Tohoku Earthquake

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We seek to quantify bulk viscoelastic flow, afterslip, and locking, within a rheological framework that is consistent over the entire earthquake cycle. We address this using an ensemble smoother. We construct a 2D finite element seismic cycle model with a power-law rheology in the mantle. A priori information, such as a realistic temperature field and a coseismic slip distribution, is integrated into the model. Model pre-stresses are initialized during repeated earthquake cycles wherein the accumulated slip deficit is released entirely. We tailor the last earthquake to match the observed co-seismic slip of the 2011 Tohoku earthquake. The heterogeneous rheology structure is derived from the temperature field and experimental flow laws. Additionally, we simulate afterslip using a thin, low-viscosity shear zone with a Newtonian rheology. We focus on constraining power-law flow parameters for the mantle, and the shear zone viscosity.

We assimilate 3D GEONET GNSS displacement time series acquired before and after the 2011 Tohoku earthquake. The data require separate visco-elastic domains in the mantle wedge above and below ~50 km depth, and in the sub-slab mantle. Power-law viscosity parameters are successfully retrieved for all three domains. The trade-off between the power-law activation energy and water fugacity hinders their individual estimation. The wedge viscosity is $>10^{19}$ Pa·s during the interseismic phase. Postseismic afterslip and bulk visco-elastic relaxation can be individually resolved from the surface deformation data. Afterslip is substantial between 40-50 km depth and extends to 80 km depth. Bulk viscoelastic relaxation in the wedge concentrates above 150 km depth with viscosities $<10^{18}$ Pa·s. Landward motion of the near-trench region occurs during the early postseismic period without the need for a separate low-viscosity channel below the slab.

Surveying Active Fault Zones in California Using Quakes-I Wide-Swath Airborne Stereoimagery

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We present new and continuing results from fault surveys collected by the QUAKES-I airborne stereoimager. Recent decades have seen a proliferation of stereoimaging techniques for mapping fault zone structure, measuring offset geomorphic features, and characterizing earthquake dynamics by correlating images collected before and after surface ruptures. Despite the merits of such studies, stereoimaging surveys are often expensive, logistically difficult, and/or time-consuming to carry out. For example, stereoimaging is often accomplished at fine scales (kilometers or less) by drone surveys, or at broad scales through purchase of high-resolution satellite imagery. Additionally, airborne lidar surveys can be flown to cover > 100-km-long ruptures, but are often confined to a narrow (~1 km) swath width due to limitations of the scanner, and may consequently miss distributed deformation. In contrast, the Quantifying Uncertainty and Kinematics in Earth Systems Imager (QUAKES-I) presents an instrument for capturing high-resolution (~1 m pixel) imagery over a wide swath (up to ~12 km) aboard a taskable aircraft that can cover a few thousand km of fault length in a single day. Using commercial photogrammetric software, the stereoimages can be converted to a 3D point cloud, a color orthomosaic, and a digital surface model (DSM). In some cases (e.g., sparse vegetation), the point cloud can be reliably classified and a digital terrain model (DTM) can be produced. The results presented here showcase examples from surveys of > 1,500 km of active fault traces in CA and the western U.S., collected in June 2021 and October 2022. Faults and fault systems surveyed include the San Andreas fault, the Hayward-Calaveras fault system, and parts of the eastern California shear zone. Using these image products, we map primary and subsidiary fault features, and displaced geomorphic markers. These images further constitute a "before" data set for comparison following potential future large earthquakes.

Improvements to Fault Displacement Models: Examples From the 2023 M7.8 Pazarcık, Türkiye Earthquake

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Fault displacement models are used to predict fault surface rupture along strike as a function of earthquake magnitude. They are useful for numerous reasons, including, for instance, forecasting the displacement of an underground pipeline crossing a fault during a future earthquake scenario (i.e., a deterministic analysis). In addition, they are the backbone of probabilistic fault hazard displacement analyses, and thus, are important for advancing seismic design guidelines. Improving fault displacement model accuracy and precision requires collecting field data, and in particular, making high-quality fault displacement measurements with robust estimates of measurement uncertainty. With the foregoing motivation, we traveled to south Türkiye to complete ten days of fieldwork in June 2023 following the 6 February 2023 M7.8 Pazarcık Earthquake. In the field, wemeasured fault displacement and estimated uncertainty using traditional surveying techniques, GNSS, and terrestrial lidar scans. We also chose sites with varying quality of offset feature reconstructions to investigate the effect of quality on measurement uncertainty. Our fault displacement measurements led to numerous observations for how to improve fault displacement models. Our fieldwork highlighted the advantages and disadvantages of the measurement techniques as a function of piercing point definition. In particular, we determined some post-earthquake reconnaissance best practices for balancing the need to capture as many high-quality fault displacement measurements as possible with the correlative need to develop robust measurement uncertainty estimates. We compare our results to previous fault displacement models and make observations about magnitude scaling, the effects of geologic conditions, and faulting complexity. The results from our work have implications for improving post-earthquake reconnaissance practices and have produced data that can be used by future fault displacement modelers.

Characterizing Surface Fault Displacement Uncertainty and Its Effects on Probabilistic Fault Displacement Hazard. Example From the 2023 M7.8 Pazarcık, Türkiye Earthquake

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Surface fault displacement poses a significant threat to distributed infrastructure systems, and as such, they need to withstand long return period events. Thus, properly characterizing the upper percentiles of the fault displacement distribution has a large impact on the design requirements. Using the 2023 M7.8 Pazarcık earthquake as an example, we developed an open-source software to characterize the measurement uncertainty in surface fault displacement of Global navigation satellite system (GNSS) fault-perpendicular profiles of offset features and rank the contribution of each component. For every iteration, both sides of the surveyed feature are extended into the rupture zone based on a principal component projection, and the displacement is measured parallel to the strike of the rupture. Considered components of uncertainty include: (1) location error in the horizontal and vertical direction, (2) rupture location uncertainty, (3) rupture azimuth uncertainty, and (4) interpretation uncertainty on which survey points are used to project the feature into the fault zone. We compared the distribution of estimated displacements against field-based methods and evaluated the impact of displacement uncertainty in the development of fault displacement models (FDMs). Ongoing analyses indicate that field-based displacement values are generally in agreement with the mean of the modeled displacement distributions and that reported minimum and maximum displacements correspond to the modeled 2nd and 98th percentiles. To quantify the impact of displacement uncertainty on FDMs, we organized the collected profiles into good, mediocre, and poor quality, estimated the uncertainty for each class, and generated synthetic datasets based on the previous rules. Regressing FDMs with and without considering the uncertainty of displacements showed that omitting the uncertainty of displacement during the regression process inflates the aleatory variability, which overestimates design values at large return periods.

Relating Large-Volume Landslides and Potentially Active Faults Using Geotechnical Analyses in the Pocuro Fault System, Central Andes (32°-33°s)

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Large-volume landslide deposits are frequent in seismically active mountain regions, such as the central Andes. Their clustered geographic distribution close to tectonically active fault systems suggests that their most likely trigger are shallow crustal earthquakes from nearby faults . We investigate landslides along the Pocuro Fault System (PFS) in the Chilean Andes (32°-33°S), using a method developed in the Argentinean central Andes to link large rock slides with potentially active faults by applying geological and geotechnical earthquake engineering tools, including numerical modelling back-analyses and application of ground motion models. Recent studies of the PFS have found that at least one major branch has Quaternary activity. We thus hypothesize that other faults of the system may be potentially active. A landslide inventory was updated for the region, obtaining morphometric parameters of the landslides. Detailed field and lab geotechnical assessments including testing of selected rock slides were performed to be used as models of a representative number of slides that were analysed using 2D seismic slope stability back-analyses. Given the lack of historic ground motion records, seismic records from abroad considering similar source mechanisms and earthquake parameters were selected to run the analyses. Then, the landslides found to be likely seismically triggered were related to nearby faults of the PFS, identifying those faults more probable to have induced the landslides and an earthquake magnitude range consistent with both the fault geometry and the slopes destabilization. Further research will look to combine these results from geo-engineering analyses with pending geochronological studies of the landslides and faults. This would provide useful information on the frequency and magnitude of ancient, large shallow crustal earthquakes, aiding the characterization of seismic hazard in a region where the contribution of shallow seismicity to seismic hazard has not been accounted for to date. This work is funded by ANID-Fondecyt 1200871 grant (L. Pinto) and the FRBC Endowment Fund (S. Sepúlveda).

Measuring Gaps Between Geodetic, Geologic, and Seismic Moment Rates Across the Western U.S.: How to Determine a Budget for Earthquake Rates?

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Updated geodetic, geologic, and seismic datasets compiled for the 2023 U.S. National Seismic Hazard Model (NSHM23) provide new views of moment rates across the western U.S. We use these updated datasets to assess regional estimates of off-fault deformation by asking: is geodetic moment completely resolved by earthquakes? There is a long-held assumption that better characterization of fault networks will yield better agreement between geodetic and geologic moment rates. We find that this is not the case because newly added faults tend to be short and have low slip rates. Using updated datasets, this discrepancy appears persistent and not significantly reducible by adding faults, incorporating geologic slip rate uncertainty, or increasing fault plane area. Furthermore, the gap cannot be closed with seismicity moment rates alone. Rather, such a difference is emblematic of volumetric crustal strain, and is therefore only partially associated with diffuse deformation around faults, typically termed "off-fault deformation." When we consider smaller areas for moment rate comparisons using a grid approach rather than broad tectonic regions, the gap between geodetic and geologic moment rates decreases as the influence of volumetric processes (i.e., distant off-fault deformation) is minimized. Some volumetric processes that may contribute to this quantity may include volcanic activity, hydrologic changes, rotations at the boundaries of fault systems, folding, post-seismic transients, interseismic locking on the Cascadia megathrust, shallow and deep creep on crustal faults, lower crustal flow, mid-crustal detachments, and some spatially variable combination of the above. These processes are not the same as diffuse deformation associated with a particular fault zone (e.g., hanging wall deformation and distributed cracking). Before geodetic off-fault deformation is incorporated into seismic hazard analyses or physics-based rupture simulations, we must understand if and how these broad-scale processes contribute to the earthquake engine.

Learning Across Geological, Geophysical & Model-Derived Observations to Constrain Earthquake Behavior [Poster Session]

Poster Session • Wednesday 1 May

Conveners: Kimberly Blisniuk, San José State University (kimberly.blisniuk@sjsu.edu); Roland Bürgmann, R., University of California, Berkeley (burgmann@berkeley.edu); Elizabeth Madden, San José State University (elizabeth.madden@sjsu.edu)

POSTER 173

Rupture Geometry and Static Stress Changes of the 2022 Mw 7.0 and Mw 6.4 Earthquakes in Abra, Philippines

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In the second half of 2022, the province of Abra in the island of Luzon, Northern Philippines was struck by two large magnitude earthquakes in a span of less than three months and within a 20- kilometer radius. On July 27, 2022, at 8:43 am (Philippine Standard Time), the area was struck by a magnitude Mw 7.0 earthquake that caused intense ground shaking. The epicenter was located at 17.64° N latitude, 120.63° E longitude, at a focal depth of 15 km. On October 25, 2022, at 10:59 p.m. (PST), a magnitude Mw 6.4 earthquake struck the same area, at an epicenter located only about 18 kilometers northeast of the July earthquake epicenter, at the same focal depth of 15 km. Destruction in both earthquakes included collapsed residential and commercial buildings, structural damage in century-old heritage churches, government buildings, bridges, and roads. Ground deformation included numerous landslides in the mountainous regions, and liquefaction in riverbeds and coastal areas. While infrastructure damage was significant, surface ground rupture was not evident after both earthquakes. The epicentral areas are known to be prone to earthquakes due to the presence of the Philippine Fault System (PFS) there. However, the focal mechanism solutions of the main shocks suggest gently dipping fault planes which are not consistent with the known geometry of the PFS and its branches in the area. Instead, the distribution of the aftershocks, nodal plane geometries, Coulomb Stress Transfer (CST) modeling and analysis by radar interferometry suggest that the earthquake-generating faults project surface ruptures located further west, following the location and trend of other PFS fault branches. These temporally and spatially closely spaced July and October earthquakes pose new questions on the current knowledge about the PFS in northern Luzon, but also provide new insights that contribute in understanding the nature and earthquake behavior of complex fault systems, including fault asperities, post-earthquake stress transfer, seismic rate changes, aftershock evolution and earthquake triggering.

POSTER 174

Investigating Early Earthquake Rupture Characteristics With Borehole Strainmeters

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Recent studies have suggested the existence of weak determinism in the earthquake rupture process—the concept that the final magnitude of a large earthquake can be estimated using data early on after earthquake origination, before the rupture process is complete across the fault. It is hypothesized that ruptures begin as disorganized, accelerating cracks, and then transition to a more organized slip pulse propagating out from the hypocenter, with the properties of this slip pulse correlating to the final magnitude of the earthquake. As these properties can be ascertained from features of early seismic wave arrivals on displacement recordings, applications of this knowledge have the potential to improve the timeliness and accuracy of earthquake early warning. However, traditional measurement techniques can be problematic when analyzing for determinism due to magnitude saturation in seismic data and high noise in geodetic data, which obscures P-wave arrivals. We explore a new method of analyzing the early rupture process using borehole strain sensors instead; as these instruments can record both small and large perturbations in strain, we can both observe the P-wave arrivals and avoid saturation at higher magnitudes. We began with a homogeneous slip model, where slip proceeds from the hypocenter in a uniform ring with a set rupture velocity of 2.8 km/s, as in Goldberg et al. (2018). We modeled earthquakes with magnitudes ranging from M6.5-8.5 by setting average rise times for each event according to the scaling relation described in Melgar and Hayes (2017). We then used the SW4 wave propagation modeling code to forward-model strain observations and found that generally within 5-10 seconds of data arriving at each station, earthquakes were distinguishable by magnitude. Next, we examined real earthquake horizontal-component borehole strainmeter data from events >M5 in the 2019 Ridgecrest Sequence. In analyzing the earliest-arriving data (less than ~20s after the P-wave arrival), we observed that there are different regimes of growth over time, potentially indicative of different rupture modes.

POSTER 175

Hybrid Model: A Tool for Combining Fault and Area Sources in Seismic Hazard Assessment

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We present an update to the methodology proposed by Rivas-Medinas et al. (2018) for combining fault and zone sources in seismic hazard calculations. Initially, the method distributed the seismic potential of the region between the zone and faults based on observed seismicity (seismic catalog) within a range of minimum magnitude (M_{min}) to maximum completeness magnitude (MMC). The expert had to predefine MMC and the maximum magnitude for the zone ($M_{max\ zone}$), significantly influencing the method's solution for distribution. This made the method applicable only to faults with low slip rates (slow faults), as high slip-rate faults (fast faults) led to inconsistent results. To solve this, the hybrid method has been enhanced through an iterative process, aiming to assist the expert in reducing decision-making in key parameters for seismic source characterization (e.g., MMC magnitude, $M_{max\ zone}$ magnitude, fault *b-value*, zone *b-value*).

For this purpose, a tool has been developed using R-studio and Python programming languages, featuring a user-friendly interface for ease of use and comprehension. As a result, a set of possible solutions is provided, displaying different combinations in which the magnitude-frequency distribution (MFD) model can be adopted to maintain system balance, and distribution is carried out as specified by the user in input parameters. The user must analyze and choose one or more combinations that suit the tectonic conditions of the region. Once done, the program allows graphing the MFD of all selected solutions and generates source parameters for seismic hazard calculations [e.g., beta (β), *b-value*, *a-value*, cumulative seismic rate ($N_{(m)}$)]. Two application cases are presented: one in the southeast of Spain with slow fault systems and another in Guatemala where faults are fast due to the interaction of the North American and Caribbean plates.

POSTER 176

A New View on Interseismic Locking of the Hikurangi Megathrust Along the North Island of New Zealand

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The largest earthquakes in subduction zones occur where significant interseismic slip deficit has accumulated on the plate interface. Slip deficit accumulates most quickly in mechanically locked regions, and these also cause the regions around them to accumulate slip deficit; therefore, large earthquakes are typically expected to rupture in and around locked areas. Resolving the locations and dimensions of these mechanically locked zones from kinematic geodesy (leveling, GNSS and/or InSAR time series) has been difficult, particularly when the overriding plate is subject to multiple drivers of active deformation at significant rates, like the Pacific Northwest and Alaska.

We focus on the North Island of New Zealand, where GNSS velocities show the superposition of locking of the Hikurangi megathrust and backarc extension in the Taupo system. To be able to use both horizontal and vertical time series data we develop a mechanical model with the 3D geometry of the Hikurangi slab from Slab2 (Hayes et al., 2018). The slab and shallow overriding plate are taken to be elastic, and the mantle wedge and sub-slab asthenosphere have linear viscoelastic properties. We discuss the relevance of including major trench-parallel faults that bound forearc blocks, like the Wairarapa fault. We show results of assuming the megathrust locking pattern found in previous studies, and the corresponding backarc extension imprint on the North Island. We discuss how prior information may help improve the reliability of locking estimates, and Bayesian inference methods that aim to constrain the uncertainties of future megathrust locking estimates.

POSTER 177

Geological Constraints on the Seismic Activity of the Mid-section of the Minjiang Fault in the Eastern Margin of the Tibet Plateau

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The Minjiang Fault, located in the western boundary of the Minshan active block, is situated above a large-scale, east-dipping electrical structure boundary zone. The upward flow of the Songpan-Ganzi lower-crust low-resistivity layer beneath the Minshan active block provides an important driving force for the frequent large earthquakes along the Minjiang Fault. In this study, we constrained the seismic activity of the mid-section of the Minjiang Fault through a detailed analysis of three paleoseismic trenches and the dating of samples. Our study found that at the Gusicun section, the occurrence ages of three paleoearthquake events (EG3, EG2, and EG1) are estimated to be 10827-4034 aBP, 3907-2023 aBP, and 1945-685 aBP, respectively. At the Lajichang section, the occurrence ages of the EL3, EL2, and EL1 events are 6159-5820 aBP, 3904-2305 aBP, and 2139-300 aBP, respectively. In addition, the Luoshigou trench's most recent event (ES1) occurred in 3258-1171 aBP. By using the incremental dating method, the ages of the three paleoearthquake events (E3, E2, and E1) along the fault are estimated to be 6158-5829 aBP, 3283-2292 aBP, and 1980-1130 aBP, respectively. The elapsed time since the most recent event is estimated to be 2021-1201 aBP. Using the OxCal software, the average earthquake recurrence period of the fault is estimated to be 2218±262 years (μ±2σ), with a variation coefficient of 0.64.

According to the study, no fresh surface/near-surface rupture corresponding to the Diexi earthquake was found in the mid-section of the Minjiang Fault, and the dating results of the most recent earthquake event do not match the Diexi earthquake. Therefore, the Diexi earthquake is not closely related to the mid-section of the Minjiang Fault. Due to the recent occurrence of a major earthquake close to the recurrence interval, combined with the seismic activity characteristics around the Minshan active block, it is necessary to pay attention to the future seismic hazard of the Minjiang Fault.

POSTER 178

Seismic Structure, Lithospheric Deformation and Seismicity of the Indian Plate in Sikkim Himalaya

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Seismic structure, lithospheric deformation and seismogenic capacity of the Indian plate in Sikkim Himalaya is poorly understood amidst the well-explored regions of Bhutan, Nepal and Tibet. Study of this region is key to understanding the evolutionary past, on-going collisional dynamics and its implication on future seismic hazard potential. A well thought seismic experiment was planned in 2019 with the installation of 27 broadband seismic stations covering Sikkim Himalaya. The network was operational till May, 2023. Precious data gathered from this project have been crucial in providing high resolution crustal images using 12,288 receiver functions, robust earthquake catalouge of 1,496 earthquakes, and patterns of mantle deformation. The observations reveal an intermittent contrast in amplitudes related to Main Himalayan Thrust, contrary to prominent and continuous arrivals from this boundary from Nepal Himalaya. Prominent seismicity clusters in the upper crust follow this layer and are marked by the presence of low velocity zones. The seismic activity indicates active shearing along Main Himalayan Thrust in response to collision. Lower crust is observed to possess an imbricated Moho possibly resulting due to accumulation from crustal shortening, which is corroborated with seismicity exhibiting thrusting mechanism. The convergence in this segment of Himalaya can be thus stated to be partially accommodated by imbricate structures in the upper and lower crust. Sandwiched between upper and lower crust is the dextrally deforming mid-crustal Dhubri-Chungthang Fault Zone postulated to be segmenting the Himalayan arc. Seismicity studies delineate the northward discontinuation of the seismogenic extent of this fault beyond Chungthang in Sikkim. Distinct deformation is observed across Dhubri-Chungthang Fault Zone by the fast-axis orientations determined from core-refracted shear waves. Complex dynamics coupled with intricate geometry of the faults pose an intermediate risk of occurrence of a great earthquake in Sikkim Himalaya raising the cause of concern of seismic hazard potential in the region.

POSTER 179

Earthquake Rate Modelling Tools to Explore Uncertainties in Fault Source Parameters The Case of the Alboran Sea

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The Alboran Sea accommodates part of the current NW-SE convergence between the African and Eurasian plates (4-5 mm/yr). Despite it is considered as a relatively low tectonic deformation region with diffuse seismicity, large earthquakes (I_{EMS}>IX) have occurred since historical times. One of the main issues for the characterization of the seismic hazard in the Alboran Sea, common to many low-deformation regions, lies in accurately constraining the seismic parameters that define fault activity and their behavior (i.e., slip rates, recurrence or multi-fault rupture capability). This issue is further aggravated by the fact that these faults are mostly located offshore, making their investigation more challenging. As a result, most faults in the Alboran Sea have poor slip and activity rate estimates, while their capability to interact and rupture in complex rupture patterns has not been explored yet. In this study, we compute several models of earthquake rupture rates for the Alboran Sea with the SHERIFS code and using a systematic parameter exploration tree to determine the parameters of each model. We base the exploration tree on the slip rate and multi-fault rupture scenarios, allowing us to investigate the epistemic uncertainty linked to these parameters. To check the feasibility of the computed earthquake rates of each model, we compare them with the observed seismicity rates in the region. As a result, this enables us to identify which parameter combinations best match the recorded seismicity, prioritizing those that perform better for the hazard assessment. In addition, these optimal values might be used as indicators for further studies focused on better constraining the fault parameters, as well as for preliminary fault-based seismic hazard assessments. By extension, the limitations of the modelling in terms of slip rate budget distribution and fault rupture scenarios can also be used to determine which areas should be prioritized for further research. We expect that the results of our work enhance discussion among researchers working in the area and motivate further investigations into fault dynamics.

POSTER 180

Mapping Finite-Fault Slip in 3D From Spatial Correlation Between Seismicity and Point-Source Coulomb Stress Change

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The main fault slip and energy release of earthquakes occurs many kilometers below the Earth's surface at seismogenic depth. Complete understanding of large earthquakes requires mapping the orientation, extent and amount of this fault slip. Such *finite-fault slip* maps are typically obtained from inversion of measured or inferred *surface* phenomena, such as fault offsets, shaking intensity, and time-varying or differential ground motion from seismograms, GNSS or InSAR. Here we introduce and illustrate a procedure for mapping finite-fault slip directly from seismicity and aftershocks—phenomena occurring *at seismogenic depth around an earthquake rupture*. For specified source and receiver faults, we construct 3D maps of source-fault slip by correlation of point-source Coulomb failure stress change (ΔCFS) kernels across the spatial distribution of seismicity around an earthquake. This procedure finds for points in 3D space what fault slip best explains, through ΔCFS, the surrounding distribution of seismicity. These *seismicity-stress* maps show potential, relative, finite-fault slip; they can also be used directly for quasi data-driven aftershock forecasting, and as prior constraint for other slip inversion methods.

We confirm that the seismicity-stress procedure recovers the location of a synthetic point-source given random seismicity predicted by ΔCFS for the point-source. We next show slip maps from this procedure for the Parkfield CA area that match well other estimates of co- and post-seismic slip for the 2004 M6 Parkfield earthquake, and of nearby, long-term slip related to fast creep. We further confirm agreement between co- and post-seismic slip obtained by this procedure and by other methods for the 2021 M6 Antelope Valley CA normal-faulting earthquake. Finally, we show for the 2018 M7.1 Anchorage AK intra-slab earthquake how the seismicity-stress procedure, combined with multi-scale precise hypocenter relocation, can resolve the enigma of which mainshock faulting plane ruptured (the shallow, east-dipping plane), and clarify what structures in the slab were activated in the energetic aftershock sequence.

POSTER 181

Microseismicity and Fault Structure in the Daliangshan Subblock Within the Southeastern Tibetan Plateau

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The Daliangshan subblock is located between the Tibetan Plateau and the South China block, characterized by intense tectonic deformation and complex fault structures. In this study, we analyze more than two years of continuous seismic records recorded by a recently deployed dense seismic array from December 2018 to April 2021. We used a recently developed machine learning-based earthquake location workflow (ESPRH) to construct a high-precision earthquake catalog for the region and obtained ~3000 earthquakes. Then, we mapped our final seismic location results to an existing S-wave velocity structure obtained through ambient seismic noise tomography. The seismicity distribution not only confirms the nature of the faults marked on the map but also delineates the detailed geometry of the unmapped faults. Earthquakes mainly occur at the boundaries of high- and low-velocity bodies or on high-velocity bodies, which is consistent with the tomography result. Combining the focal mechanism solution of historical earthquakes and the fault geometry of this paper, we also observed that the western side of the Daliangshan block is dominated by strike-slip faults, and the fault properties on the eastern side are complex. This tectonic phenomenon is attributed to the fact that during the lateral extrusion of the southeastern edge of the Chuandian fragments, the northeastern part of the Daliangshan subblock was squeezed by the South China block more strongly than its southwestern part was.

POSTER 182

Mapping Outerrise Normal (and other) Dip-slip Fault Parameters using Semi-automated and Newly Developed Python Toolbox

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Previous studies report that there is a connection between the propagation of tsunamis and outer-rise normal fault characteristics in deep sea trench regions. However, the true seismic and tsunami potential of these faults are poorly understood, as their driving forces are controlled more from plate bending forces than tectonic rates. Such is the example along the Puerto Rico trench, where bathymetry reveals large normal faults outward of the trench, and its risk to nearby populations is not yet quantified. To help quantify the seismogenic and tsunami potential here, we created a set of tools to semi-automatically determine basic fault properties from topographic relief. We use bathymetric data compiled in the Global Multi-Resolution Topography (GMRT) synthesis. The data is presented as shaded relief within a Python figure that the operator visually inspects for suspected faults, selecting either a number of points or endpoints defining the raised footwall along one side of the fault. From here, transects are automatically determined orthogonal to these points, and the elevation, gradients, and extent of curvature are extracted. These are used to determine breaks in slope along the scarp associated with lower-bounds on fault offset, as well as extrapolated points to account for erosion and deposition along the scarp crown and toe, estimating the original, uneroded fault traces along the same transects. From these profiles, we then calculated the median and distribution of dip and offset values, for evaluation of the magnitude and robustness of individual fault profiles. With the compiled and cataloged dataset of significant outerrise faults, we can incorporate convergence rates to determine the total slip rate across these faults, putting an upper-bound on the earthquake and tsunami potential of these faults. Given the generalizable nature of this tool, we next plan to apply it to outerrise behaviors at other subduction zone environments.

POSTER 183

Diatom Evidence of Tsunami Inundation Extent Following the Great Ca. 1700 Ce Earthquake(s) at the Salmon River Estuary, Oregon, USA

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Although the Cascadia Subduction Zone (CSZ) has not experienced a great (>M_w 8) megathrust earthquake in more than 300 years, coastal marshes along the CSZ preserve widespread stratigraphic evidence from the most recent great earthquake, or series of earthquakes, circa (ca.) 1700 CE. At the Salmon River estuary, stratigraphic evidence of earthquake subsidence and tsunami inundation ca. 1700 is preserved as intertidal wetland soils sharply capped by sand overlain by intertidal silt. The inland extent of sandy deposits above buried wetland soils has been used as a minimum inundation constraint in tsunami modeling. However, observations of modern tsunamis have demonstrated that the true inundation extent can exceed the inland limit of sandy sediment deposition by 50% or more in extensive, relatively flat, coastal plains, while mud-sized tsunami sediments can be deposited up to the full extent of inundation. Because sediment availability, site morphology, and deposit preservation contribute to the variability in tsunami deposit thickness, high-resolution tsunami deposit mapping is necessary to accurately estimate the inundation extents of prehistoric tsunamis. Through careful analyses of fossil diatoms, grain size, and computed tomography (CT) scans, we search for evidence of tsunami inundation in the fine-grained sediment above earthquake subsidence contacts in cores beyond the previously mapped inland extent of tsunami-deposited sand from the ca. 1700 CE rupture at the Salmon River estuary. Preliminary results show the diatom assemblage observed within the sandy portion of the mapped tsunami deposit are also found in silty sediments above the ca. 1700 CE earthquake subsidence contact at sites beyond the mapped inland extent of sandy tsunami deposits. Fragmentation of diatoms is consistent with transport in a tsunami both in sandy and silty tsunami sediments. Delineating the full extent of tsunami inundation along the CSZ provides more accurate constraints for tsunami and earthquake source models of past events and will improve our understanding of potential impacts and hazards of future events.

POSTER 184

Moment Tensor Analysis for Earthquakes in Armenia

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The Republic of Armenia and the neighboring areas are located in the central part of the Arabia-Eurasia collision zone, characterized by active seismicity. Moment tensor analysis (MTA) was carried out for the earthquakes (M>=3.0) that occurred in the territory of Armenia from 2017 to 2021. The data for this analysis were collected from a temporary broadband regional network, part of the project Collaborative Research: The Uplift and Seismic Structure (CNET). The inversion for the moment tensor, centroid depth, and source time function involves modeling the entire 3-component seismograms (Nabelek and Xia, 1995). For each earthquake, seismograms were band-pass filtered to enhance the signal. Earthquakes of magnitude 3.0 and greater were well recorded by many stations, resulting in well-resolved estimated parameters. Most events suitable for the moment-tensor analysis occurred in Javakheti and northwest Armenia regions and are right-lateral strike-slip, with two outliers, normal fault and thrust fault. A right-lateral strike-slip event near Vanadzor is consistent with the slip on the Pambak-Sevan fault. The most significant event (Mw=4.7) near Yerevan has a mixed strike-slip-thrust mechanism with a west-oriented tension axis. For this event was also calculated focal mechanism solution using P-wave first motion method, which shows that this 2021 M4.9 earthquake is characterized by a thrust fault mechanism with a strike-slip component (Sargsyan L., et al. 2022). The discussion of historical seismicity that has occurred over the course of a century in direct proximity to Yerevan, demonstrates that the Yerevan Fault and Parakar sub-fault are seismically active systems. The problem of possible NW and SE extensions of the Yerevan fault was addressed.

POSTER 185

Preliminary Constraints on Quaternary Fault Activity in the Malawi Rift from New High-resolution Bathymetry and Seismic Data

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Active rifts such as the Malawi Rift in the East Africa Rift System host faults capable of hosting large earthquakes. Many questions remain on the distribution of deformation, fault growth and linkage, and influence of surface processes on fault behavior. The potential of >100-km-long border faults to host large earthquakes has long been recognized, but recent earthquakes up to M6 near Karonga, Malawi highlight the earthquake hazard posed by intrarift faults, including faults below Lake Malawi. Existing seismic reflection imaging shows that many intrarift faults offset the lake floor and youngest sediments, providing further evidence that they are active. However, these profiles are generally too sparse and low resolution to constrain fault lengths and recent activity. We plan to acquire high-resolution bathymetric data to image the geometries and linkage of faults beneath Lake Malawi and CHIRP data to map sediments and faults up to ~50-100 m below the lake bottom. A team of US and Malawian scientists plan to acquire multibeam bathymetric and CHIRP data in several focus regions in the North and Central Basins of Lake Malawi in January-February 2024 aboard the M/V *Timba,* a ship operated by the Malawi Department of Surveys. This will be the first time that modern bathymetric data have been collected in Lake Malawi. New geophysical data will be integrated with existing seismic and drilling data to determine the positions, geometries, and Quaternary slip rates on faults below Lake Malawi. In this presentation, we will show preliminary results from this new project.

POSTER 186

Constraining Earthquake Nucleation using Response of Seismicity to Transient Slow-slip Event and Hydrological Surface Load

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The seismicity rate often fluctuates with varying effective stress in the Earth's crust. Common sources of stress perturbations include spontaneous slow-slip events, large-scale hydrological loading, solid Earth tides, and anthropogenic factors related to fluid injection or gas extraction. By studying how the driving stress relates to variations in seismicity rate, we can better understand the earthquake nucleation process. Here, we consider two case studies from different spatial and temporal scales. The first case study is the 2020 Westmorland, California earthquake swarm that lasted approximately five days. 5-min sampled GPS and InSAR reveal a shallow Mw 5.19 slow-slip event that started 12 hours prior to the onset of seismicity. Using a stress-driven model based on rate-and-state friction, we can explain the overall spatial and temporal evolution of seismicity using the transient stress from the slow-slip event, including the time lag between the slow-slip event and the onset of seismicity. The second case study considers the annual modulation of the seismicity rate in California. We decluster the catalog using the nearest-neighbor approach and search for periodicities using the Schuster spectrum. For areas with detectable seasonal modulation of seismicity, we find a correlation between the amplitude of seismicity rate modulation and the amplitudes of driving stress due to seasonal changes in surface hydrological loads. Furthermore, the peak seismicity rate occurs approximately one month after the peak stressing rate. Both case studies reveal that earthquake nucleation is not instantaneous. The constrained frictional-stress parameter is also consistent with one another at a few kPa, suggesting a smaller rate-and-state direct effect than those typically measured in the laboratory, the prevalence of high fluid pore pressure, or a combination, at least for the areas where the earthquakes occurred.

POSTER 187

Towards Systematic Kinematic Source Models of Historically Large Earthquakes

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We are interested in systematically analyzing large ruptures to establish scaling laws of kinematic properties, such as rise times, slip rates, and rupture speeds. The challenge is that kinematic models for large (M6+) events are often produced with heterogeneous methodologies and datasets. This makes synthesis of general behaviors challenging and results ambiguous. Additionally, as methods continue to develop, past events with good observations do not necessarily have slip models produced with modern methods. Thus, retrospective analysis of slip distributions is fundamental to allow us to further investigate general characteristics of source parameters during a rupture.

Here we will discuss our plans to retrospectively process significant ruptures with new inversion techniques that are capable of jointly inverting teleseimsic body and surface waves, static and high-rate GNSS, InSAR, strong motion and tsunami data. We will highlight the approach by focusing on the M9.1 Tohoku-oki earthquake to showcase the advantages of the new approach. This earthquake in 2011 stands as one of the largest ruptures ever recorded and most closely observed earthquake in history due to the dense array of seismic and geodetic instrumentation in Japan. This provided an unprecedented opportunity to study this megathrust event and collect data near source.

This analysis extends beyond the great M9.1 Tohoku-oki earthquake, actively contributing to the ongoing reevaluation of finite-fault models for large earthquakes dating back to the 1990s, while also incorporating regional data when available. Ultimately, we aim to refine source scaling properties of large earthquakes worldwide. Therefore, we will present our proposed workflow that involves not only systematizing the inversion process but also the creation of standardized and analysis-ready input source products. This is particularly important for InSAR and GNSS, which are quickly expanding their temporal and spatial sampling of crustal deformation worldwide.

POSTER 189

Study on the Latest Activity and the Maximum Potential Earthquake in the Middle Section of the Minjiang Fault

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The Indo-Asian collision has resulted in the rapid uplift of the Tibet Plateau, forming the Minshan active block on the northeastern margin of the plateau. The Minshan active block is characterized by high intensity and frequency of seismic activity, with many of the seismogenic structures located within densely populated valleys flanked by high terrain. The large earthquakes and associated geological hazards, such as massive landslides, have caused significant loss of life and property in this region. Therefore, it is crucial to evaluate the fault activity and seismic hazard in this area. The Minjiang fault, located at the western boundary of the Minshan active block, has been extensively studied through field investigations. However, the lack of continuous surface exposures in the middle segment of the fault has limited research on its latest activity and maximum potential earthquake, hindering the assessment of seismic hazard in the area. In this study, we conducted detailed remote-sensing image interpretation and field investigations of the middle segment of the Minjiang fault to quantitatively evaluate its latest activity, maximum potential earthquake magnitude, and seismic hazard. The middle segment of the Minjiang fault is a Holocene active fault. Using the empirical formulas, we estimated its maximum potential earthquake magnitude to be approximately Ms7.3. We also suggest the existence of two seismic hazard zones on the periphery of the Minshan active block, including the southern segment of the Huya fault and the middle segment of the Minjiang fault. The research provides data support for the assessment of seismic and geological hazards in this region, and enhances the further understanding of the tectonic deformation patterns and dynamic mechanisms of the northeastern margin of the Tibet Plateau.

Leveraging Cutting-Edge Cyberinfrastructure for Large Scale Data Analysis and Education

Oral Session • Thursday 2 May • 4:30 PM Pacific

Conveners: Alice-Agnes Gabriel, University of California, San Diego (algabriel@ucsd.edu); Henry Berglund, EarthScope Consortium (henry.berglund@earthscope.org); Marine A. Denolle, University of Washington (mdenolle@uw.edu); Tim Dittmann, EarthScope Consortium (tim.dittmann@earthscope.org); Zoe Krauss, University of Washington (zkrauss@uw.edu); Eileen Martin, Colorado School of Mines (eileenrmartin@mines.edu); Amanda Thomas, University of Oregon (amthomas@uoregon.edu); Chad Trabant, EarthScope Consortium (chad.trabant@earthscope.org); Ian Wang, University of Texas at Austin (iwang@tacc.utexas.edu)

Advancing USGS Scientific Modeling Through Cloud Computing

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The U.S. Federal Government released an Executive Order to carry out a Cloud Smart strategy aimed at adopting cloud-based solutions for modernizing cyberinfrastructure, enhancing security, and providing the American people with higher quality services and products (https://cloud.cio.gov/strategy/). Software developers at the U.S. Geological Survey (USGS) Geologic Hazards Science Center (GHSC) are adopting this strategy by moving IT infrastructure from on-premises servers to the cloud. Here, we give an overview of how the GHSC is running various scientific applications on the cloud. We will discuss the hybrid cloud systems (a cloud architecture that lies between liftand-shift and purely cloud native approaches) used for running 1) the USGS earthquake-triggered global ShakeMap and down-stream near-real-time Ground Failure product, 2) user-initiated high-throughput computing simulations of seismic site response using the finite element platform OpenSees, 3) a semi-automatic approach for running finite fault inversions, and 4) USGS slab models via a web form request. Adopting the Cloud Smart strategy has not only educated GHSC developers on the capabilities of cloud computing but has prompted the development of new USGS earthquake hazard products (e.g., the Sequence Product, which links USGS event pages for foreshocks, mainshocks, and aftershocks), and has shifted seismic workflows (e.g., aftershock relocations) to follow cloud-native serverless approaches. We will also address examples of how USGS scientists interact with these cloud systems, benefits and drawbacks of migrating to the cloud, associated costs, and how one can get started with cloud computing.

Parallel Processing of Large Seismic Data Sets With Mspass

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The size and accessibility of seismology data have undergone a transformative change due to large-scale projects like the USArray component of Earthscope. This has ushered in an era of unprecedented data resources for the seismology community. Collaborative endeavors like SCOPED (Seismic COmputational Platform for Empowering Discovery) aim to provide data and computation as a service, with MsPASS (Massive Parallel Analysis System for Seismologists) as a pivotal component within this platform. MsPASS is open-source, fully containerized, operates on parallel schedulers, and utilizes a NoSQL database for data management. These features make it the only framework in existence today for generic seismic processing on systems of any scale. The newest release of MsPASS (v2.0) has major enhancements in parallel IO capabilities, prototype methods for working on cloud computering systems, and improvements to documentation. Current work is focused on added interoperability with existing Machine Learning packages, such as SeisBench and PhaseNet. We will demonstrate current capabilities with results from processing a large dataset of all broadband channels located within the contiguous United States that operated during the USArray recording period. MsPASS can also leverage AWS Lambda functions for preprocessing data hosted on the cloud. We demonstrate the improvement in throughput performance with a workflow processing the SCEDC dataset on AWS. Another notable development is the seamless integration of MsPASS into large HPC systems through the SCOPED Gateway, a science gateway facilitating seismic data processing as a service over the web. This not only boosts the accessibility and flexibility of MsPASS but also significantly lowers the intellectual entry barrier often encountered with new software systems. With these new developments, we aim to transform MsPASS into a community tool for large-scale seismic data processing, thereby enhancing capabilities, fostering collaboration, and innovating data mining within the seismology community.

Enabling Large Data Analysis on the Earthscope Data Repositories

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In 2024, all geophysical data managed by the EarthScope consortium for NSF's GAGE and SAGE facilities will be stored in a commercial cloud system. This move will enable EarthScope and the research communities it supports to leverage the enormous capabilities of cloud computing. To fully utilize the abundant compute, cost-effectiveness, and direct access to huge data sets in the cloud, data processing systems need to be adapted for this new paradigm. EarthScope has initiated a project to create resources that will help researchers transition their data analyses to this environment. These resources are intended to help researchers working at different scales, with a particular highlight on the capability to access very large datasets that this paradigm change will allow. In addition to documentation, EarthScope will provide a notebook hub to support easy and democratized access to compute adjacent to the data. Workshops will be developed and conducted both in person and online to train researchers how to use these new resources and generally transition their work to the cloud. With the ability to apply cloud computing to deep geophysical data sets the future is bright, and we are excited to enable this for multiple geoscience domains.

Exploring the Impact of Lossy Compression on Passive Seismic Event Detection and Arrival Time Precision

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New seismic sensing technologies such as distributed acoustic sensing (DAS) and low-cost accelerometer nodes are making it easier than ever before to continuously collect high-resolution, large-scale seismic data. Public seismology data archives are struggling to host the full datasets, research teams spend huge amounts of time and/or electricity to transfer the full datasets, and our ability to interactively visualize and rapidly understand these data is hindered by their large size. When data acquisition settings are selected appropriately (e.g. not oversampled in time or space), lossy compression techniques allow us to greatly reduce the size of the data without introducing the limitations of subsampling (e.g. array aliasing). However, lossy compression techniques are unable to exactly reconstruct our original array data at the same precision they were recorded at. While prior studies have characterized the errors introduced into the raw and reconstructed data for some types of lossy compression, we aim to understand the extent to which these errors propagate into meaningful changes in our characterization of seismic signals, including through template matching and event picking workflows. We quantitatively compare the changes in an open DAS dataset (the Bradys Hot Springs PoroTomo data) under varying levels of lossy compression using singular value decomposition (SVD) compression, wavelet-based compression, and zfp compression strategies. We show the quantitative tradeoffs in event catalogs resulting from template matching of data that has undergone substantial levels of compression. Further, we quantify the distribution of array-wide event pick time changes, which are shown to incur little to no average bias. We have released open-source, fully reproducible codes for comparing compression strategies for all workflows in this study to encourage others to use these tools in evaluating the suitability of lossy compression for sharing other datasets.

Towards End-to-End Earthquake Monitoring Using a Multitask Deep Learning Model

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Advancements in seismic data processing provide crucial insights into earthquake characteristics. Conventional methods used for earthquake monitoring tasks, such as earthquake detection and phase picking, are being enhanced by the rapid advancements in deep learning. However, most current efforts focus on developing separate models for each specific task, leaving the potential of an end-to-end framework relatively unexplored. To address this gap, we expend the PhaseNet model to create a multitask framework. This enhanced model, PhaseNet+, can simultaneously perform talks of phase arrival time picking, first motion polarity determination, and earthquake source parameter prediction. The outputs from these perception-based models can then be processed by specialized physics-based algorithms to accurately determine earthquake location and focal mechanism. Our approach aims to enhance seismic monitoring by adopting a more unified and efficient approach.

Leveraging Cutting-Edge Cyberinfrastructure for Large Scale Data Analysis and Education [Poster Session]

Poster Session • Thursday 2 May

Conveners: Alice-Agnes Gabriel, University of California, San Diego (algabriel@ucsd.edu); Henry Berglund, EarthScope Consortium (henry.berglund@earthscope.org); Marine A. Denolle, University of Washington (mdenolle@uw.edu); Tim Dittmann, EarthScope Consortium (tim.dittmann@earthscope.org); Zoe Krauss, University of Washington

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POSTER 33

SCOPED Update: A Cloud and HPC Software Platform for Computational Seismology

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The goal of the SCOPED (Seismic COmputational Platform for Empowering Discovery) project is to develop a cyberinfrastructure that enables hybrid model-data research in seismology. The open-source software development will make it easier for researchers to connect and collaborate via common platforms like GitHub and containers like Docker. Seismological research is typically either data-driven or model-driven. Data-driven workflows are well-suited for cloud infrastructure, while model-driven workflows are best suited for HPC. The SCOPED platform includes tools for data discovery, theoretical seismology, wavefield simulations, and inversion workflows for velocity Earth models and earthquake source characterization. The platform containerizes our seismological software to run on both HPC and cloud platforms. Tutorials are also included to guide new users on how to run the software. Additionally, the SCOPED Gateway is available as a preliminary implementation, which enables these containers as services over the web.

In this SCOPED update, we present several advances. First, we demonstrate using the SCOPED gateway for HPC simulations of seismic wavefields and their inversion using MTUQ and SPECFEM. In addition, we will discuss the current and future I/O problems and potential remedies for large-scale full-waveform inversions on HPC systems. Second, we demonstrate cloud-native workflows on Amazon WebServes (AWS). We demonstrate how to do ambient noise seismology with NoisePy, deep-learning seismology using SeisBench and QuakeFlow, and unsupervised ML for source characterization and discovery. We demonstrate how to use AWS tools and Infrastructure-as-a-service tools such as Coiled to abstract cloud systems for easier access. Finally, we show how SCOPED ways to bridge cloud and HPC using the SeismoDB data lake.

POSTER 34

Updates to the U.S. Geological Survey's Product Distribution Layer and Impacts on Comcat and Realtime Systems

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The U.S. Geological Survey's (USGS) Product Distribution Layer (PDL; https://ghsc.code-pages.usgs.gov/hazdev/pdl/docs/) is a tool integral to many systems, including, but not limited to, the ANSS Comprehensive Catalog of seismic events (ComCat; https://earthquake.usgs.gov/data/comcat/), Real-time feeds (e.g. https://earthquake.usgs.gov/earthquakes/feed/v1.0/geojson.php), the latest earthquakes map and list (https://earthquake.usgs.gov/earthquakes/map/), and automated data delivery to Advanced National Seismic System (ANSS) contributors. PDL and these affiliated systems are critical for receiving and distributing large amounts of earthquake data in near real-time. In recent years, the Geologic Hazards Science Center's (GHSC) Hazards Development Team (HazDev) has worked to move PDL systems from on-premises servers into the Cloud. A non-exhaustive list of the benefits of these migrations include scalability, enhanced security, and the ability to implement continuous integration/continuous deployment (CI/CD) and Infrastructure as Code (IaC) for fast system deployment and recovery.

The purpose of this talk is two-fold. First, we will detail the large-scale ComCat database upgrade that occurred following the significant events of the 2023 Kahramanmaraş earthquake sequence, which exposed limitations in the cloud system, and we will discuss the observed effectiveness of Amazon Web Services (AWS) relational database service's (RDS) scalability before and after the upgrade. Second, we will outline ongoing work to improve PDL's Java client and systems, and we will discuss the implications for our data consumers and producers.

POSTER 35

Alaska Earthquake Center's Workforce Development Program Takes Shape

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The Alaska Earthquake Center has committed to helping develop a strong and diverse Alaskan workforce. In 2022, we joined with the T3 (Teaching Through Technology) Alaska program to bring seismic instrumentation training to rural Alaska students in communities across the state. In the first year of the program, 22 students from 7 communities participated. Now in its second year, over 30 students from 16 schools are enrolled in the Earth Observation Club. We have refined how the program runs, and expanded the suite of tools available for training to align with Alaska Geophysical Network instrumentation. The school-year program relies on a teacher at each school to act as the local coordinator. An in-person kick-off event forges early connections, and weekly online meetings provide a classroom-type environment for students to connect and brainstorm ideas for community-based projects. Students discuss individual community concerns, like permafrost thaw that leads to ground instability and erosion. They decide on which real-time monitoring tool(s)—seismometer, soil probe, weather station, camera—they will use to collect the data to make informed community decisions. For example, months-long data from a soil temperature profiler in Quinhagak can help the village make an informed decision on where to place a new road. The students set up and run their project, and present their efforts at an in-person event in the spring, such as this year's SSA meeting.

This year we have also introduced a credentialing program that is aimed at training students in the field and technical skills needed to troubleshoot, fix, and install remote seismic stations. The program includes basic, intermediate, and advanced stages, and culminates in in-person training and the opportunity to apply for summer internships. Our plans for the next few years include creating credentialing pathways in data analysis, computer systems, and communications, and building industry partnerships for student employment.

POSTER 36

Cloud-Based Gnss Processing Pipeline for the Shakealert Earthquake Early Warning System

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ShakeAlert is an earthquake early warning (EEW) system that modernizes earthquake response procedures by alerting people and automated systems

before strong/damaging ground shaking arrives. EarthScope is working with the United States Geological Survey (USGS) to integrate the Global Navigation Satellite System (GNSS) data into the ShakeAlert monitoring system. Unlike seismic data, GNSS positions do not saturate and capture sensor displacement during strong shaking. EarthScope's Data Services (DS) is developing a cloud-native, low-latency processing pipeline that normalizes real-time position streams from various sources, including receivers operated by ShakeAlert partner networks, raw GNSS observations, and pre-processed position data.

Real-time GNSS position data are used to rapidly determine Peak Ground Displacement (PGD) for near source, strong earthquakes ~>Mw6. Algorithms use PGD data to rapidly estimate the magnitude of an event during, or soon after, the fault rupture sequence. Earthquake size estimates calculated from PGD data are robust and inform the geographical extent of an issued ShakeAlert warning. EarthScope DS designed the cloud-native nature of the newly developed ShakeAlert GNSS processing pipeline to facilitate the integration of new technologies, including the adaptation of machine learning algorithms to real-time GNSS and seismic data streams. The new ShakeAlert system developed in partnership with the USGS will enable the research and operational hazard response communities to process and respond to seismic events accurately by leveraging the advantages of cloud-based operations on geophysical data.

POSTER 37

Deep Implicit Time Series Modeling for Earthquake Phase Picking on Edge Devices

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Earthquake monitoring and understanding seismic activities are pivotal in assessing seismic hazards and ensuring community resilience. One critical aspect of earthquake analysis involves accurate phase picking, where precise identification of seismic wave arrival times is fundamental for robust event characterization. Traditionally, seismic phase picking demands labor-intensive efforts and often struggles with noises, irregularities, and other complexities inherent in seismic data, until the emergence of deep learning-based automatic phase pickers. State-of-the-art models like EQTransformer and Phasenet have transformed this task, exhibiting remarkable precision in detecting and classifying seismic phases, significantly augmenting the efficiency of earthquake monitoring. However, these advanced models often rely on high-powered servers with multiple GPUs, limiting accessibility, especially for those reliant on mobile or edge devices (e.g. Raspberry Shakes) that lack significant computing capabilities. To address these challenges, we explore a novel deep-learning framework—times series modeling with a deep implicit model—on the seismic phase picking problem. The implicit model uses a state-driven approach, which distinguishes itself from its traditional, layered-based deep learning counterparts. It is capable of emulating classical feedforward-based neural networks while offering promise in compressing models without exhaustive retraining. We plan to first train the implicit model on the STEAD dataset. The trained model will then be compressed by utilizing the low-rank technique. An offline performance test on data collected by Raspberry Pi and Shake will then be performed to understand the effectiveness of model compression. We hope this approach advances seismic phase picking accuracy and pioneers a pathway to democratize deep learning for seismic monitoring on resource-constrained devices.

POSTER 38

Using Learning Analytics to Evaluate the Instructional Design and Student Performance in a Large-Enrollment Scientific Computing Workshop

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Addressing today's complex scientific challenges will require geoscience curricula to develop skills and competencies, such as scientific computing, in addition to subdisciplinary content knowledge. Online training shows promise for teaching domain-specific scientific computing and for broadening access. However, what results in effective course design, pedagogy, and retention needs further exploration. Online courses such as the Seismology Skill Building Workshop, which helps students build scientific computing skills through seismology-focused programming, generate rich datasets of student interactions and performance that can be used to explore the effectiveness of instructional design to a degree not possible in traditional courses. The workshop consists of over 35 interactive assignments with more than 1000 questions. It was designed to engage students in key skills (e.g. seismology, programming, quantitative literacy), frequently with higher order thinking, and with increasing challenge as the workshop progresses. To explore the efficacy of the instructional design, we created a table of specification categorizing each question from the 2022 course according to skill and Bloom's Revised taxonomy. We then compared the distribution of categories to the design intent and examined each category using facility and discrimination indices to evaluate students' performance.

Results indicate the instructional design of the course did not fully align with the original intentions. For example, 80% of the questions fell within the lowest 2 levels of Bloom's taxonomy. In addition, the rigor did not increase through the workshop. Changes enacted in 2023 increased the number of higher order thinking questions, progressively reduced scaffolding, and reduced the number of no-skill questions and increased the number of multi-skill questions. To evaluate the impact of these changes on student learning outcomes, a pre/post test targeting each of the categorized skills was administered in 2023. Results show improved performance for all of the key skills and more consistent and larger gains for higher order thinking.

Machine Learning for Full Waveform Inversion: From Hybrid to End-to-End Approaches

Oral Session • Friday 3 May • 4:30 PM Pacific

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Advancing Seismic Full Waveform Inversion: A Hybrid Approach of Machine Learning and Physical Models for Improved Generalizability and Efficiency

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Computational seismic full waveform inversion (FWI) is crucial for energy exploration, civil infrastructure, Earthquake detection and early warning, and so on. However, nearly all of the earth's interior is inaccessible to direct observation. Inference of unknown subsurface properties, therefore, relies on indirect and limited seismic measurements taken at or near the surface. The relevant data analysis capability for solving computational seismic imaging problems is inadequate, mainly due to the ill-posed nature of the problems and the high computational costs of solving them. Recently, machine learning (ML) based computational methods have been pursued in the context of scientific computational imaging problems. Some success has been attained when an abundance of simulations and labels are available. Nevertheless, ML models, trained using physical simulations, usually suffer from weak generalizability when applied to a moderately different real-world dataset. Moreover, obtaining corresponding training labels is typically prohibitively expensive due to the high demand for subject-matter expertise. On the other hand, different from problems in a typical computer vision context, many scientific imaging problems are governed by underlying physical equations. For example, the wave equation, describing how a wave signal is propagated through a subsurface medium over time, is the governing physics for seismic imaging problems. To fully unleash the power and flexibility of ML for solving large-scale computational seismic FWI problems, I have developed new computational methods to bridge the technical gap by addressing the critical issues of weak generalizability, label scarcity, and high training cost. In this talk, I will discuss the details of my R&D effort in leveraging both the power of machine learning and underlying physics. A series of numerical experiments are conducted using datasets from synthetic simulations to field applications to evaluate the effectiveness of the new FWI methods.

Ambient Noise Full Waveform Inversion With Neural Operators

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Numerical simulations of seismic wave propagation are central to investigating velocity structures and for improving seismic hazard assessment, but standard methods such as finite element or finite difference are computationally expensive. Recent studies have shown that a new class of machine learning models, called Neural Operators, are able to solve the elastodynamic wave equation orders of magnitude faster than these conventional numerical methods. Full waveform inversion is a prime beneficiary of the accelerated simulations. Neural operators, combined with automatic differentiation, provide an alternative approach to full waveform inversion that does not involve the Born approximation. It thus can potentially overcome some of the cycle skipping problems present in traditional adjoint state formulations. Here we demonstrate the first application of Neural Operators for full waveform inversion on a real seismic dataset: several nodal transects collected across the San Gabriel and San Bernardino Basins in the Los Angeles metropolitan area.

Application of TCN, UMAP, and XGBoost to Pg and Lg Wave Amplitude to Identify Mining vs. Non Mining and Deep vs. Shallow Events

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Using the CNRS bulletin from the seismic network in Morocco, we collected 4542 regional waveforms for both mining and non-mining events occurring around the station MD31. The events have occurred within 50 to 250 km of the station. Using this mixed bag of waveforms and criterion that SNR must be greater than 2, we selected 260 mining and 161 non-mining events to conduct this study. We processed these waveforms to construct a meta-data file consisting of the RMS amplitude of the Pg and Lg waves in five frequency bands at 4-6, 6-8, 8-10, 6-12 and 8-16Hz. The mining events occurred during the day and they had characteristically strong Pg and weak Lg waves, especially at high frequencies. We observed that while the Pg and Lg amplitude alone did not separate, the high-frequency Pg/Lg amplitude ratios separated the two population quite well. Mining events are shallow and occurred at a single site. For this reason alone we did not perform any MDAC correction to these amplitudes. The supervised 80:20 and 50:50 training and testing of data and analysis of the impact factor of the attributes using the XGBoost algorithm illustrated a high level of success in identifying the source types. Using a supervised trained 90:10 model, we could further identify additional source types for about 428 events in the area. We are currently applying the TCN and UMAP to the same data set to determine the performance in the classification of these events from Morocco. We are now compiling a similar data set in areas where earthquakes occur at many depths, where deep earthquakes may exhibit strong P and weak-to-moderate level of Lg waves. Our primary focus is to evaluate the performance of the algorithms in identifying "deep vs shallow" and "mining explosions vs. shallow and deep" earthquakes.

Scaling Up Large Fourier Neural Operator Training in 3D Seismic Waveform Modeling

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Recent developments in using Fourier Neural Operators (FNO) to solve 2D and 3D elastic wave equations provide the basis for using machine learning tools for seismic wave modeling, thus enabling fast full waveform inversion in various applications. However, training these models usually requires heavy computation both in time and hardware, such as HPCs, with limitations in scaling the model up. In this presentation, we build on the prior efforts (Yang et al., 2023; Zou et al., 2023) to experiment with ways to improve the larger model training to facilitate the use of this approach in large-scale real-world applications. We test transfer learning, model parallelization, physics-informed neural operators to make training larger models easier. This evaluation of different approaches provides guidance for future training of large neural operator models for full waveform inversion applications.

Physics-Informed Deep Generative Models to Quantify Uncertainties in the Geophysical Full-Waveform Inversion

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Full-waveform inversion (FWI) has the potential to provide high resolution maps for subsurface velocity models. However, due to the challenges and limitations of FWI, e.g., noisy measurements and the absence of low frequency content, it is usually hard to obtain reliable subsurface velocity models due to those uncertainties. Methods based on sampling, e.g., Markov Chain Monte Carlo (MCMC) were developed to quantify the uncertainties in the FWI. However, sampling-based methods are generally computationally very expensive. Contrary to sampling methods, the variational-based methods provide approximate, yet more efficient solutions to the large-scale probabilistic problems such as FWI. We have developed a variational probabilistic framework for FWI where the goal is to map the seismograms to a distribution of velocity models (posterior distribution). Given their high potentials in solving challenging probabilistic inverse problems, in this work, we study the feasibility of using deep generative models to reconstruct the posterior probability distribution of the subsurface velocity model. Specifically, we consider two generative model architectures, i.e., the variational autoencoder (VAE) and the invertible neural network (INN) where the input is the shot gathers, and the output are several samples of velocity models. We use these samples to estimate uncertainties, e.g., compute the mean and standard deviation of the populations. Moreover, we iteratively update the network parameters in an un-supervised manner. To achieve this, we backpropagate the FWI gradient information into the network to guide the network parameters' update based on the underlying physics. In this talk, we will present the details of our framework and discuss the outcomes, ongoing efforts and our vision for possible future directions. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Machine Learning for Full Waveform Inversion: From Hybrid to End-to-End Approaches [Poster Session]

Poster Session • Friday 3 May

Conveners: Jennifer L. Harding, Sandia National Laboratories (jlhardi@sandia.gov); Mrinal K. Sen, University of Texas at Austin (mrinal@utexas.edu); Hongkyu Yoon, Sandia National Laboratories (hyoon@sandia.gov)

POSTER 100

Physics-Guided Neural Network for Full Waveform Inversion With Structural Enhancement

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Seismic velocity modeling plays a critical role in understanding subsurface structures. Full-waveform inversion (FWI) is a powerful technique that enables high-resolution velocity modeling by iteratively minimizing the discrepancies between observed and predicted seismic waveforms. However, the inherent strong nonlinearity of FWI can often lead to convergence in local minima, especially when fitting oscillatory waveforms. This challenge becomes even more pronounced when dealing with insufficient starting models and noisy data characterized by low signal-to-noise ratios.

Our study introduces an innovative learning-based approach to FWI, which integrates deep learning with physical equations. In this method, we parameterize the velocity model using a convolutional neural network (CNN). CNN inherently introduces spatial correlations, serving as regularization for the velocity model. This renders deep learning well-suited for FWI, effectively mitigating noise in model gradients and alleviating issues related to local minima. The velocity model generated by the CNN is seamlessly incorporated into the acoustic partial differential equation (PDE) solvers used in traditional FWI. Automatic differentiation is harnessed to compute PDE gradients, facilitating the updating of network parameters through backpropagation. Additionally, inspired by recent developments in structure-tensor coherence techniques, we further improve FWI through anisotropic diffusion smoothing. We compute oriented derivatives along directions both perpendicular and parallel to seismic reflectors, giving rise to oriented structure tensors. These oriented tensors enhance the representation of lateral velocity discontinuities, particularly those associated with features that align with dipping structures in the velocity model. The numerical experiments conducted using the well-established Marmousi model demonstrate better representations of discontinuous and stratigraphic velocity features compared to conventional FWI.

POSTER 101

Physics-Guided Unsupervised Deep Learning Approach for the Inversion of Receiver Functions in Dipping and Anisotropic Media

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The converted wave technique namely Receiver function (RF) has been utilized routinely for probing the crust and mantle structures. In the analysis of receiver functions, deterministic physical methods such as inversions are frequently employed to refine the estimations to image the subsurface realistic geological structure. Despite their utility, the presence of dipping and anisotropic geological structures very often complicates and can even hinder the inversion process. To address these complexities, here we introduce a Physics-Guided unsupervised deep learning approach for the inversion of receiver function data. We employ unsupervised deep learning, enhanced with implicit neural representations, allowing for the prediction of inverted Earth model parameters: thickness (H), S-wave velocity (Vs), anisotropy, trend, plunge, strike and dip without requiring any labeled data. For determining the optimal model parameters, the output parameters are used in a forward modeling scheme to simulate the receiver functions. During training, the model iteratively adjusts and improves these parameters based on discrepancies between the simulated and observed receiver functions. Inversion results from both synthetic and field examples from the Indian shield suggest that physics-guided unsupervised deep learning approach is effective in inversion tasks, particularly when dealing with intricate geological settings like dipping and anisotropic media. With its application aimed at understanding subsurface structures, we believe that this approach holds potential to broaden the capabilities of subsurface exploration.

POSTER 102

Towards a Practical Physics-Informed Neural Network Method for End-to-End Full Waveform Inversion

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Our aim is to explore the viability of end-to-end deep learning (DL) methods for full waveform inversion (FWI) towards practical use for active-source seismic data shot gathers, which may be able to overcome some of the challenges of traditional FWI. We developed a DL-based FWI method that inputs elastic full-waveform shot gathers along a seismic line and outputs a 2-D P-wave velocity model. We employ a physics-informed neural network (PINN) that solves the acoustic wave equation for enhanced generalizability and physics-based inverse solution. This method takes a starting velocity model guess and iterates over solving for the acoustic wave equation via PINN with boundary and initial condition constraints, including a point source location and source function, while fitting the input data for an updated velocity model that honors the physics. We generate a starting velocity model using a data-driven neural network trained on over three thousand velocity model and shot gather pairs. We explore multiple PINN architectures, including a physics-informed (PI)-DeepONet, which is a neural operator that allows for further generalizability and flexibility for enforcing boundary condition constraints (e.g., shot location and source function).

We find that our current methodology requires long training times for each inversion when incorporating a PINN and the solution struggles to converge for the source frequencies of interest. The S-wave energy in our elastic data further complicates our training and appears to confuse the NN and results in poorer solutions. Further research into PINN convergence for the wave equation, ways to limit frequency bias during learning, preprocessing techniques for sseismic data, and training strategies (e.g., domain decomposition, frequency staging), will pave the way for future end-to-end method that can compete with traditional or hybrid FWI methods at the scale and frequencies generally of interest for practical applications.

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POSTER 103

An Autoencoder-Based Prior for Bayesian Full Waveform Inversion

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To quantify the uncertainties of seismic full waveform inversion (FWI), one can solve FWI in Bayesian inference framework by estimating the posterior probability distribution (PPD) of subsurface model given seismic data. Sampling-based methods, e.g. Markov chain Monte Carlo (MCMC), draw samples from the PPD of the Bayesian inference problem and those samples can be used to estimate the PPD and make inference of the model. For Bayesian FWI problem, MCMC sampling suffers from low-convergence and inefficiency due to the high dimensionality of the model space.

In this abstract, we propose to train an autoencoder based on a subset of posterior samples and use it as prior for Bayesian FWI problem. We design a convolutional autoencoder (CAE) with a bottleneck latent layer with only a few variables. By training the CAE, the model space dimension can be reduced greatly. The proposed workflow starts with a short-run adaptive MCMC chain in physical domain model space for the FWI problem, generating a subset of posterior samples. Then the subset samples are used to train the CAE. Lastly, we run new MCMC chains in latent model space and use the decoder part of the CAE to transform the latent samples to physical domain samples. We verify the feasibility of the proposed method with Marmousi synthetic model example. Compared to physical domain MCMC chains, the proposed method improves the efficiency of MCMC in solving Bayesian FWI problem.

Marine Seismoacoustics

Oral Session • Wednesday 1 May • 4:30 PM Pacific

Conveners: Kasey Aderhold, EarthScope Consortium (kasey.aderhold@earthscope.org); Helen Janiszewski, University of Hawaiʻi at Mānoa (hajanisz@hawaii.edu); Siobhan Niklasson, Los Alamos National Laboratory (sniklasson@lanl.gov); Charlotte Rowe, Los Alamos National Laboratory (char@lanl.gov)

Rupture Behavior of Large Strike-Slip Earthquakes at Equatorial Atlantic Oceanic Transform Faults: Constraints From Hydroacoustic Data

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Oceanic transform faults (OTFs) are tectonic strike-slip plate boundaries that offset mid-ocean ridges by tens to hundreds of kilometers, thus reaching the globally largest oceanic offset with up to 900 km in the equatorial Atlantic Ocean (EAO). Earthquakes along OTFs can produce moment magnitudes (Mw) of >7, with global networks monitoring in real time. Previous studies used teleseismic data, numerical modeling, and thermal constraints to yield characteristics of the seismic rupture behaviors along the OTFs. In this study, we take a different approach by using hydroacoustic T-waves arriving at the International Monitoring System hydrophone triplet deployed at Ascension Island and belonging to the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) to study the rupture of 43 strike-slip earthquakes in the EAO. The earthquakes occurred along nine OTFs in EAO with $5.6>M_w<7.1$ reported by the Global Centroid Moment Tensor catalog. We use cross-correlation and arrival-time difference variations to identify the T-wave source directions (back-azimuth) and compare interceptions of the directions with mapped fault traces from multibeam bathymetric data to reveal the total rupture length of the earthquakes. Our technique is based on sound propagation through the ocean and provides a new alternative characterization of the rupture behavior of large strike-slip earthquakes. Our preliminary results show rupture lengths reaching from 5.34±1.0 to 101.98±12.8 km and rupture velocities between 0.83±0.29 and 4.5±0.8 km/s, with a well-correlated least-square regression between the rupture length and Mw. Most of the earthquakes show a unilateral rupture moving. Furthermore, we also identified a two-stage (eastward and westward) rupture propagation to the 2016 Mw 7.1 Romanche earthquake like results published by a recent study. This complex two-stage rupture style was similarly observed in the 2022 Mw 6.6 Vema earthquake. Therefore, we show that rupture parameters of large strike-slip earthquakes in OTFs can be revealed not just by commonly used teleseismic methods but also by solely using hydroacoustic data.

Waveform Modeling of Hydroacoustic Teleseismic Earthquake Records from Autonomous Mermaid Floats

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We present a computational technique to model hydroacoustic waveforms from teleseismic earthquakes recorded by mid-column MERMAID floats deployed in the Pacific, taking into consideration bathymetric effects that modify seismo-acoustic conversions at the ocean bottom and acoustic wave propagation in the ocean layer, including reverberations. Our approach couples axisymmetric spectral-element simulations performed for moment-tensor earthquakes in a one-dimensional solid Earth to a two-dimensional Cartesian fluid-solid coupled spectral-element simulation that captures the conversion from displacement to acoustic pressure at an ocean-bottom interface with accurate bathymetry. We applied our workflow to 1,129 seismograms for 682 earthquakes from 16 MERMAIDs owned by Princeton University that were deployed in the Southern Pacific as part of the South Pacific Plume Imaging and Modeling (SPPIM) project. We compare the modeled synthetic waveforms to the observed records in individually selected frequency bands aimed at reducing local noise levels while maximizing earthquake- generated signal content. The modeled waveforms match the observations very well, with a median correlation coefficient of 0.72, and some as high as 0.95. We compare our correlation-based travel-time measurements to measurements made on the same data sets determined by arrival-time picking and ray-traced travel-time predictions, with the aim of opening up the use of MERMAID records for global seismic tomography via full-waveform inversion.

Decoding the Submarine Ambient Noise Field with Distributed Acoustic Sensing

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Microseism constitutes a major component of seismic ambient noise on Earth. However, a comprehensive understanding of its generation and propagation were limited by sparse seismic instrumentations in the ocean. Distributed acoustic sensing (DAS) is bridging this gap by enabling direct measurements of microseism sources and seafloor sedimentary structures that host the resulting noise field. In this study, we use DAS data from offshore Oregon to analyze the principal factors that modulate these vibrations, sources and site amplification. With ambient noise tomography, we obtain the subsurface velocity structures and can then calculate the relative surface wave amplification along the DAS array. The microseism source distribution can be inverted from the directional asymmetry of noise cross-correlation signal amplitudes, which determines the energy received by each DAS channel. The integration of these two effects satisfactorily predicts the power spectral density (PSD) observations. At low frequencies, the source heterogeneity is mitigated by minimal attenuation and the site amplification is dominant. Conversely, at high frequencies, the contribution from local sources becomes crucial as well, and the PSD is a composite outcome of both site and source effects. The spatial variations of noise can be explained by the interplay between the bathymetry, sedimentary structures and frequency-dependent ocean wave properties. Consequently, we demonstrate that the ambient noise field on the seafloor is shaped by both geological features below and ocean activities above. Our approach also permits a quantitative evaluation of microseism excitation and offshore site amplification at a local scale, which provides vital insight for harnessing ocean energy and assessing undersea natural hazards.

Ocean Bottom Turbulence Evolution Observed by Arrayed Obs, Dpg, and a Temperature String

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Turbulent mixing in the deep sea is not well understood due to lack of long-term in-situ observation. The breaking of internal waves on sloped seafloor topography can generate turbulence that is difficult to measure comprehensively due to its multi-scale processes, in addition to the flow-flow, and flow-topography interactions. Here we deploy a high-resolution spatiotemporal array of four ocean bottom seismometers (OBS) and a 200-m vertical temperature string at 3000-meter water depth in a footprint of 1 X 1 km, in order to characterize turbulence induced by internal waves. Each OBS is also equipped with a differential pressure gauge (DPG). We found that the OBS has recorded signals induced by near-seafloor turbulence, particularly during typhoon periods. We propose that large-scale inertial breaking has occurred with upslope transport speeds of 0.2 to 0.5 m s^{-1}. We also found evidence of small-scale bathymetry causing localized wave breaking. Data from the DPG and the temperature string also document internal waves and turbulent motions, with a frequency of 0.002 to 0.1 mHz. Applying beamforming-frequency-wavenumber analysis and linear regress to the arrayed Temperature sensor and DPG, we estimated a transport speed similar to that derived from the OBS. Arrayed OBS can provide complementary observations to characterize deep-sea turbulence.

Searching for Low-Amplitude Shallow Tectonic Tremor in Cascadia Using Buried Ocean Bottom Seismometers

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Tectonic tremor is an indicator of slow slip in the shallow portions of subduction zones, which typically lie offshore. Constraining the extent of shallow tremor is important for earthquake and tsunami hazard assessment, but offshore tremor detection is complicated by emergent oceanic signals such as T-phases, ship noise, and tremor-like signals from bottom currents. In the Cascadia subduction zone, shallow tremor has not been conclusively observed. However, offshore seismic data is limited and noisy, and previous investigations have only applied traditional land-based network methods. We explore new techniques to detect low-amplitude tremor signals using a limited ocean bottom seismometer (OBS) network. We analyze seismic data from 2014-2023 for two broadband OBS spaced 20 km apart near the deformation front at ~45.5°N on the Ocean Observatories Initiative Regional Cabled Array. The OBS are buried and collocated with bottom current meters. We find no relationship between seismic noise and bottom current speeds at either OBS, suggesting that the burial of the instruments successfully eliminates current-generated noise. We do find that background noise on both OBS is linearly related to wind speeds. We use this relationship to flag time periods with increased amplitudes in the frequency band of interest (3-10 Hz for tectonic tremor) that cannot be attributed to heightened wind speeds. Within flagged periods, we identify individual emergent signals as tremor candidates. For a test window from July 2018-July 2019, we find > 1,000 candidate 300-s detections present on both stations within flagged periods, most of which are visually assessed as T-phases. We will extend this approach to the full time period and systematically classify all candidate signals as T-phases, ship noise, or potential tremor on the basis of signal characteristics, hydrophone recordings, and comparison to regional earthquake catalogs. In addition to investigating tremor in shallow Cascadia, this will produce a labeled dataset of emergent oceanic seismic signals that can be used for detection at other offshore sites and with future networks.

Marine Seismoacoustics [Poster Session]

Poster Session • Wednesday 1 May

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POSTER 34

Pushing Boundaries With Ocean Bottom Seismometers (Obs) With a Pool-Ready System: Güralp Aquarius

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Cabled Ocean Bottom Seismometer ("OBS") solutions are economically challenging and autonomous OBS systems do not provide operators with seismic data until recovery. To address this issue Güralp has developed Aquarius, an ultra-low-power, free-fall OBS system, operational at any angle and with the ability to transmit seismic data in near-real-time from the seafloor without the use of cables.

The Güralp Aquarius incorporates seafloor-to-surface acoustic communication technology that allows state-of-health and noise performance interrogation during installation followed by retrieval of seismic data throughout the deployment period.

Omnidirectional broadband seismometer components allow the Aquarius to land and operate on steep slopes without requiring a gimbal mechanism that inherently introduces noise and failure modes. Raw data is recorded uncorrected for orientation to allow users to correct during post-processing.

These unique features allow the sensor to function on uneven seafloor as well as transmitting seismic data to the surface where the operator can use noise characteristics, location, and orientation data to determine if the landing site is suitable.

Intelligent battery design allows for typical 18-month deployments, with charging being possible alongside data transfer. This allows recharging, downloading and configuration simultaneously on the ship in between deployments.

Ease of configuration, deployment, and recovery followed by simple data processing are all central themes to the Aquarius. The capital investment required to purchase OBS systems often means that the OBS instrument must be adaptable to a range of use cases.

The Aquarius is in use in 6 different countries and is the unit of choice for the Canadian OBS pool, comprising 120 units for deployment around the globe. Aquarius units have been successfully deployed in the Mediterranean, North Atlantic as well as the North and South Pacific. Here, we focus on the mechanics of deployment and recovery for demonstrating to experienced and prospective principle investigators how this system simplifies and improves confidence in deployment.

POSTER 35

Probing Further the Cascadia Initiative Data to Detect New Offshore Events

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The Cascadia subduction zone is notorious for being seismically quiet, and its young, hot, and buoyant subducting slab may narrow the seismogenic zone. Permanent seismic networks that monitor the region rely heavily on onshore stations and a few offshore stations on the OOI Regional Cabled Array. The most spatially complete offshore dataset comes from the Cascadia Initiative (CI) experiment, which successfully deployed over 60 ocean bottom seismometers (OBS) across the entire subduction zone at ~10-month increments, providing a total of 4-5 years of temporally fragmented data. Several attempts were made to detect events. Stone et al. (2018) initially found ~271 between the coast and the deformation front events using conventional network detection methods. Morton et al. (2023) used refined techniques to expand this conventional catalog with several thousand more events but found few new offshore events near the subduction front outside of the triple junction.

Recent advancements in Deep Learning have demonstrated notable success in earthquake detection and phase picking from seismograms, particularly in challenging environments in noisy offshore OBS data. Bornstein et al. (2023) used transfer learning to re-train phase pickers on a curated data set of offshore records, and Yuan et al. (2023) employed an ensemble deep-learning approach also to improve phase picking in the same dataset. We use the latter to detect events within continuous data of the CI network. Additionally, we utilize the PyOcto phase associator developed by Munchmeyer (2023) to associate and crudely locate the events. We present the preliminary results of this search with a direct comparison between the ANSS-USGS catalogs, the Stone et al. (2018), and the Morton et al. (2023) catalogs. Preliminary results indicate that ensemble deep learning finds several additional events near the subduction front, suggesting that this method can successfully supplement conventional methods in the ocean-bottom setting.

POSTER 36

Noise on Ocean Bottom Seismometers: Observations and New Directions

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The proliferation of broadband ocean bottom seismometer (BBOBS) deployments has generated key datasets from diverse marine environments, improving our understanding of otherwise inaccessible ocean basin structure and evolution as well as tectonic and earthquake processes occurring at the plate boundaries. Recent development of community software has made these datasets more accessible and, in turn, the community of scientists using this data has expanded. This growth in BBOBS data collection is likely to persist with the arrival of new seismic seafloor technologies and continued scientific interest in marine and amphibious (shoreline crossing) targets. However, the noise inherent in BBOBS data poses a challenge that is markedly different from that of terrestrial data. Sources of noise on the seafloor, the degree to which they couple to the seismometer housing, and their variation with seafloor environment are often not well understood. Here, we compute global trends in BBOBS noise (e.g., impact of water depth and seismometer type on compliance and tilt noise), and use these observations to motivate more detailed investigations of novel instrumentation and methodologies for noise characterization and removal. This includes the utility of denoising techniques for improving ambient-noise-based imaging, comparisons of temporary broadband OBS data with permanent cabled instrumentation, and exploration of non-traditional (e.g. machine learning based) noise removal strategies.

POSTER 37

Changing Ambient Noise Patterns in the Beaufort Sea

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The Arctic Ocean is rapidly changing in response to global climate change forcings, leading to myriad impacts on the Arctic system, including its acoustic environment. As the Arctic warms, the seasonal patterns of the soundscape are disrupted, with changes to the thermohaline stratification of the water column, reduced summer sea ice extent, a transition in the morphology of sea ice toward more first-year ice, and increased exposure of the ocean to wave-generating winds. The changing ambient noise conditions in the Arctic Ocean affect ecosystems as well as our ability to use seismoacoustic data to detect acoustic sources of interest. The National Oceanic and Atmospheric Administration (NOAA) has established a hydroacoustic station in the Beaufort Sea as part of an effort to track ambient sound levels in United States waters. Records from this hydrophone contain information about geophysical, biological and anthropogenic phenomena contributing to the soundscape. In this project, we present progress toward mapping seasonal sound patterns recorded at this station and evaluating their impacts on detecting regional earthquakes recorded by the hydrophone.

POSTER 38

RBRquartz³ APT: Innovative Instrumentation for Enhanced Marine Seismic Monitoring on Ocean Networks Canada's NEPTUNE Cabled Observatory

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In collaboration with Ocean Networks Canada (ONC) and the Pacific Geoscience Centre (PGC), RBR Ltd. has developed the RBRquartz³ APT—an innovative cylindrical instrument designed to measure triaxial Acceleration, Pressure, and Temperature (APT) in underwater environments. With a compact form factor (approximately 7cm in diameter and 90cm in length), the APT is typically deployed by pushing it vertically into sub-seafloor sediment to optimize coupling and to mitigate current-induced noise. Distinguishing itself from conventional strong-motion seismometers, the APT features a broad bandwidth, extending from DC to its sampling rate limit. It is available in two configurations: a low-power serial instrument suitable for extended autonomous deployments and an advanced version equipped with ethernet and NTP timing tailored for cabled Earthquake Early Warning (EEW) applications, each supporting maximum sampling rates of 16 and 20 samples per second, respectively. Beyond its role in EEW, the APT serves as a multifunctional tool, enabling the concurrent investigation of geodetic, geodynamic, seismic, and oceanographic phenomena within a unified package.

This presentation showcases data acquired from multiple APTs operated since the prototype's initial deployment in 2015, particularly those integrated into the NEPTUNE cabled observatory as part of ONC's EEW system. A comparative analysis is conducted by comparing APT performance with conventional strong-motion measurements obtained from co-located Nanometrics Titan instruments. These insights illuminate the APT's efficacy in EEW, other seismological, and oceanogrpahic applications. Additionally, preliminary findings from autonomous APT deployments, in conjunction with RBRquartz³ BPR|zero self-calibrating Bottom Pressure Recorders are presented. These autonomous deployments are part of the Northern Cascadia Subduction Zone Observatory (NCSZO) infrastructure, focusing on monitoring tectonic deformation offshore Vancouver Island.

POSTER 39

Observations From the Seafloor: Ultra-Low-Frequency Ambient Ocean-Bottom Nodal Seismology From the Gulf of Mexico

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Large-scale ocean-bottom node (OBN) arrays of 1000s of multi-component instruments deployed over 1000s of square kilometers have been used successfully for active-source seismic exploration activities including full waveform inversion (FWI) at frequencies above 2.0 Hz. The analysis of concurrently recorded lower-frequency ambient wavefield data, though, is only just beginning. A key long-term objective of such ambient wavefield analyses is to exploit the sensitivity of naturally occurring sub-2.0 Hz energy to build long-wavelength elastic models to facilitate FWI. However, doing so requires a detailed understanding of ambient wavefield information recorded on the seafloor including the types, frequency structure and effective source distribution of recorded surface-wave modes, the near-seafloor elastic model structure, and the sensitivity of recorded wave modes to model structure. We present an ambient wavefield analysis of (ultra)low-frequency ambient data (defined as <1.0 Hz) acquired on 2712 conventional OBN stations covering 2750 km^2 of the Gulf of Mexico. After applying prestack ambient data preprocessing and cross-coherence interferometry workflows, we demonstrate that: (1) the resulting virtual shot gather (VSG) volumes contain evidence for Scholte, leaky Rayleigh and guided P-wave mode propagation between the 0.001-1.0 Hz; (2) propagation remains coherent to distances of 80 km or more; and (3) surface-wave scattering from shallow salt-body structure is present in VSG data. Overall, these observations likely have important consequences for the early stages of initial model building for elastic FWI analysis in deep-water settings.

POSTER 40

High-Resolution Acoustic Seabed Quantification with an Autonomous Underwater Vehicle

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We infer the structure and acoustic properties of muddy and sandy sediment layers along a 12-km seabed transect on the Malta Plateau in the Mediterranean Sea. The data are acquired by an autonomous underwater vehicle with a towed source and towed array of hydrophones. The source emits linear frequency modulated sweeps and the direct and bottom-reflected paths are processed in terms of reflection coefficients as a function of frequency and angle. The processing procedure accounts for path effects and beam pattern of the source. The seabed is parametrized by a sequence of one dimensional models of homogeneous layers with the number of layers treated as unknown. The homogeneous layers are considered as a porous medium via viscous grain-shearing theory. Parameter uncertainties are quantified by Bayesian inference and results are shown for sound speed, attenuation, density, and porosity. The seabed properties agree closely with core samples at two control points. The layering structure agrees closely with an independent sub-bottom seismic survey. Recovering high resolution seabed properties over large areas is shown to be feasible, which can be useful for geohazard surveys and more broadly marine industries, navies and oceanic research organizations.

POSTER 41

Implementation Plan for the Cascadia Offshore Subduction Zone Observatory

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The Cascadia Offshore Subduction Zone Observatory (COSZO) is an NSF-funded mid-scale infrastructure project that will add new geophysical capabilities to NSF's Ocean Observatories Initiative Regional Cabled Array (RCA). The Cascadia subduction zone is an endmember among global subduction systems which is characterized by warm young subducting lithosphere blanketed by thick sediment cover and a resulting seismogenic zone that is narrow and shallow. Geodetic observations and a dearth of offshore seismicity near the plate interface suggest that the megathrust is locked in many places from near the coastline to the deformation front. However, off central Oregon, the geophysical observations are consistent with a narrowly locked megathrust near the deformation front that transitions to creeping behavior beneath the shelf where there are two distinct clusters of earthquakes on the megathrust, including repeating and very low frequency earthquakes. Although the RCA was sited off Newport, Oregon to support coastal oceanography, it is well positioned to study the transition in megathrust locking off central Oregon. The COSZO project will add science junction boxes to three primary nodes on the continental slope and shelf that currently do not support seafloor geophysical observations. Each science junction box will host a sensor suite comprising a buried broadband seismometer, strong motion accelerometers, a low-frequency hydrophone, a pressure gauge, calibrated pressure sensors and a current meter, and include open ports for additional sensors. A fourth broadband seismometer and strong motion accelerometer will be added to an existing science junction box at another site on the shelf. Together with the seismometers and pressure gauges already on the OOI RCA at the Slope Base and Southern Hydrate Ridge sites, this infrastructure will form a pioneering "critical mass" offshore geophysical observatory to study fault coupling and deformation of the Cascadia megathrust and the overlying accretionary prism across a ~100 km section offshore and support efforts to prototype offshore earthquake and tsunami early warning.

POSTER 42

CHIRP Acoustic Reflection Imaging: Toward Improved Signal Processing in Extant Glacial Lakes

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Compressed-High-Intensity-Radar-Pulse (CHIRP) acoustic reflection data acquired in lakes and other shallow water areas are generally recorded as an amplitude envelope for each trace. This format allows real-time imaging and optimizes planning for rapid follow-up invasive sediment sampling; however, improving the signal-to-noise ratio in this format using typical vendor visualization software is generally limited to simple gain and bandpass filtering functions. The resultant images are often capable of providing a usable representation of the shallow sub-bottom geology, but we find further signal processing (e.g., migration, weighted trace mixing, and/or FX deconvolution, etc.) can significantly improve overall image quality and provide enhanced ability to discriminate and interpret subtle earthquake-related features, as well as provide better comparisons with synthetic seismograms. However, these additional processing steps are precluded by the amplitude envelope format. To overcome this constraint, we calculate the first derivative of the amplitude envelope and apply a bandpass filter (and sometimes rotation) to simulate a representative full-reflection amplitude waveform, thus allowing it to be imported into seismic data processing software for the widest range of signal-to-noise enhancement algorithms. For investigators without access to, or expertise with, more sophisticated signal processing programs, these simple fundamental procedures are often also available in many seismic interpretation software packages. We provide examples of our processing workflow from two glacial lake basins in the western United States with a history of seismic hazards: Convict Lake (Sierra Nevada, California) and Jackson Lake (Grand Teton National Park, Wyoming). Both lakes have steep margin-adjacent topography and prominent axial deltas conducive to slope failures, which appears to help shape sub-lacustrine depositional processes during earthquakes. Extensive CHIRP and long sediment core datasets from these lakes, which differ considerably in bathymetric and stratal characteristics, provide the feedstock for method validation.

Multidisciplinary Approaches for Volcanic Eruption Forecasting

Oral Session • Thursday 2 May • 2:00 PM Pacific

Conveners: Alberto Ardid, University of Canterbury (alberto.ardid@canterbury.ac.nz); Francesca Bianco, Istituto Nazionale di Geofisica e Vulcanologia (francesca.bianco@ingv.it); Társilo Girona, Alaska Volcano Observatory, University of Alaska Fairbanks (tarsilo.girona@alaska.edu); Janire Prudencio, Universidad de Granada (janire@ugr.es)

Fracture Insights and Predicting Failures: Acoustic Emission Study in Peteroa Volcano's Basalt Rock

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Acoustic Emission (AE) is a valuable non-destructive testing method for detecting and analyzing elastic waves that occur in a material subjected to external forces. This research is acutely attuned to the significance of AE in the context of volcanic monitoring and focuses on the application of AE in the study of Basalt rock samples extracted from the Peteroa volcano in Argentina. Uniaxial compression tests were performed on these rocks to investigate their fracture properties under different stress states until reaching failure. AE signals were continuously recorded during the experiments and AE parameters were utilized to evaluate the rock's fracture process. Also, 3D location of AE events was performed to monitor damage and map microfractures. Additionally, secondary AE parameters FM/RA, entropy, b-value, AE energy b-value and energy for frequency band were employed to predict and classify fracture modes, distinguishing between tensile and shear-dominated fractures. The analysis of accumulated AE hits and their correlation with the applied force-time curve revealed a significant increase in AE emission rate and energy around a specific critical loading level (2/3 load max approx) indicating a progressive damage of the rock specimen, possibly associated with microfracturing. Furthermore, a decrease in the AE event rate was observed when the force remained constant, suggesting changes in fracture activity during the compression process. Overall, the accumulated AE hit counts proved to be a better indicator of intermediate damage than the accumulated energy, showcasing their potential in tracking the evolution of compression-induced damage in the rock. The 3D localization of AE events was conducted using the Simulated Annealing algorithm. To improve localization accuracy and mitigate noise interference, a novel technique utilizing the Akaike information criterion (AIC) on modes obtained through Empirical Ensemble Mode Decomposition (EEMD) of AE signals was applied.

Small Earthquakes Matter for Triggering Volcanic Unrest

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The occurrence of large earthquakes often inspires questions about their potential to trigger volcanic unrest. Most prior studies that address these questions focus on case studies of a single earthquake and its impact on a specific eruption or on changes in eruptive activity at all volcanoes within a certain distance. Instead of this earthquake-centric strategy we take a novel volcano-centered approach, in which we compare volcanic activity at a single volcano with a calculated, continuous time series of stress changes due to all potentially impactful earthquakes. This approach accounts for the facts that the amplitudes of stress changes from small to large earthquakes are comparable within near-field distances, which roughly scale with earthquake source dimensions, and that the numbers of earthquakes increases as magnitude decreases. We assume any stress change smaller than typical, ever-present, tidal values of ~0.01 MPa may be neglected, and consider spatial decays consistent with earthquake-generated static, quasi-static, and dynamic stress changes. Noting that stresses may relax over time, particularly in volcanic systems, we also consider a range of temporal decay rates, and we remove earthquakes close to the volcano that are likely to be driven by the magmatic system itself.

Our approach is general, and we have tested it on the Turrialba, Costa Rica and Redoubt, Alaska volcanoes, which have different tectonic settings and eruptive styles. Turrialba has been persistently active since 2010, while Redoubt has had two short-lived eruptive phases within decades of quiescence. Although we calculate stress changes using a very simple model, preliminary results for a range of plausible models show the summed stresses from smaller earthquakes closer to a volcano may be more perturbing than the stress from a single or a few larger more distant earthquakes, particularly if considering dynamic stress changes. Connecting earthquake-generated stress changes with volcanic unrest may be more complex than previously thought.

Toward Unbiased Volcano-Seismic Monitoring: Leveraging Weakly Supervised Learning for Comprehensive Insights

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Real-time monitoring of volcano-seismic signals presents a multifaceted challenge. Typically, automated systems are constructed through the assimilation of vast seismic catalogues, wherein each entry is accompanied by a label denoting its source mechanism. However, the creation of comprehensive catalogues is hindered by the prohibitive cost associated with data labeling. Although current machine learning techniques have demonstrated considerable success in crafting predictive monitoring tools, reliance on catalogue-based learning introduces potential bias to the system.

In our study, we demonstrate that while monitoring systems successfully identify nearly 90% of events annotated in seismic catalogues, they may overlook additional information crucial for understanding volcanic behavior. We discovered that weakly supervised learning approaches exhibit exceptional capabilities by simultaneously identifying unannotated seismic traces in the catalogue and rectifying mislabeled entries. By incorporating a system trained with a master dataset and catalogue as a pseudo-labeller within the framework of weakly supervised learning, we unveil and update information pertaining to volcanic dynamics.

Our findings suggest the potential for advancing more sophisticated semi-supervised models to enhance the reliability of monitoring tools. For instance, the exploration of advanced pseudo-labelling techniques involving data from multiple catalogues could be pursued. Ultimately, this research paves the way for the development of universal monitoring tools capable of accommodating unforeseen temporal changes in monitored signals across various volcanic settings.

Volcanic Eruption Forecasts Through Seismic Data Assimilation: The 2023 Paroxysms of Shishaldin Volcano, Alaska

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Establishing connections between geophysical observables and subsurface processes is critical for detecting volcanic unrest and anticipating eruptions. One of the most important observables to monitor pre-eruptive volcanic activity is tremor, a more or less persistent ground vibration often recorded at active volcanoes. Tremor may manifest or alter its characteristics before eruptions; for instance, variations in the dominant frequency, the appearance or disappearance of overtones, and changes in seismic amplitude have been observed before eruptions. Nevertheless, similar variations can also occur during non-eruptive periods or when volcanic activity decreases. Consequently, this raises important questions: How does tremor reflect subsurface overpressure? Can we deduce alterations in pressure underneath volcanoes by monitoring tremor? This study introduces a novel data assimilation framework that integrates seismic data, a physics-based model of volcanic tremor, an optimization approach utilizing genetic algorithms, and time series modeling based on neural networks to track volcanic pressure changes and to produce physics-based eruption forecasts. Specifically, our physics-based model (an extension from Girona et al., 2019; https://doi.org/10.1029/2019JB017482) presumes that tremor occurs when gas randomly enters shallow levels of the volcanic plumbing system, accumulates temporarily in the subsurface, and transfers to the surface via permeable flow. The performance of our framework is examined by analyzing the recent 13 paroxysms of Shishaldin Volcano, Alaska, between July and November in 2023; these paroxysms are ideal for testing our approach as they were heralded by variations in tremor. Our framework suggests that the recent Shishaldin paroxysms resulted from a combination of magma ascent, escalating gas flux, and conduit sealing, leading to pressure increases of up to several MPa and increases in eruption probability within hours to the events. This data assimilation strategy exhibits promising potential to produce physics-based eruption forecasts from seismic tremor data in near-real-time.

Source Mechanism and Catalog Statistics for the Last Decade of Seismicity at the Campi Flegrei Volcanic Complex, Italy.

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Over the past two years, the rate, spatial extent and magnitude of seismicity affecting the Campi Flegrei volcanic complex (Italy) have increased dramatically, accompanying ground uplift of up to 15 mm/month. Moment tensor solutions for the most significant (Md > 3) earthquakes indicate a dominance of double-couple (DC) and compensated linear vector dipole (CLVD) mechanisms. The statistical significance of these results is however questionable, and for about 80% of the cases a simple DC mechanism is sufficient to explain the data. The clustering properties of the catalog are investigated through the nearest-neighbor distances (NND) in a combined space-time-magnitude metric. The early stages of the sequence are characterized by a bimodal pattern of NNDs, associated with the background seismicity occurring at large inter-event times and distances, and clustered events separated by short temporal and spatial ranges. Such bimodal behavior is typical of environments where seismicity is purely driven by tectonic loading. Conversely, for the most recent seismicity the distribution of NNDs merges into a single-mode pattern, similar to what has been observed at Long Valley Caldera (US) and interpreted in terms of upward migration of volatile-rich volcanic fluids. The b-value of Gutenberg and Richter's distribution does not vary significantly over time, and the same holds for Vp / Vs ratio. The thickness of the seismogenic layer exhibits significant lateral variations, with no clear correlation with the deformation pattern. All these elements suggest that seismicity is mainly driven by the combination of tensile failure in the central portion of the deforming area, and stress accumulation along pre-existing mechanical discontinuities at its border. The lack of long- and/or very-long-period seismicity, and the significance of double-couple components, indicate that either magmatic or hydrothermal fluids are not playing an active role in the seismogenic process. Nonetheless, fault weakening and/or rupture triggering by fluid pore pressure increase cannot be excluded.

Resonance in the Earth's Crust as a Generation Mechanism of Very-Long-Period Volcanic Tremor

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Volcanic tremor indicates subsurface magma transport in the conduit and along sills. As a known precursor to volcanic eruptions, along with increased gas emissions and ground deformation, these signals have great value for eruption forecasting. Volcanic tremor contains a unique feature in the very-long-period (VLP) range of approximately 10 s, where the sustained vibration is harmonic and can persist for several cycles. Interestingly, these VLP features are consistent across different volcanic edifices. Here, we show that VLP tremor corresponds to distinct seismic resonance in the thin plate of the Earth's crust decoupled by subsurface sills filled with molten magma. The feasibility of the excitation mechanism is validated through a consistent theoretical prediction of VLP spectra at Aso, Stromboli, Kilauea, Erebus, and the newly-discovered underwater volcano near Mayotte, as well as through consistent magma viscosities obtained via petrological analysis. As well as magma viscosity, tremor amplitude is strongly influenced by the cross-sectional dimensions of the magma conduit. This research demonstrates that volcanic tremor is a direct indicator of pressure variations in the magma chamber that can be used to forecast volcanic eruption intensity. In addition, this study illustrates a geophysical method for evaluating subsurface magma viscosity.

Volcanic Eruption Forecasting Using Shannon Entropy: 2021 Tajogaite Eruption (Spain)

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Recent eruptions such as the one that occurred in La Palma (Spain, 2021) have demonstrated how small eruptions disrupted the economy, environment, and human systems, proving how vulnerable we are to these phenomena. Despite technological advances, it remains unclear if and when melt will solidify at depth or ascend into shallower systems and lead to eruptions. Thus, one of the grand challenges of volcanology is to make accurate volcanic forecasts to reduce volcanic risk. Many volcanological observatories count on how many events are recorded to make a probabilistic forecast, therefore, they focused their efforts on automated event detectors and classifiers. Another approach to forecasting volcanic eruptions is to analyze geophysical data to detect changes or patterns that can be used as precursor elements of a possible volcanic eruption.

Previous work from Rey-Devesa et al., (2023a,b) has shown that pre-eruptive variations in Shannon Entropy are a confident short-term volcanic eruption forecasting tool. SE is a statistical quantifier introduced in the framework of Information Theory and indicates the level of randomness in a system. The range of possible values of SE is between 0 and 1; SE is 0 if all the available data belong to the same class, in this case, it is possible to predict the class of new data; the highest SE value is obtained when the probabilities of all the class is the same.

In this work, we study the evolution of SE before and during the 2021 Tajogaite eruption in La Palma (Canary Island, Spain) from January 2021 to December 2022. The results show that the SE drops several hours before the eruption starts and increases when the eruption ends. Hence, SE could be used as a complementary tool in seismic volcano monitoring, showing its successful behavior before eruptions, giving time enough to alert the population and prepare for the consequences of an imminent and well-predicted moment of the eruption.

Automated Identification and Characterization of Very Long-Period Seismic Events for Applications in Monitoring Volcanic Activities.

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Real-time applications in seismology play a crucial role in monitoring and surveilling active volcanoes, serving as invaluable tools for the early detection of volcanic unrest. Particularly at open-vent active volcanoes like Stromboli in Italy, the identification of Very Long Period (VLP) seismicity is essential. VLP seismicity, often associated with mild and persistent explosive activity, holds significance in volcano monitoring, with variations in occurrence rate and magnitude serving as potential precursors to an eruption.

In this study, we present a novel method for the automatic real-time detection and characterization of VLP seismicity at Stromboli. The detection algorithm relies on Three-Component Amplitude (TCA), derived from waveform polarization and spectral analysis of continuous recordings. This approach provides crucial information such as time of detection, azimuth, incidence, amplitude, and frequency of the identified VLP events.

Furthermore, VLP amplitudes obtained from all monitoring network stations, presented as peak-to-peak amplitudes and mean square amplitudes, are employed for an automated localization of the seismic VLP source. The results of our automatic detection algorithm are then compared with those obtained through manual and automatic inspections of seismic records, as well as with VLP time histories from existing published datasets.

The comparative analysis reveals that the VLP detection time series generated by our automatic algorithm effectively mirrors fluctuations in VLP activity observed manually by operators over an approximately 20-year period. This success allows for the integration of our approach into the real-time processing framework employed at Stromboli for ongoing volcano surveillance.

Volcanic Eruption Forecasts Through Seismic Pattern Recognition: The 2023 Paroxysms of Shishaldin Volcano, Alaska

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Identifying patterns within geophysical data is critical for the detection of volcanic unrest and the forecasting of eruptions. Seismicity, encompassing volcano-tectonic earthquakes, long-period events, and tremor, among other geophysical signals, provides pivotal information about the state of unrest of a volcano. Tremor, specifically, tends to exhibit variations in its characteristics during eruption run-up, including changes in dominant frequency, the emergence or disappearance of overtones, and fluctuations in seismic amplitude. These variations raise the following question: Can we consistently quantify the probability of eruption based on the recognition of seismic tremor patterns? To address this question, we introduce a pattern recognition based-framework (building upon the work of Dempsey et al., 2020 [https://doi.org/10.1038/s41467-020-17375-2]; Ardid et al., 2023 [https://doi.org/10.21203/rs.3.rs-3483573/v1]; and Girona and Kyriaki, *In Review*) that merges seismic features from tremor data (e.g., dominant frequency, kurtosis, seismic amplitude, Shannon entropy) with several supervised machine learning models and Monte Carlo simulations to estimate the probability of an imminent eruption and its uncertainty. In particular, our framework integrates logistic regression, k-nearest neighbors, linear discriminant analysis, decision trees, random forest, support vector machine, and neural network models; and is designed to enable retraining, automatically updating the models whenever a new paroxysm takes place. The performance of our approach is assessed using the recent 13 paroxysms of Shishaldin Volcano, Alaska, occurring from July to November 2023, all of which were preceded by seismic tremor with escalating amplitude. We find that our framework captures successfully the seismic data trends that correlated with imminent paroxysms, reflected in a noticeable and consistent increase in the probability of eruption before the actual eruption occurs. This strategy exhibits promising potential for producing near real-time probabilistic eruption forecasts based on the recognition of patterns in seismic tremor data.

Enhancing Eruption Forecasting at Axial Seamount With Real-Time, Machine Learning-Based Seismic Monitoring

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Axial Seamount, an extensively instrumented submarine volcano, lies at the intersection of the Cobb-Eickelberg hot spot and the Juan de Fuca Ridge. Since late 2014, the Ocean Observatories Initiative (OOI) has operated a seven-station cabled Ocean bottom seismometers (OBS) array that captured Axial's last eruption in April 2015. This network streams data in real-time, facilitating seismic monitoring and analysis for volcanic unrest detection and eruption forecasting. In this study, we introduce a machine learning (ML) based real-time seismic monitoring framework for Axial Seamount. Utilizing both supervised and unsupervised ML techniques, we constructed a comprehensive, high-resolution earthquake catalog, and effectively discriminated between various seismic and acoustic events. These signals include earthquakes generated by different physical processes, acoustic signals of lava-water interaction, and oceanic sources such as whale calls. Notably, our unsupervised ML analysis revealed two subgroups of earthquakes that have different spectral features and spatiotemporal behavior before and during the 2015 eruption. We interpret them as being driven by two distinct mechanisms: earthquakes on the caldera ring faults triggered by tidal stress changes, and mixed frequency earthquakes (MFEs) generated by brittle crack opening followed by influx of magma or volatile. Our system integrates ML- and double-difference based catalog construction and semi-supervised event classification in real time. Operational since 2022, it enables the discrimination and tracking of different seismic events as they occur, including precursory MFEs that potentially indicate the preparation of an eruption and seafloor impulsive events that can be used to track magma outflows during an eruption. The high-resolution earthquake catalog and real-time analysis capability complement the current deformation-based long-term forecasting methods, providing valuable short-term constraints that may enhance eruption forecasting at Axial Seamount and potentially other volcanoes.

Multidisciplinary Approaches for Volcanic Eruption Forecasting [Poster Session]

Poster Session • Thursday 2 May

Conveners: Alberto Ardid, University of Canterbury (alberto.ardid@canterbury.ac.nz); Francesca Bianco, Istituto Nazionale di Geofisica e Vulcanologia (francesca.bianco@ingv.it); Társilo Girona, Alaska Volcano Observatory, University of Alaska Fairbanks (tarsilo.girona@alaska.edu); Janire Prudencio, Universidad de Granada (janire@ugr.es)

POSTER 46

Information Theory in the Context of Volcano Seismic Singals for Forecasting Purposes

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Information Theory is a field that addresses how to send and reconstruct messages, through a noisy channel, with low probability of error, and how to quantitatively measure the information contained in this message. Studies performed by Nyquist and Hartley, found that, logarithmic function is the most appropriate to measure the amount of information contained in a message. Shannon complete these studies and propose the Entropy as the measure of the information of a random variable, were each of the possible outcomes of the variable has a defined probability of occurrence and the value associated with the outcome is aleatory.

Important word in Information theory are: *Information* is related with the knowledge obtained when a specific event is observed, for example, realizations of a random variable with low probability are less expected and give more information that one with high probability. *Uncertainty* is the amount of information we expect an experiment to reveal. For uniform probabilities distribution the result is unpredictable and the uncertainty is maximum, and if the distribution of probabilities is more concentrated then the result is more predictable and there is a lower uncertainty. *Entropy* indicate the amount of uncertainty associated with a variable when only its distribution is known. The entropy provided a mathematical way of determining the information contained in a message. In the context of Information Theory, the Information is independent of the previous knowledge and only depend of the source via the probability function of each of the symbols issued.

We propose the application of different definitions of entropy proposed in the literature to the time series of seismic signals of volcanic origin. Taking into account previous works developed, we consider that it is of interest to study the evolution throughout the different evolutionary periods of volcanoes. We propose the comparative study of differential entropy, Shannon entropy, approximation entropy and Rényi entropy.

POSTER 47

Unraveling Dynamical Influences on Volcanic Structures Through Seismic Signatures

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Detecting the transition from volcanic quiescence to unrest is a crucial but challenging task for volcano monitoring agencies. Using insights drawn from continuous seismic records, this study explores the long-term dynamics of two volcanoes with the goal of tracking the transition to renewed activity. First, we investigate seismic velocity changes (dv/v) over time through cross-correlation of ambient seismic noise using the MSNoise package [Lecocq et al. 2014; https://doi.org/10.1785/0220130073] with the Wavelet Cross-Spectrum method [Mao et al. 2020; https://doi.org/10.1093/gji/ggz495]. Second, we examine the kernel sensitivity of the surface waves to identify potential depths related to dv/v changes based on wave frequency and realistic velocity models. Finally, we estimate the associated seismic attenuation to identify subsurface stress changes over time.

By applying these methods to our case studies, we observe and compare different behaviors, which highlights the importance of continuous monitoring of subsurface variations over time. For instance, we found a decreasing trend of dv/v at around 2 km depth since August 2021 beneath Askja volcano (Iceland), coinciding with an uplift of up to 65 cm by September 2023 and with an increased seismicity rate. The sudden shift in the trend of dv/v contrasts with the gradual long-term deflation that has been observed in the last few decades.

The 2016 Kumamoto earthquake impacted the Aso volcano in Japan, causing a decrease in dv/v of 0.5%. The seismic velocity changes suggest a healing process initiated post-earthquake, which stopped 6 months after with Aso eruption (0.3% dv/v drop).

During the summer of 2021, there was seismic unrest at Gareloi (Alaska) [AVO website, 2005; https://avo.alaska.edu]. This unrest was detected with the appearance of tremors in addition to persistent long-period activity. The dv/v result confirmed this observation with a 1% drop around 3 km depth. This helps to establish a baseline for normal volcanic behavior and contextualize observations, with the aim of characterizing the seismic signatures and changes associated with volcanic unrest.

POSTER 48

Simulating Ground Deformation From Magma Migration Utilizing a Dipole Source

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The ability to detect and monitor magma movement in volcanic areas is vital for predicting eruptions and mitigating associated risks. This research focuses on the simulation of ground deformation resulting from magma migration using a new dipole source within volcanic regions. Typically, predictive models, either analytical or numerical, incorporating internal Earth forces such as pressure and volume changes, are employed to infer ground deformation. Dynamic patterns associated with volcanic deformation sources, such as inflation and deflation for volumetric sources, and opening and closing for dyke-type sources, are well-established. This study seeks to present an analytical solution for surface deformation caused by the migration of a volumetric source, specifically applicable to minor movements in an elastic half-space. The proposed model resembles a volumetric dipole, characterized by an oriented axis connecting the source's initial and final positions. This approach facilitates the modeling of ground deformation based on source migration, and the estimation of source migration from measured ground deformation through data inversion. To evaluate the dipole solution, a comparison is made with the fundamental volumetric source in terms of its peculiarities, capabilities, and applicability. The examination of continuous deformation data from GNSS stations on Mt. Etna discloses that a dipole source becomes active several days prior to the December 2018 eruption, providing valuable insight into the identification of the final magma ascent.

POSTER 49

Surface-Wave Relocation and Characterization of the October 2023 Izu Islands, Japan Earthquake Swarm

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From October 1-8, 2023, a moderate-magnitude ($4.1 < M <= 6.1$) earthquake swarm occurred in the Izu Islands region of Japan. The swarm included 151 shallow events (depth < 30 km) catalogued by the U.S. Geological Survey and was categorized by three $M >= 6$ earthquakes and a cluster of 15 M 4.3 to M 5.4 earthquakes. Many of the earthquakes in the final cluster generated subsequent T-phases and were associated with tsunami waves, one of which had a maximum amplitude of 60 centimeters. However, tsunamigenesis for moderate-magnitude earthquakes is unlikely and suggests that the ocean displacements were generated from a volcanic or landslide source. Shallow-depth earthquakes in the Izu Islands region occur near seamounts and volcanic islands, but the precise characterization of volcano-related seismicity can be challenging with no local seismic monitoring. Leveraging a surface-wave relative relocation approach, we estimated precise epicentroid locations of seismic events from the swarm using over 100,000 regional-to-teleseismic surface-wave relative time shifts. Epicentroid locations show a north-northwest migration of earthquakes over eight days that initiated to the west of the Sofugan seamount. Moment tensor solutions for several swarm events are consistent with normal-faulting source mechanisms, while others are consistent with a vertical tension axis compensated-linear-vector-dipole (CLVD). The locations of epicentroids with CLVD mechanisms relative to those with normal-faulting mechanisms suggest the presence of two different but concurrent volcanic processes. The linear positioning of the normal-faulting events and the presence of CLVD mechanisms are consistent with diking activity and caldera collapse, respectively. Our relative relocation analysis of the Izu Islands swarm demonstrates the ability of surface-wave analysis to measure volcanic unrest and characterize subsequent volcanic behavior. Implemented in near real-time, surface-wave relative relocation may improve volcano monitoring efforts by providing more precise earthquake locations, time history, and characterization of seismicity in remote areas.

POSTER 50

The Relationship Between a 2022-2023 Magmatic Intrusion at Aniakchak Caldera and the 2021 m8.2 Chignik Earthquake, Alaska

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A sequence of earthquakes at Aniakchak Caldera (AC), Alaska, began in October 2022 and was accompanied by rapid ground deformation, first observed in February 2023. AC is located only ~160 km from the epicenter of the July 2021 M8.2 Chignik megathrust earthquake, for which co-seismic fault slip >6 m has been modeled; the observed immediate rapid postseismic afterslip slowed in early 2022. This spatio-temporal relationship, especially if considering down-dip afterslip, motivates us to ask whether the Chignik earthquake and its postseismic deformation contributed to the unrest episode at AC, and why the neighboring Veniaminof Caldera, with an eruption in April 2021, has shown no or only very recent (Dec 2023-Jan 2024 deep-long period events) unrest? This is in line with global statistical analyses (e.g., Nishimura, 2021), which suggest that eruption likelihood doubles within 5 years for volcanoes within 200 km of M>7.5 earthquakes.

Our L-band interferograms spanning 2022-2023 resolve >60 cm LOS shortening inside the Aniakchak caldera and GNSS installed in summer 2023 recorded the stop of deformation in September 2023. We can explain the deformation with a shallow spheroidal inflation source centered under AC at ~2.8 km depth with a volume change of about ~28 Mm3. Static normal stress (tensile) increased at both calderas after the Chignik event (0.1-0.3 MPa), suggesting unclamping, which is favorable for magma ascent / bubble formation. While AC earthquakes relocated with a revised velocity model show that DLP events started a few weeks after the Chignik earthquake, eventually culminating into shallow volcano tectonic earthquakes, the full catalog spanning 1997-2023 contains sequences of DLP events without large earthquakes, providing only a weak first order link between the earthquake and volcanic unrest. Here, we explore connections between the earthquake and the magmatic unrest through modeling of time-delayed magmatic processes such as bubble formation and magma migration. We furthermore investigate the impact of postseismic deformation and related additional tensile stress increase on these processes.

POSTER 51

Characterization of the Onset of the 2021 Great Sitkin Dome-Building Eruption Through the Trans-Dimensional Bayesian Inversion of LP Seismicity

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Long-period (LP) volcanic seismicity and tremor are thought to be triggered by the subsurface transport of magmatic and/or hydrothermal fluids. A mechanistic model of LP events and tremor, called the "leaky gas pocket model", was proposed by Girona et al. (2019). This model shows that the transport of gas through permeable materials (e.g., lava domes) triggers spontaneous LP/tremor-like pressure oscillations. Building upon the leaky gas pocket model, our project addresses two key questions regarding LP seismicity and its relation to volcanic activity: (1) To what extent can the leaky gas pocket model accurately elucidate the physical properties of a volcanic dome? (2) Can the variation of physical properties during the onset of a dome-building eruption be explained by the inversion of LP seismicity? To explore these questions, we integrate the leaky gas pocket model with a reversible-jump (trans-dimensional) Markov Chain Monte Carlo (RJ-MCMC) framework to invert LP seismicity recorded during the early-stages of the 2021 dome-building eruption of Great Sitkin volcano (Alaska). With this approach, we aim to comprehensively quantify the probability density function of the model parameters for each LP event; these parameters include dome thickness and permeability, gas flow rate and temperature, and seismic attenuation factor, among others. Our preliminary results suggest a gradual accumulation of gas beneath the dome and a possible decrease of dome thickness around the start of the eruption (July 23, 2021). This is consistent with a pre-eruptive gas accumulation and pressurization in the shallow volcanic conduit, which we determine in the range from ~10^2 Pa to ~10^4 Pa. The gas flow rate is constrained within the range from 5 ton/day to 200 ton/day, representing the minimum amount of gas supplied to the base of the dome (more gas might be released with no contribution to seismicity). Our analysis represents a pioneering physics-based approach to infer the properties and conditions of volcanic interiors from the inversion of seismic data.

POSTER 52

How Is Differential Shannon Entropy Related to Volcanic Processes?

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Previous studies show that Shannon Entropy (SE) calculated on continuous seismic records can be used to track unrest and eruptive activity at active volcanoes (Rey-Devesa et al., 2023 a, b). SE usually remains constant, and decays for a short-term period before an eruption occurs, reaching minimum values just in the run-up to a paroxysm. This has been observed in a large set of different volcanoes around the globe, although it remains unclear how SE relates to physical processes and how it can be used for improving routine forecasting strategies.

SE, or Differential Shannon Entropy (DSE) when the source is continuous, is used in information theory to understand the uncertainty of a source of information (Shannon, 1948). The uncertainty is related to the amount of information required for describing the next element in a sequence, or how predictable a sequence is. Thus, a very probable event is translated as a low value of uncertainty and DSE. In this context, we can interpret the decay in the DSE of the seismic signal as an indicator of a reorganization happening in the volcanic system, approaching an eruptive outcome. However, in the real-time monitoring scenario, the performance of the feature needs some fine-tunning, since signals usually contain different types of noise (wind, tides, and storms) that can also generate a decay in the DSE.

In this work, we propose a synthetic analysis of the DSE, studying how it varies with the type and characteristics of noise. The goal is to identify if DSE can detect changes in the systematic noise. In addition, we apply the conclusions to a real-life scenario, the eruption of Shishaldin in 2023, associating every decay of the DSE in one year record to different sources or external processes.

Preliminary results show that more predictable noises imply lower values of DSE. We also see that the amplitude of the decay and the frequency band containing the energy of the signal are relevant features to associate the decay with their sources.

A better understanding of DSE and its evolution is crucial for improving the quality of the DSE as a volcanic eruption monitoring tool.

POSTER 53

Systematic Investigation and Comparison of the 2018 and 2020 Kīlauea Volcano Eruptions Based on Ambient Seismic Noise Analysis

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Detection of precursors for volcanic eruptions is crucial for mitigating the soci- etal and environmental impacts of these destructive geological hazards. Seismic ambient noise analysis has become increasingly popular for revealing temporal velocity variations before and after volcanic eruptions. These variations may inform us of crustal perturbations due to the movement of magma, gas, or flu- ids. In 2018, Kīlauea volcano in Hawai'i experienced its largest Lower East Rift Zone eruption and summit caldera collapse in at least 200 years. After just over a year of quiescence, its summit underwent a series of much smaller eruptions from December 2020 to September 2023. In this study, we systematically investigate and compare the 2018 and 2020 eruptions by applying seismic ambient noise analysis.

We download continuous waveform data from the Incorporated Research Institutions for Seismology (IRIS), recorded by the Hawaiian Volcano Obser- vatory broadband seismometers in the summit area and the Middle East Rift Zone (MERZ) of Kīlauea. After pre-processing of the data, we perform the stretching technique to solve for velocity changes from 2015 through 2023. We find that while there are velocity decreases for the summit stations during the 2020 eruption, they are significantly smaller than those corresponding to the 2018 eruption. We also observe large variations for the MERZ stations during the 2020 eruption, indicating magma presence and migration. Our results sug- gest that combination of horizontal and vertical components in cross-correlation analysis can provide additional knowledge on magmatic activity. In addition, our estimated velocity variations are larger than those from previous studies in general. GPS and InSAR data are integrated to provide further analysis of our results. Our study illustrates how the subsurface velocity structure varies in response to volcanic eruptions and may offer new insight into how a volcano readjusts itself after a large eruption.

POSTER 54

Real-Time Seismic Estimation of Vei: Improving Reduced Displacement & Introducing the Mvo Energy Magnitude Scale

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The Volcanic Explosivity Index (Newhall and Self, 1982) was conceived as a crude magnitude scale for past volcanic eruptions, based on field observations such as volume of material ejected, and eruption column height. Within days of the Hunga Tonga eruption in January 2022, there was online discussion about whether to classify it as a VEI 5 based on erupted material (with an unknown volume in the ocean) or VEI 6 based on pressure and gravity waves that propagated many times around the globe, similar to the VEI 6 eruption of Pinatubo in 1991. There were also attempts to estimate VEI based on seismic data. However, these were not new, as there were previous attempts to correlate ash column height with seismic amplitude (McNutt 1994) using a measure called "reduced displacement", which was described as "a magnitude scale for volcanic tremor". Moreover, in year 2000 a real-time volcano-seismic magnitude scale was implemented at the Montserrat Volcano Observatory. Reduced pressure is another measurement that can be used when infrasound or barometric data are available. We propose a simple seismo-acoustic VEI estimator based on reduced displacement, reduced pressure, and energy magnitude, and have implemented these as part of a Python/ObsPy package.

Network Seismology: Recent Developments, Challenges and Lessons Learned

Oral Session • Wednesday 1 May • 2:00 PM Pacific

Conveners: Blaine Bockholt, Idaho National Laboratory (blaine.bockholt@inl.gov); Renate Hartog, University of Washington (jhartog@uw.edu); Kristine L. Pankow, University of Utah (pankowseis2@gmail.com); Adam Ringler, U.S. Geological Survey (aringler@usgs.gov); Dmitry Storchak, International Seismological Centre (dmitry@isc.ac.uk)

ISC: Collaborating With Seismic Networks Worldwide

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The mission of the International Seismological Centre (ISC) is to produce the most long-term and complete Bulletin of instrumentally recorded seismicity on a global scale by running parametric data exchange with ~150 seismic networks in ~100 countries. We also take additional measurements from publicly available waveforms to improve event source parametrization. For instance, we aim to better constrain the depths of moderate to large seismic events by taking the depth phase arrival time measurements and calculating Probabilistic Point Source Model solutions (ISC-PPSM). We also started taking automated IASPEI-compliant amplitude and period measurements to complement similar measurements supplied by networks.

In addition, we produce a number of data products that stem from the ISC Bulletin and allow the ISC to assist several areas of research. These include the ISC-EHB dataset (1964-2021), ISC-GEM catalogue (1904-2019), IASPEI Reference Event List (GT, 1959-2020) and ISC Event Bibliography (1904-2024). We also maintain supplementary services: the Electronic Archive of Printed Station/Network bulletins, the International Seismological Contacts, and the ISC Dataset Repository. We look forward to further extending our collaboration with both permanent and temporary networks worldwide.

The International Monitoring System Sustainment: A Technical Strategy

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The International Monitoring System (IMS) of the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) consists of 170 seismic, 60 infrasound, 11 hydroacoustic, 80 radionuclide stations and 16 radionuclide laboratories. Currently, the network is 90% complete. The network was initially developed, and deployment began in 1996 when the Treaty was opened for signature. During the first 12 years, the focus was on the installation and certification of the stations; operation and maintenance have been part of the daily focus of the IMS. However, after 25 years of continuous operation, many stations are reaching the end of their life cycle and will need recapitalization. Therefore, a mid- and long-term sustainment strategy has been developed. This work will present the technical basis for such a strategy. In the first place, the goal is to identify the status of each station and to assess the risk of downtime in the next two years, six years, and beyond. Then, prioritization takes place to define an action plan for the two immediate years and a foreseen scenario for the mid- and long-term strategy. The stations' status and risk assessment are done every six months, and the action plans are reviewed annually.

The Chilean Seismic Network: An Update

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More than 500 instruments (accelerometers, BB, and GNSS devices), comprise the National Seismic Network, of which 118 are six-component (BB + strong ground motion) transmitting their data in real-time to the Data Center. The network includes two devices installed on the Chilean Pacific Islands, one station in the Antarctic Peninsula, and those stations that are part of the Integrated Plate Boundary Observatory in northern Chile (IPOC).

The main mission of the CSN is to rapidly characterize -within 5 minutes of O.T.- the location and size of earthquakes M≥3.7, particularly those that could generate tsunamis. Because the main thrust region is mostly concentrated between the trench and the coast, with an average width of about 150 km, the monitoring system is distributed all along the country and includes real-time GNSS capabilities, both on-site position estimations as well as at a central server, based on Precise Point Positioning techniques. In near-real-time applications, as well as in the near field, unsaturated direct-displacement-estimations based on GNSS observations become critical for the determination of fault finiteness of M ~ 7 (or larger) earthquakes that affect the coastal part of the country, with their associated significant tsunamigenic potential. GNSS records also facilitate more robust estimates of magnitude and W-phase solutions, as well as finite fault models.

This network allows the detection of M>3 earthquakes along the country, including regions not previously monitored permanently. Additional efforts are concentrated on EEW for central Chile and, during 2023, we installed three DAS systems (fiber-optic seismology) with Geoazur to increase the observation capabilities underwater, where most of the large-magnitude seismicity is generated.

Geophysical and Sea Level Monitoring in Puerto Rico

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The Puerto Rico Seismic Network (PRSN) and the Puerto Rico Strong Motion Program (PRSMP) make up the PR network which is the regional authority for monitoring ground shaking in Puerto Rico and the Virgin Islands. The mission of the PR is to monitor and rapidly determine the parameters of all

earthquakes, support the TSP (Tsunami Service Provider) and help the local and federal monitoring and emergency authorities to disseminate alerts in the Area of Responsibility to concerned agencies and stakeholders. The PR compiles the microseismic catalogue, continuous waveforms, and earthquake effects which serve as a foundation for basic and applied earth science & oceanography research in Puerto Rico and the Caribbean. The PR net also promote the education and preparedness of our population to mitigate the effects of a significant earthquake or tsunami, working together with local, commonwealth and federal partners.

The circum-Caribbean region has a documented history of large damaging earthquakes and tsunamis that have affected coastal areas, including the events of Jamaica in 1692, the Virgin Islands in 1867, Mona Passage in 1918, the Dominican Republic in 1946, the 2010 Mw 7.0 Haiti event which killed more than 250,000 people, and the M6.4 in Puerto Rico which affected severely the southwestern region of the Island. There is clear evidence that tsunamis have been triggered by large earthquakes that deformed the ocean floor around the Caribbean Plate (CP) boundary. Seismic events originating in the prominent NE Caribbean fault system are considered to be a near-field hazard for Hispaniola, Puerto Rico and the Virgin Islands because tsunamis generated by these events can reach coastal areas within a few minutes after the earthquake. Sources for regional and teleseismic tsunami-earthquakes have also been identified in the Caribbean and Atlantic Basins.

The goal of this presentation is to describe the PR system, including the real time earthquake and tsunami monitoring as well as the specific protocols used to broadcast earthquake/tsunami messages locally.

Retrospective of the USGS National Earthquake Information Center Strategic Plan, 2019-23: How We Did and Future Directions

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The USGS National Earthquake Information Center (NEIC) monitors earthquakes 24/7/365 worldwide and reports on US earthquakes cooperatively with US Regional Seismic Networks (RSNs) as part of the Advanced National Seismic System (ANSS). In 2019, following the international Powell Center Working Group for Earthquake Monitoring, the NEIC published a 5-year strategic plan. We will present the successes and challenges in meeting the plan's fundamental and aspirational goals and discuss planned future advancements. We seek to input from the community on areas to prioritize for future strategic planning.

Accomplishments from NEIC's fundamental goals include improved earthquake detection with a new Global Associator algorithm, phase-picker and improved interoperability and coordination with RSNs through site visits and tabletop exercises. Advancements to NEIC's infrastructure include expanded redundancy, migration to a service-oriented architecture, web-centric Graphical User Interfaces, and using cloud technologies. ShakeMap ground motion calculations and PAGER estimates of earthquake fatalities and economic loss have been improved by expanding scenario capabilities and redesigning the code to be more modular to support cloud technologies. The ANSS Comprehensive Catalog (ComCat) now includes more historical earthquakes and automatic quality control tools. The challenges faced during COVID slowed progress in some areas but motivated improvements in NEIC's remote and automatic processing capabilities. Realized NEIC's aspirational goals include the implementation of machine learning phase identification and timing, improved rupture modeling using remote sensing data (GNSS, optical imagery, and InSAR), implementation of a sequence-based web interface that links mainshocks and aftershocks, and advanced modeling of earthquake impacts through the incorporation of ground truth loss information. Future work will expand on these topics and focus on greater automation of real-time solutions and catalog generation using machine learning and array processing.

Why Non-Seismic Sensors Are Actually Valuable to Network Seismology: Examples From Alaska

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The Advanced National Seismic System (ANSS) provides earthquake data, products, and monitoring services, built primarily on networks of broadband and strong motion seismometers distributed across the nation. It is increasingly common to leverage these networks to operate other types of sensing equipment with objectives ranging from meteorology and wildfire management, to nuclear treaty verification and space weather. We demonstrate here that these other sensing types can have direct applicability to the seismic mission of networks and related programs including the ANSS.

The seismic network in Alaska has expanded considerably through a mix of upgrades and adoptions tied to the NSF EarthScope program, coupled with strategic investments. Renamed as the Alaska Geophysical Network, these stations now include some combination of GNSS, weather, infrasound, webcam, or soil temperature sensing. Recent large earthquakes demonstrate how GNSS can be integrated directly to make up for displacement and amplitude shortcomings in seismic data. Colocated wind records track the influence of vegetation, snow, and station design on seismic noise at frequencies critical to regional monitoring. Infrasound has recently been used to reconstruct vertical component ground motion in locations where seismic sensors have clipped. And webcams and weather sensors can facilitate field work logistics decisions saving thousands of dollars in air transport.

The colocation model does have challenges. It can be difficult to account for shared resources, including field logistics, power system needs, communication costs, and computing systems. It is bureaucratically non-trivial to build collaboration between funding agencies that each have narrow, but well-defined, missions and accountability. And long-term planning is challenging when many stakeholders represent just a single objective. However, the scientific benefits are clear, and the costs are modest. We see benefit to our seismic mission in continuing to develop models that facilitate the inclusion of non-seismic data types.

Seismic Network Station Infrastructure as the Basis for Multi-Disciplinary Geophysical Stations

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Geophysical monitoring requires the highest level of performance and reliability from purpose-built and tightly integrated instrumentation and infrastructure. Parallel and separate efforts between different scientific disciplines seen in the past came at the expense of duplicated infrastructure, telemetry and power subsystems, and even land use permits. This duplication increases costs, ultimately limiting station counts and reducing "the reach" of monitoring networks. Recent ambitions to combine multi-disciplinary geophysical applications into streamlined deployments led to initiatives such as the European Plate Observing System (EPOS) and the recent amalgamation of the SAGE and GAGE programs in the United States.

Modern seismic dataloggers, such as the Nanometrics Centaur, support a wide range of seismo-acoustic sensor interfaces and sensor types while maintaining ultra-low power consumption, precise timing, and reliable data transport with automatic back-fill features over flexible telemetry mediums. These properties transformed the Centaur's capabilities to act as a highly versatile foundation in multi-disciplinary geophysical station deployments.

Despite initially being designed as a high-performance data recorder for seismic applications, Centaur's applicability has evolved to include data collection for the infrasonic, geodetic, magnetic, and meteorological domains. This triggered the development and addition of purpose-built features to support multi-disciplinary use cases with the same proven performance and reliability of a Centaur seismic station.

Both existing and planned capabilities that enable reliable and efficient multi-disciplinary science are discussed.

Small Aperture Seismic Arrays for Offshore Out-of-Network Events

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Two small-aperture (~350 m) five-element seismic arrays of accelerometers were installed on southwestern Vancouver Island, British Columbia, Canada, as part of a pilot study related to Earthquake Early Warning (EEW) in Canada. The location uncertainty for offshore (out-of-network) earthquakes remains an order of magnitude greater than for most within-network events . Small-aperture arrays installed within existing EEW networks have been shown to improve EEW performance for out-of-network earthquakes through robust back-azimuth and slowness vector determination [Eisermann et al., 2019; Netanel et al., 2021], and are independent of regional velocity model assumptions. To test the ability of both standalone and network-integrated arrays to (1) reduce earthquake location uncertainty for offshore events within 250 km of the coast and (2) improve EEW alerting timeliness to coastal communities, we deployed two small-aperture arrays along a coastline known for its high seismic and tsunamigenic hazard. Both arrays are located less than 1 km from the Pacific Coast and are approximately 55 km apart, to target offshore seismicity. The first array near Tofino (aperture 361 m) has a minimum element spacing of 82 m, and the array near Bamfield (aperture 338 m) has a minimum element spacing of 76 m. Real-time, low-noise, high-gain (1/4g) TitanSMA accelerometers were installed in single-story buildings with existing power and various communications infrastructure. Each element installation has a standalone GPS receiver for timing. Preliminary results from these arrays will be presented and their utility in the context of the existing Canadian EEW network discussed.

Determining the Feasibility of DAS for Urban Earthquake Monitoring in Athens, Greece

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As the global network of telecommunication fibers rapidly expands, we often hear of the increasing potential to apply DAS and other fiber-optic seismology methods over large distances, and in novel and challenging environments. Many of these fibers are installed within urban environments, and it has been demonstrated that these can be useful for seismic event detection and shallow subsurface modeling. However, there remains a disconnect between DAS deployments and traditional long-term/permanent seismic networks. In particular, we are interested in exploring whether the incorporation of DAS into seismic networks for regional earthquake detection and monitoring may prove to be beneficial, and assessing the costs and benefits of such a long-term deployment.

To do this, we analyze a dataset collected in Athens, Greece from September–October 2021. Data were collected over 24 km of in-situ fiber owned by the OTE Group (one of the largest telecommunication companies in Greece). This study area is chosen due to the significant seismic risk in Athens; due to its proximity to many active fault systems, dense urban population, and a large number of older buildings and structures. We develop a rapid event-detection workflow, based on standard seismic tools such as STA/LTA, while also utilizing the high spatial density of DAS to improve the detection rate for small events. We are able to detect several hundred local seismic events, down to local magnitude 0.55. Given the urban location of our study, we also apply careful processing to address the challenges of detecting and isolating seismic events within noisy urban DAS data. For suitable events, we estimate event locations using the DAS data. Finally, we test the event detection and localization capabilities of DAS, both in comparison to, and in conjunction with the existing regional network operated by NOA (National Observatory of Athens).

Towards the Inclusion of Distributed Acoustic Sensing in Earthquake Monitoring and Early Warning Operations

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Distributed Acoustic Sensing (DAS) instrumentation deployed on existing telecommunications fiber cables has emerged as a highly effective tool for seismological applications. Its unique capability to convert extensive lengths of fibers into dense seismic arrays offers unparalleled observational advantages compared to conventional seismic stations. While substantial progress has been made in utilizing DAS data for earthquake science, considerable challenges persist when it comes to continuous earthquake monitoring and real-time data processing algorithms.

Considering the ever-expanding fiber network both onshore and offshore, widespread adoption of DAS has the potential to revolutionize earthquake detection and enhance early warning capabilities. Here, we describe how we are taking the first steps toward the inclusion of DAS data within seismic network operations, from providing additional constraints to earthquake detection and localization to improving early warning performance. We start by highlighting how metadata standards are employed to enable the usage of streamed DAS channels within existing network monitoring procedures. We illustrate how novel machine-learning approaches combined with efficient processing algorithms enable the incorporation of DAS data within existing seismic network systems as well as the potential definition of the next generation of monitoring and early warning tools. Specifically, we employed PhaseNet-DAS to fully exploit the high-spatial density nature of DAS to accurately pick earthquake arrival times. Finally, we demonstrate how high-performance computing processing, picking (i.e., PhaseNet-DAS), and localization tools can enable real-time earthquake detection and early warning.

Making Phase-Picking Neural Networks More Consistent and Interpretable

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Improving the reliability and interpretability of phase-picking neural networks (herein referred to as NN-pickers) remain as important tasks to facilitate their deployment to seismic monitoring programs. Existing NN-pickers seek to estimate sample points in a given windowed waveform that is most likely to represent the arrival of a seismic phase by identifying the peaks in the output prediction score. Ideally, this score would scale with the confidence of the prediction result, so that applying a higher threshold would lead to fewer false detections. However, it has been reported that predictions from existing NN-pickers do not necessarily correlate with diagnostic waveform characteristics (e.g. the signal-to-noise ratio) and fluctuate rather arbitrarily depending on how the continuous waveform data is windowed. This lack of interpretability makes it challenging to control the quality of seismic monitoring products. Here, we present two approaches to increase the consistency of the existing NN-pickers and to improve their interpretability. First, we apply an anti-aliasing filter at down- and up-sampling layers inside neural networks, a popular technique applied within in the computer vision community to make convolutional neural networks more consistent. Second, we alter the training procedure such that shifted versions of the waveforms are systematically included in the training dataset. We demonstrate the improvements by applying the approaches to one of the most widely used NN-pickers and test on the waveform data that recorded the 2019 Ridgecrest earthquake sequence from July 4 to July 16. We show that using a batch containing sequentially shifted versions of a single waveform at each training iteration can significantly improve the consistency of the NN-picker we tested. We also show that with the help from an anti-aliasing filter, this training strategy can make the output prediction score scale with the signal-to-noise ratios of waveforms.

Evaluation of Deep Learning Phase Picking Models

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Deep learning phase pickers have been shown to outperform traditional models. Deep learning models are trained using large, labeled datasets and then applied to incoming data or new datasets for automated creation of seismic catalogs. However, they suffer from the generalizability problem, i.e., their performance tends to drop when applied to new regions due to differences in regional geological structures, sources, measurement instruments, and environmental effects. In addition, a large, labeled dataset, required to train deep learning models from scratch, may not be available for a region of interest. Previous studies have demonstrated improved performance on a new region when phase picking models are fine-tuned using a labeled dataset corresponding to this new region. In this work, we evaluate and compare three models: a model trained using STEAD data (Model 0), a model trained using INSTANCE data (Model 1), and a model with weights initialized from Model 0 and fine-tuned using INSTANCE data (Model 2). We present our approach for model performance evaluation and metrics used. Specifically, we evaluate model transferability through transfer learning by evaluating how the amount of data used for fine-tuning impacts performance of Model 2. Through an ensemble-based approach, we also perform uncertainty quantification for model predictions.

A Comparison of Machine Learning Methods of Association

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The association of phase picks to form events is one of the most fundamental components of seismology. Any error in association due to the inclusion of errant phase picks will introduce errors in the later characterization of the event, such as its location, magnitude, and focal mechanism. Large and dense sensor networks, such as nodal arrays (and DAS), offer unique challenges in association due to vast number of observations, high likelihood of errant picks or multiple events occurring within the array at the same time. Also the large number of stations can greatly increase the time it takes to perform the association. For this reason, machine learning might provide a more optimal method of association. In this work, we examine how well machine learning methods (e.g., GaMMA, Phaselink, and GENIE) can incorporate dense nodal arrays into regional networks and how well they handle the density of stations. We test their capabilities on two nodal deployments, one within Rock Valley Nevada (80 Nodes), and the LArge-n Seismic Survey in Oklahoma (LASSO) dense nodal array (>1800 nodes). These two nodal arrays will test two particular issues that the machine learning algorithms might face: 1) The Rock Valley Array is a small array (<10 kms) within a large regional network and it will allow tests of how the algorithms are able to merge the two during association. 2) The Oklahoma LASSO array spans 10's of kms and contains multiple earthquake sequences and it will allow tests of each algorithm's ability to associate events that might be happening simultaneously. We then compare their associated bulletins to those obtained using Rapid Earthquake Association and Location algorithm (REAL), a more traditional method of association. We find that there are often vast differences between findings of certain methods. Some methods finding roughly half the events of others while others cannot integrate the nodal array with the regional network. We even find that certain methods break apart larger events into multiple events. Prepared by LLNL under Contract DE-AC52-07NA27344.

A Comprehensive Earthquake Focal Mechanism Catalog for Nevada Obtained Through Deep Learning Algorithms

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The state of Nevada is one of the most seismically active areas of the United States, with numerous active fault systems throughout the Walker Lane and Basin and Range tectonic faults. Despite high rates of seismic activity, Nevada currently lacks a comprehensive catalog of earthquake focal mechanisms that could be used to better understand seismotectonic processes. Determining the focal mechanisms of small earthquakes poses a considerable challenge due to the difficulty of distinguishing phase arrivals and first-motion polarities from noise. To address this issue, we augment the first-motion polarity database maintained by the Nevada Seismological Laboratory with additional measurements obtained using a convolutional neural network algorithm. We then complement polarity data with new measurements of S/P amplitude ratios to provide additional constraints on event mechanisms. By incorporating both existing and newly obtained data, we construct a comprehensive focal mechanism catalog for the state of Nevada from 2008 through 2023, utilizing a revised implementation of the HASH method originally developed by Hardebeck and Shearer (2002). With the new focal mechanism catalog, we analyze changes in focal mechanism characteristics resulting from significant mainshocks like the 2020 Mw6.5 Monte-Cristo and other prominent earthquake sequences like the Spanish Springs, Hawthorne, Nine-Mile Ranch, and Sheldon sequences. The enhanced resolution of the new catalog will play a crucial role in advancing our understanding of the crustal stress field, mechanisms triggering earthquakes, fault zone geometry, and strain partitioning across the state.

Deep Learning Enhanced Earthquake Catalog for Northern California

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Improving the completeness and accuracy of earthquake catalogs can reveal new insights into spatio-temporal trends in seismicity, identify fault structures in improved detail, and provide rich datasets for tomography. We present work on a comprehensive earthquake catalog for northern California between 2000 - 2023, spanning from Parkfield to the Mendocino Triple Junction, and from the west coast into the Sierras and western Nevada. To develop this catalog, we use PhaseNet-based picks (Zhu and Beroza, 2018) followed by GENIE-based association (McBrearty and Beroza, 2023). The original GENIE is a graph neural network associator that relies on all pairs of source and station nodes. We implement a more memory efficient version that uses only a subset of all source-station pairs. We also experiment with using amplitudes and phase types in addition to arrival times. These modifications improve the performance of the model and enable accurate associations across the full spatial domain, despite the heterogeneity in station coverage, source distribution, and time-varying seismic networks.

The combination of these two deep learning processing steps, followed by double-difference relocation (Waldhauser and Ellsworth, 2000), reveals dense seismicity throughout all of the expected seismogenic zones of northern California, while increasing the rates of detection compared to the USGS catalog by 4–8x depending on the detection thresholds used. We observe significant earthquake activity at Geysers geothermal field, along the Calaveras and Hayward faults, and at Long Valley Caldera and the Mendocino Triple Junction. The highest event activities occur during the 2003 San Simeon, 2004 Parkfield, and the 2014 Napa Valley earthquake sequences. We assess the reliability of the results based on known seismicity, expected earthquakes statistics, and association assignments across the seismic network with respect to source locations and event magnitudes.

An Agent Based Model to Quantify Gains in Network Processing

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Explosion monitoring agencies and state-sponsored seismic networks that surveil the globe for signatures of nuclear explosions generally implement some version of what we call an Event Processing Pipeline (EEP) or just a pipeline. Pipelines comprise a sequence of tasks that subject matter experts and their algorithms (collectively called "agents") apply to detect, locate and characterize the source of such signatures (among other efforts). Both the details of agent implementation, such as whether they work in series or parallel, and their individual success rates, such as the probability that a source depth estimate is accurate, quantify the overall efficacy of an EEP. Researchers and network operators often question if a particular sequence of monitoring functions provides a more complete seismic catalog relative to a reference catalog. Explosion monitoring researchers therefore require the capability to measure how any loss or improvements to agent cooperation and performance impact the likelihood that EEPs will output an accurately characterized special event source, over such a reference (baseline) value. Here, we provide a high-level model of EEP performance and quantify how changes to individual agents improve the overall EEP success rate. In particular, we model an EEP as a series of monitoring function modules that teams of resource-limited agents (working in series or parallel) can achieve with specific probabilities. This model takes the form of a relational object known as a graph. We quantify improvements to EEP over several operational baseline models in terms of such graphs, which directly relate agent performance to that of an EEP. Lastly, we demonstrate our method against a simple example that employs correlation detectors against explosion sourced data.

Seismology as a Service: Portable Product Generation at the Southern California Seismic Network Using Service-Oriented Architecture and Cloud Computing

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Rapid advancements in machine learning, cloud computing, and new data types such as DAS bring both opportunities and challenges for seismic networks. These algorithms and technologies can enable networks to produce more accurate data products in a more timely, and robust manner. Recently, the Southern California Seismic Network (SCSN) began incorporating machine learning picks from the PhaseNet algorithm to produce higher quality phase arrivals and more accurate origins prior to analyst review. Work presented at the 2023 SSA Annual Meeting showed how cloud native services can make processing scalable in a large sequence. For a network to take advantage of these continually evolving efforts, its staff must be able to evaluate different algorithms, which require efficient deployment and testing. Networks using the same code and algorithms may wish to operate them in a cloud, hybrid, or on-premises environment to fit their individual considerations, such as network bandwidth, computational resources, or budget. To deal with this variability, it is important to make network processing components modular and agnostic to the infrastructure. This would expedite testing and enable faster incorporation of new scientific algorithms, software, and other infrastructure into operational earthquake monitoring.

In this presentation, we configure the AQMS automated origin refinement process, "hypomag", to a service-oriented architecture. This workflow refines and adds phase picks around expected time windows based on the real-time origin to improve the origin and magnitude. We organize these processing steps into services that could be hosted in the cloud or on premises. We examine modularity by incorporating different picker services that produce picks based on different algorithms. We also examine scalability and cost considerations if these services are deployed in AWS. This work will inform network operators on methods to make their processing flows more adaptable and versatile. It will also familiarize researchers with what is required to make new algorithms a part of an operational environment.

NEIC Developments: Updates on the U.S. Geological Survey National Earthquake Information Center's Earthquake Monitoring Systems

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The U.S. Geological Survey (USGS) National Earthquake Information Center's (NEIC) real-time global monitoring systems support the NEIC missions to detect earthquakes globally, estimate source parameters, and produce a reviewed earthquake bulletin. The NEIC continually develops and deploys seismic algorithms, systems, and interfaces to meet the NEIC's evolving needs. NEIC analysts, developers, and researchers have made several significant algorithmic advancements to improve the NEIC's ability to characterize earthquakes, including the updates to its W-Phase moment tensor and location algorithms, new web-based services and seismic analysis interfaces, and improvements to machine learning characterization of seismic phases.

The NEIC has rewritten its W-Phase moment-tensor software to improve its computational speed and the stability of its automatic solutions and is now working towards transforming this software into a web service. The NEIC retired its legacy Fortran locator in favor of a new Java version which is implemented as a web service. This new locator has additional algorithmic improvements including slab models to help constrain event depths, updated statistics of phase-distance specific uncertainties, new strategies to better compute locations with mixed local-to-teleseismic observations, and more robust uncertainty estimates. The NEIC continues to develop a new seismic analysis system, Motus, and has largely completed the back-end web data notification services and a new web-based interface for real-time and research analysis of W-Phase moment magnitude (Mww). The NEIC is currently developing new web-based repicking and modernized Catalog Review interfaces, both extensions of the completed Quick-Look interface. The NEIC has developed the AI-Driven Earthquake Monitor (AIDEM), a python package that provides a framework to test and implement machine learning models in our operational settings. AIDEM takes continuous waveform data as an input and produces phase detections along with characterization labels provided by single-station ML models, which are utilized by the NEIC associator to improve detections.

gCent: Geodetic Centroid Products for Earthquake Monitoring

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This presentation provides an overview and update of the Geodetic Centroid (gCent) catalog—a satellite imagery-derived earthquake centroid catalog developed for regional and global earthquake response. Geodetic remote sensing imagery from optical correlation ("pixel tracking") and interferometric synthetic aperture radar (InSAR) serve an increasingly diverse and important role in earthquake monitoring and response. The geodetic observations provide precise information for determining the finite fault characteristics of moderate to large (magnitude 5 and larger) terrestrial and near-shore earthquakes that compliment seismological approaches. This source information in turn directly informs USGS/Advanced National Seismic System (ANSS) Finite Fault Model, ShakeMap, and PAGER products. Since late 2019, we have systematically processed satellite imagery of earthquakes magnitude 5.5 and larger, PAGER Yellow and above, and other earthquakes of unique interest. We then derive source models of earthquakes that produce measurable surface displacements. This effort has led to a growing earthquake catalog that currently includes >120 earthquakes spanning M4.1-M7.8. In this presentation, I will give an overview of the rationale for and production of the gCent catalog, highlight key contributions of gCent products in ANSS/USGS earthquake response efforts, and detail future developments for gCent products and the gCent catalog.

Overcoming Challenges in Near-Field Seismic Velocity Estimation: Insights from continuos GPS and Strong Motion Data

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Strong motion data have multiple applications in earthquake seismology. However, a common problem is obtaining near-field seismic velocity from strong motion records. Moreover, they cannot capture the low-frequency portion of ground motion, and thus, double integration is not accurate in obtaining displacements unambiguously. This is often referred to as baseline offset correction and is mostly due to the tilting of the inertial sensor. The inability to record long-period motions leads to magnitude saturation in the near field, and as a result, other seismic parameters are not accurately estimated. To solve this problem, it is necessary to have a collocated GPS to constrain the long-period displacement and the integration to match the static offset. GPS instruments, while noisier than the strong motion sensors, overcome all these limitations for large earthquake characterization. Here, we compare seismogeodetic velocity from collocated GPS and strong motion sensors in the near field for large earthquakes, such as the Mw 9.0 Tohoku-oki, the Mw 7.2 El Mayor-Cucapah, the Mw 8.2 Iquique, and the Mw 8.3 Illapel events. We provide new rules to correct integration to obtain seismic velocity for cases in which no continuous GPS data are available. We will show the implications of these strong motion corrections to the data on the application of finite fault earthquake rupture models and spectrum calculation.

Precision and Accuracy of Earthquake Locators: Insights From a Synthetic 2019 Ridgecrest Sequence Experiment

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By solving the inverse problem, various earthquake location programs serve as important tools for the precise determination of earthquake hypocenters. However, the variety of algorithms and misfit norms raises questions about the efficiency and accuracy of different methods. With limited knowledge of the true velocity structure and sparse seismic network coverage, the efficacy of these tools for accurately pinpointing the true locations remains uncertain. Some programs incorporate uncertainty analysis; however, due to the inherent nonlinearity of the problem, the reliability of the resultant confidence measures of earthquake locations deserves some scrutiny. This study embarks on an evaluation of widely used earthquake location methods through a controlled synthetic experiment to compare the outputs of seven programs (HypoDD, GrowClust, HypoInverse, VELEST, XCORLOC, NonLinLoc, HypoSVI) using the 2019 Ridgecrest earthquake sequence. We calculate arrival times by the Fast-Marching Method using a 3D velocity model extracted from the SCEC Community Velocity Model with a von Karman perturbation superimposed to represent unmodeled small scale structure, including elevation effects. We mimic a realistic seismic network monitoring scenario by introducing picking errors, phase availabilities, and phase outliers into the synthetic traveltimes. Our comparative analysis of the recovered locations utilizing the uniform traveltime dataset and 1D velocity structure reveals the superior precision of relative location methods compared to absolute location methods (except VELEST). We demonstrate that near source S phases are important for constraining the focal depth; however, our study shows the limited ability of consistently recovering depths under a 1D velocity structure approximation. As established uncertainty techniques frequently fall short of encompassing true hypocenters, our findings should motivate revisting earthquake location uncertainty assessment.

Improving Shear-Arrival Time Estimates for Real-Time Association and Location Algorithms

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Machine learning and, in particular, deep-learning frameworks have markedly changed the capability of regional seismic networks to detect, classify, and quantify seismic phase arrivals. Yet, in real-time seismic monitoring frameworks, our association and location tools are not necessarily well-equipped to utilize these new and improved automatic characterizations. This limitation is particularly true for shear-wave arrivals which deep-learning detectors appear to generate at a rate of approximately equal to or greater than primary-wave arrivals. The main challenge posed by shear-wave arrivals is that in monitoring regions with substantial three-dimensional velocity heterogeneities, predicting shear-arrival times requires a time-intensive tomography process. To mitigate this tomography requirement, University of Utah Seismograph Stations (UUSS) has recently begun to accommodate 3D structural effects with source-specific station corrections (SSSCs). In this abstract, we review ongoing work at UUSS that combines conventional phase-specific station corrections with SSSCs to better predict phase arrivals at regional monitoring scales. The correction estimation and implementation strategies to be presented appear to be effective, safe, conceptually simple, data-driven, low-overhead, and well-suited for integration into typical earthquake association and location frameworks. Time permitting, we will also review the performance of these correction strategies in a live-acquisition, real-time environment.

Comparing Three-Dimensional Seismic Velocity Models for Location Accuracy

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Location algorithms have traditionally relied on one-dimensional (1D) velocity models for fast, seismic event locations. 3D seismic velocity models are becoming readily available and usually provide more accurate event locations over 1D models. We have previously demonstrated and validated the ability to quickly create 3D travel-time lookup surfaces (3DTTLS) for seismic event location algorithms using an open-source framework (PCalc+GeoTess, www.sandia.gov/salsa3d, www.sandia.gov/geotess) that easily stores spatially varying data, including 3D travel-time corrections to a standard 1D velocity model. This framework allows for fair and consistent comparisons of 3D velocity models because the lookup tables can be generated using the exact ray-tracing algorithm that is preferred for a given 3D model. We have created first-P and first-S 3DTTLS for several publicly available 3D models (e.g., RSTT, SALSA3D, G3D, DETOX-P2, etc.). Using several global-scale seismic events, we compare epicenter location accuracy (LocOO3D, www.sandia.gov/salsa3d) using 3DTTLS for these 3D models to demonstrate how velocity models can be fairly compared for special events. In addition to standard epicenter comparisons, we will investigate combining epicenter determinations into an ensemble location for each analyzed event.

Regionalization of ML and Its Relation to Mw

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The specification of seismicity rates for Probabilistic Seismic Hazard Analysis often relies on an empirical relation between ML and Mw for small (M < 4) earthquakes, but this requires a consistent definition of ML that accounts for regional differences in wave propagation. The IASPEI ML definition is ML = log10 (A) + 1.11 log10 R + 00189 R - 2.09, where A is the peak horizontal amplitude of a simulated Wood-Anderson seismometer in nm, and R is the hypocentral distance in km (within 1000 km). The first and second distance terms are interpreted as corrections for geometrical spreading and anelastic attenuation, respectively, To regionalize, we propose that events with the same A at short distance (e.g., 10 km) have the same ML, and that only the anelastic attenuation term varies. Given sufficient observations, a plot of the IASPEI ML vs R will exhibit a linear trend, which is sufficient to modify the anelastic attenuation term. The benefits of this approach is that one can always define an ML, even in a relatively aseismic region, if there are sufficient observations with distance. In more seismic regions, similar processing of many events leads to a well determined regional anelastic attenuation correction.

A systematic study of events with M > 3.5 since 2010 has led to the determination of the appropriate anelastic attenuation coefficient for parts of North America. Still there are large regions for which these coefficients are not available because of a lack of earthquakes. We examine the utility of using independently determined Lg-Q values to fill in these gaps. Finally using a database of over 2,500 regional moment tensor inversions for which ML was estimated, the relation between regional ML and Mw is examined for robustness.

Noisy Stations Make Earthquake Magnitudes Larger

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The magnitude of a moderate earthquake (e.g., $4<M<6.5$) at a teleseismic distance is often estimated by way of the body-wave magnitude (*mb*). *mb* is estimated at a station by recording the peak-to-peak amplitude, scaling this by the dominant period, and finally applying an attenuation correction. Using a collection of station *mb* estimates, it is then possible to estimate the event *mb* by way of averaging. In order to understand how sensitive *mb* estimates are to local site conditions, we first estimate background noise levels at stations used by the National Earthquake Information Center (NEIC) for all *mb* estimates between January 1, 2021, and January 1, 2023 (over 57,000 events). Then, we find a direct correlation between station noise levels and the calculated station *mb*. For example, stations with background noise levels of 10 nm displacements can routinely produce an overestimate in the station magnitude by 0.5 magnitude units. This suggests that events estimated using only stations in high noise environments (e.g., coastal stations) could produce *mb* values that are greater than when low-noise stations are used. In order to better understand these phenomena, we produce theoretical and data-driven models that can help to predict the potential bias in station *mb* estimates.

Network Seismology: Recent Developments, Challenges and Lessons Learned [Poster Session]

Poster Session • Wednesday 1 May

Conveners: Blaine Bockholt, Idaho National Laboratory (blaine.bockholt@inl.gov); Renate Hartog, University of Washington (jhartog@uw.edu); Kristine L. Pankow, University of Utah (pankowseis2@gmail.com); Adam Ringler, U.S. Geological Survey (aringler@usgs.gov); Dmitry Storchak, International Seismological Centre (dmitry@isc.ac.uk)

POSTER 1

Picking Regional Earthquake Waveforms With Neural Networks

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We present a set of deep learning models trained to perform seismic phase picking at regional distances. These models use raw seismometer data, as well as a combination of raw data and featured engineered data. Also, we present a multiview learning approach that takes advantage of having multiple instruments at the same location, like a seismometer and an accelerometer. The training of these models was done on a quality controlled dataset of over 1.5 million, 5 minute long three component waveforms that contain both P and S labeled arrivals. Our base model handles the first arriving P and S waves, whereas other models handle both the first and secondary arrivals, like picking Pn and Pg, Sn and Sg simultaneously. We show the performance of these models on train/test splits along with deploying the models to continuous data to find new uncataloged earthquakes.

POSTER 2

Moment Magnitude Estimation Using Machine Learning Algorithms for Western United States

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Accurately estimating the moment magnitude (M_w) earthquakes are fundamental for risk assessment, seismic hazard analysis, other seismological studies, and structural design. This study presents a comprehensive analysis of moment magnitude estimation using a dataset from the NGA-West2 database of about 21,000 earthquake records. We use machine learning regression techniques to train and test a model to predict M_w considering the following input features: Peak Ground Acceleration (PGA), 5%-damped pseudo-spectral acceleration (PSA) at 21 different periods, hypocentral distance (R_{hypo}), and the timed-average shear-wave velocity of the upper 30 m of soil (V_{s30}), fault mechanism, and the depth to the top of the rupture plane (Z_{tor}). The machine learning models considered in this study include Artificial Neural Networks, Support Vector Regression, Random Forest, and Gradient Boosting, each known for their predictive ability in nonlinear and complex datasets. Tree-based algorithms like Random forest and Gradient Boosting offer a more accurate model than Support vector and Neural networks. The proposed model uses a stacking method to combine different machine-learning techniques to provide a more accurate and robust framework. The proposed approach overcomes the limitations of conventional techniques by creating a rapid and straightforward process for estimating M_w. We use mean square error (MSE), mean absolute error (MAE), and the coefficient of determination (R^2) to indicate that machine learning regression models can significantly improve moment magnitude estimations.

POSTER 3

National Strong Motion Project's Advancements in Station Health and Integration to the Earthquake Early Warning System in the San Francisco Bay Area

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The rollout of Earthquake Early Warning (EEW) in the western U.S. highlights an increased need to ensure the continued operation of seismic stations in urban centers. The United States Geological Survey's (USGS), Advance National Seismic System (ANSS), National Strong Motion Project (NSMP) network, includes seismic stations located on human-built infrastructure to better understand how ground motions from earthquakes affect the integrity and performance of structures and seismic risk upon urban regions. The availability of ground motion records is important for design of earthquake resilient infrastructure and to assess safety following a major earthquake. The NSMP maintains several structural arrays (Buildings: 107, Dams: 77, Bridges: 19, Geotechnical Arrays: 21) and free-field accelerometers (> 450 stations) across the continental United States and in Alaska, Hawaii, and Puerto Rico, which ensure ground motions from large magnitude earthquakes are recorded at locations in the near-field fault source. The increase of EEW contributing stations in the Western U.S. has increased the need for NSMP to strategically manage field operations. Here we highlight new tools to manage knowledge of instrument state of health, planning for ongoing field maintenance campaigns to keep critical stations operating, and upgrades to modernize equipment to allow for real-time dataflow for our field campaigns in the San Francisco Bay Area and beyond. To visualize our networks health in a living state, we are leveraging ArcGIS Online Dashboards combined with Jupyter notebook-based python queries to combine station metadata location and instrumentation information with instrument state of health (battery voltage, clock quality, data flow). This presentation will also include advancements NSMP is focusing on regarding new layout designs that incorporate energy efficient hardware and user-friendly enclosures to protect and expand the longevity of the station's equipment. We are also exploring adopting field-app based notification of field visits to seismic stations to improve field to data exchange of information.

POSTER 4

Building an Operational Low-Cost Seismic Network in Ukraine

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A robust seismic network is vital for ensuring safety and facilitating research in Ukraine; however, currently the Institute of Geophysics at the National Academy of Sciences of Ukraine faces challenges in its existing seismic network, limiting its ability to provide accurate seismic information and emphasizing the need for reconstruction. The seismic landscape in Ukraine displays marked variations, encompassing notable areas like the Carpathians and Crimean-Black Sea segments, alongside considerations for the western and southern regions impacted by the Vrancea seismic zone. In response to various challenges, we are initiating the deployment of budget-friendly seismometers, specifically the Raspberry Shake Seismographs, across Ukraine. First and foremost, this network is envisioned as a responsive interim solution to bolster the seismic infrastructure across the region while awaiting the deployment of broadband stations. Secondly, this initiative unfolds as an effort to enrich educational experiences within the academic sphere, with a focus on schools and universities in Ukraine. Presently, numerous educational seismic networks span the globe, underscoring the significance and necessity of disseminating seismic sensors to schools for educational purposes. This initiative acknowledges the challenges facing Ukraine's existing seismic network and the demographics at the Institute of Geophysics. The scarcity of younger scientists entering the field raises concerns about the future of scientific research in Ukraine.

The GFZ German Research Centre for Geosciences has provided 28 Raspberry Shake Seismographs with laptops, planned for deployment across schools and universities in Ukraine. Raspberry Shake 3D Seismographs have been installed at the Institute of Geophysics in Kyiv, Lviv Polytechnic National University, and Ivan Franko National University of Lviv. In November 2023, educational materials for seismology at middle and high school levels in Ukraine were developed with the assistance of the GFZ German Research Centre for Geosciences.

POSTER 5

Automated and Efficient Installation of AQMS

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AQMS is the open source ANSS Quake Management System that wraps around the Earthworm software system. AQMS is a robust but complex set of software that requires many components to be correctly installed and configured for it to work properly. Recent advances in computing such as virtualization and automation have streamlined the build and installation procedures for software systems.

In this presentation we introduce a method to automate the installation of AQMS and its many dependencies. The core of this method uses Ansible, an automation framework developed by Red Hat. Installation tasks known as 'plays' are organized into 'playbooks' and combined to form 'deployments'. The installation runs sequentially, and emulates how a human would perform an installation, but using plays designed to be repeatable yet non-destructive, a concept known as idempotence.

We discuss advantages of this methodology such as speed, accuracy, consistency, scalability, configurability and security. Highlighted methods cover configuration management using git, metadata updates, systems administration tools, and analyst resources. We also demonstrate how this project utilizes and supports the seismic communities open source projects.

POSTER 6

Enhancing Data Resiliency With Dual-Feed Telemetry

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The Southern California Seismic Network (SCSN), operated by Caltech and USGS, records on average 256 events of M>=3.0 per year including aftershocks and one M>=6.0 every 3 years. The SCSN utilizes state of the art computing technologies to provide timely earthquake event notification, ShakeMap, and other data products. Because of its critical role providing real time data for public safety, the SCSN maintains a robust and resilient network of more than 350 digital strong motion and broadband seismic stations to achieve this goal. We also import real-time data for an additional 170 stations from partner networks. We use a variety of digital data communications, including cell modems, private microwave network, digital radios, satellite, and the Internet. This presentation describes how we use dual-feed telemetry to improve resiliency of data delivery.

At the SCSN, all our seismic dataloggers in the field are capable of continuous dual-feed telemetry, i.e., sending the same seismic data to multiple acquisition servers. To improve the resiliency of our network, we use two acquisition servers all the time to receive continuous data from most seismic stations. One acquisition server is in the data center in Pasadena, CA, while the other uses an Elastic Cloud Computing (EC2) instance provided by Amazon Web Services (AWS). All the 100 sample/second seismic data acquired are rapidly distributed in 1-second packets via multicast network protocol to the real-time AQMS (ANSS Quake Monitoring System) servers. We have redundant AQMS servers locally in Pasadena, and an EC2-based AQMS instance in AWS.

To accomplish data resiliency, both streams of the 100 sample/second seismic data from each dual-feed station are available continuously to all the AQMS servers. Each AQMS server uses the fastest 1-second data packet, between the local and cloud acquisition, for that specific dual-feed station. Each AQMS system can directly distribute products using Product Distribution Layer (PDL), email, and SMS, to USGS, FEMA, Cal OES, and other government agencies.

POSTER 7

Next Generation In-Vault Power Distribution to Increase Network Reliability and Remote Ops Capability

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Power management, distribution and control at remote seismic and infrasound stations is foundational to operating a high quality and high uptime station. The Wilson Alaska Technical Center (WATC) developed a next generation in-vault power distribution unit, the WATC PowerHub, to maximize command-and-control and State of Health (SOH) collection in each vault. The PowerHub can operate in AC or DC environments and is scalable to suit each station's needs and limitations. It was designed to extend the functionality of a modern UPS (uninterruptible power supply) and PDU (power distribution unit) into a cost-effective, low power in-vault solution. The WATC PowerHub has command and control of up to six independent loads. It monitors the SOH of all charge sources, each independent load, and up to six individual batteries versus a single battery bank. It employs a configurable phased Low Voltage Disconnect to allow a station operator the ability to define a de-escalating phased power down. Using a PCB (printed circuit board) as its base, the WATC PowerHub has a 3-d printed housing and leverages a modular I/O and relay suite for scalability. The PowerHub improves in-vault command-and-control points and SOH station operators are able to leverage remotely, significantly improving remote operations, troubleshooting, response time, and in turn increased up-time across the network. In this presentation we describe the WATC Powerhub and operational improvements observed from recent deployments across the globe.

POSTER 8

Evaluation of Station Performance of the Idaho National Laboratory Seismic Monitoring Network Using Network Detection Thresholds

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The Idaho National Laboratory (INL) Seismic Monitoring Network is located in Eastern Idaho and monitors a portion of the Intermountain Seismic Belt. It has been in place for 50 years and has undergone several major changes. The most recent of which has been the transition to the Antelope real-time acquisition system and the implementation of automatic phase picking algorithms to aid in analysis. This study discusses the efforts to evaluate the performance of the INL seismic monitoring network (and other surrounding stations) using the new real-time acquisition system. The method outlined by Wilson et al. (2021) is used to develop an empirical relationship between the observability of local earthquakes as a function of magnitude and distance. This relationship is used to produce detection thresholds for both P and S waves for all stations of interest. The INL seismic network has two main goals: monitor tectonic and volcanic related events and measure ground motions for input into seismic hazard analysis. Because of these two overall objectives, several seismic stations are installed near critical facilities and therefore are not as quiet as stations which are used primarily for earthquake detection. This is reflected in their detection thresholds, which are much smaller for stations near facilities. This study also shows "holes" in the monitoring network where the detection of smaller earthquakes is highly dependent on sparsely placed seismic stations. The results of this study will be used to govern plans for expansion of earthquake monitoring in Idaho and the surrounding region and to fine tune the detection thresholds for individual stations.

POSTER 9

Field Evaluation of Seismic Sensors for Monitoring Earthquakes, Tsunamis, Volcanoes, and Geodesy

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Real-time seismic and geodetic networks increase the resilience of societies by monitoring geophysical hazards and providing high-quality data for underlying scientific studies. Traditional broadband seismometers and tiltmeters do not have the range to measure strong seismic events, and traditional strong motion sensors lack the sensitivity or stability to make good long-term geodetic measurements. There is a need for improved, high-resolution measurements of earthquake shaking, tilts, Earth tides, slow-slip events, and geodesy over a time spectrum spanning fractions of a second to years. Three fundamental science requirements to measure geohazards and geodesy for both onshore and offshore sites are:

·Low noise floor

·Long-term stability

·Wide dynamic range (no clipping and omni-directionality)

We tested seismic and tilt sensors in a moderately quiet vault near Hanford, Washington. We present analyses of sensor performance including noise floor, short-term examples of local and distant earthquakes, measurements of Earth tides, and long-term stability for slow slip events and geodesy.

The sensors represent different technologies, including: (1) resonant quartz crystal - Quartz Seismic Sensors, (2) optical interferometric - Silicon Audio, and (3) conventional broadband—Nanometrics Trillium 120PA. Data are openly available from the EarthScope DMC archive. Initial results showed that the quartz accelerometers and tiltmeters met the most important noise floor requirements at longer periods (>5s) and their observations of Earth tides were higher fidelity (better signal to noise) than the broadband seismometer. The quartz sensors can also make long-term measurements of geodesy that are only limited by instrument drift. The optical interferometric accelerometers performed well at higher frequencies, but they are not omni-directional, and their design precludes long-term geodetic measurements.

POSTER 10

Performance of Raspberry Shake vs. Kentucky Seismic and Strong-Motion Network Instruments

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Kentucky is affected by three seismic zones: the New Madrid (NMSZ), Wabash Valley, and Eastern Tennessee Seismic Zones. The NMSZ is of particular interest as it previously hosted several large earthquakes >7.0 M in 1811-1812 and maintains the highest seismicity rate in the Central and Eastern U.S. This heightened risk of strong shaking has motivated improvements in detection capabilities of regional seismic networks for possible implementation of earthquake early warning (EEW) systems. EEW detection capabilities can be improved by upgrading existing seismic stations with more sensitive instrumentation, or by densifying the backbone regional network with lower cost sensors like Raspberry Shake (RS) devices. Here we tested the performance of RS geophones and accelerometers by collocating five RS-3D and one RS-4D at five Kentucky Seismic and Strong-Motion Network (KSSMN) permanent stations and monitoring seismicity. During this two-year deployment, 25 usable earthquakes (magnitude ≥ 2.5) were recorded. Our comparisons were based on peak ground velocity (PGV), duration of strong shaking, Arias intensity values, as well as waveform and spectral amplitudes of the RS devices relative to the KSSMN instruments. Preliminary results indicate that the PGV and shaking-duration of small magnitude events are very comparable between RS and KSSMN instruments. Waveforms and spectral amplitudes also match well between RS and KSSMN instruments, specifically where RS and KSSMN instruments were installed within the same vault. Other sites where the RS was located 2-5 m away from the permanent KSSMN instrument exhibited slightly lower spectral amplitudes than KSSMN instruments. This shift may be related to unaccounted-for responses of the RS geophones, the installation locations of the RS relative to the permanent KSSMN instruments, or a combination of both. Because the ground-motions captured were all weak-motion, the instrument self-noise of the RS-4D's MEMS strong-motion accelerometer channels prevented directly comparing its performance.

POSTER 11

Access to Seismic Waveform Data, Services and Products in the Euro-Mediterranean Region and Beyond: Status and Outlook of Orfeus Coordinated Programs

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ORFEUS (Observatories and Research Facilities for European Seismology, http://orfeus-eu.org) is a non-profit foundation that harmonizes the collection, archival and distribution of seismic waveform (meta)data, services and products targeted to a broad community of seismological data users, on behalf of more than 60 participating seismological Institutions (https://orfeus.readthedocs.io/en/latest/governance.html) representing the community of Euro-Mediterranean seismic networks and monitoring agencies. ORFEUS is one of the founding members of EPOS Seismology (www.epos-eu.org/tcs/seismology) and a fundamental partner of EC-funded projects (http://orfeus-eu.org/organization/projects/). ORFEUS services are largely integrated in the EPOS Data Access Portal (www.ics-c.epos-eu.org). ORFEUS comprises: (i) the European Integrated waveform Data Archive (EIDA; orfeus-eu.org/data/eida); (ii) the European Strong-Motion databases (orfeus-eu.org/data/strong); and iii) the European mobile intrument pools (orfeus-eu.org/data/mobile). Products and services for computational seismology are also considered for integration in the ORFEUS domain. Currently, ORFEUS services provide access to the waveforms acquired by ~24,000 stations, including dense temporary experiments, with strong emphasis on open, high-quality data. Access to data and products is ensured through state-of-the-art information and communication technologies, with strong emphasis on federated web services, clear policies and licenses, and acknowledging the crucial role played by data providers. Significant efforts are underway, by ORFEUS participating institutions, to enhance the existing services to tackle the challenges posed Big Data, and to actively encourage interoperability and integration of multidisciplinary datasets in seismological and Earth Science workflows. ORFEUS and its Participants actively collaborate with global and regional initiatives with similar scope like the FDSN and EarthScope. ORFEUS also implements Community services that include software and travel grants, webinars, workshops and editorial initiatives.

POSTER 12

From Dense Seismic Monitoring to Mass-Movement Hazards and Their Impacts: Demonstrating an Operational Workflow and Associated Data Services

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We present and discuss a seismological workflow that uses rapid ground shaking information from ShakeMap (https://usgs.github.io/shakemap/) as input to the calculation of mass-movement hazards and their possible impacts on lifelines. The workflow is demonstrated in the Swiss Alpine region, where the Swiss Seismological Service (SED) at ETH Zürich (http://www.seismo.ethz.ch/en/home/) presently operates real-time nation-wide seismic monitoring networks comprising more than 75 broadband, 193 strong-motion, and 23 short-period sensors (e.g., CH network: https://doi.org/10.12686/SED/NETWORKS/CH; other networks at https://networks.seismo.ethz.ch/), along with a portfolio of real-time and rapid earthquake products including ShakeMap (https://doi.org/10.1785/0220220087). ShakeMap is used in this application as ground shaking information input to the calculation of mass-movement occurrence probabilities - made available as ShakeMap-associated products - which are in turn convolved with lifeline exposure data to estimate possible impacts along with costs and benefits of selected mitigation actions during an ongoing earthquake sequence. Based on free and open source software frameworks, the strategy to calculate ground-shaking and mass-movement hazard information is highly portable to other and broader contexts, and interoperability is being established with the European ShakeMap framework (https://doi.org/10.5194/egusphere-egu23-5937) within ongoing national and EC projects (e.g. https://www.geo-inquire.eu/).

POSTER 13

Evolution of Volcano Hazards Monitoring of the Cascades Chain in Washington and Oregon: Cascades Volcano Observatory

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The U.S. Geological Survey Cascades Volcano Observatory (USGS CVO) began expanding its geophysical network for monitoring hazards associated with the Cascades Volcanoes throughout Washington and Oregon in 2001. Nine of the Washington and Oregon volcanoes have been classified as High- or Very-High-Threat by the USGS due to their eruptive history, types of hazards, and potential impact to populations and infrastructure. CVO's

hazard-monitoring goals are to detect and interpret real-time geophysical and geochemical signals to provide early and accurate warnings of volcanic unrest and eruptions. Throughout this timeframe CVO has worked in collaboration with the Pacific Northwest Seismic Network (PNSN) with support from the EarthScope GAGE facility in growing the network to cover 6 of the 9 High- and Very-High-Threat volcanoes. At present the CVO network has a total of 86 real-time stations including a broad spectrum of stand-alone and co-located monitoring instrumentation (seismic, infrasound, deformation, gas, and cameras) with metadata and continuous waveform data shared publicly in near-real-time and daily GNSS data and metadata available from EarthScope SAGE & GAGE, respectively. Volcano networks have unique challenges regarding power requirements and telemetry paths due to their remoteness and harsh winter environments. The CVO network has seen significant changes in technology, federal regulations, and funding over the last several decades that have both hindered and aided the growth of the network. Changes in federal regulations forced agencies to switch from analog to digital telemetry which proved to be a challenge early on but advances in cellular and satellite telemetry technology along with increases in funding have made the switch more viable. Even with substantial growth and enhancements, significant monitoring gaps still exist at most Washington and Oregon High- and Very-High-Threat volcanoes. Because of this, CVO's network will continue to improve real-time monitoring capabilities to aid scientists in better assessing volcanic processes in near-real time throughout Washington and Oregon.

POSTER 14

Seismic Network Modernization and Expansion in Ukraine

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The Subbotin Institute of Geophysics of the National Academy of Science of Ukraine started research to expand the Ukrainian National Seismic Network (network code UT) through the installation of permanent broadband seismic stations. The initiative to expand and modernize of the seismic network in Ukraine aims to enhance the country's national seismic monitoring and earthquake response capabilities. It will also facilitate real-time access to high-quality data from newly established stations, benefiting the global scientific community. The initial project was realized with the support and collaboration of the U.S. Department of Energy, Lawrence Livermore National Laboratory, Michigan State University, and the EarthScope Consortium.

Optimizing the effectiveness of investigating both existing and new seismic sites requires careful consideration of various factors during the initial selection, preparation, and installation of seismic stations. A crucial aspect of the site selection process for any seismic network involves evaluating the seismic noise levels at potential locations. The ability of a seismic station to accurately detect earthquakes and capture high-quality waveforms is contingent upon understanding the signal and noise characteristics of the chosen site. In addition to the inherent background noise of the Earth, it is essential to account for other sources of noise, such as those associated with nearby infrastructure.

An initial noise survey was conducted for some existing and new sites of the Ukrainian National Seismic Network: at some existing sites LUBU (Liubeshka, Lviv district), SHIU (Shidnytsia, Lviv district), PLTV (Poltava city), and at new sites: SUGL (Mala Uhol`ka, Zakarpattia district), TURU (Tur`je, Lviv district), and GOSU (Hoshiv, Lviv district). We analyzed and reported the data in the form of both time-history examples and standardized Probability Density Function noise plots. Seismic spectral analysis is based on the calculation of Power Spectral Density distribution using a Probability Density Function following the approach of McNamara and Buland (2004).

POSTER 15

Hydrothermal Monitoring Site in Norris Geyser Basin, Yellowstone National Park, Wyoming, United States of America

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Yellowstone National Park houses one of the largest and most active hydrothermal systems in the world containing over half of all known geysers. Additionally, the largest hydrothermal eruption crater is positioned in northern Yellowstone Lake (Mary Bay) approximately 35 kilometers to the southwest of Norris Geyser Basin. In addition, a small hydrothermal explosion occurred in the Norris Geyser Basin in 1989 when Porkchop Geyser exploded sending rocks and hot water/mud many meters from the feature. With such high seismic and hydrothermal risk, a network of monitoring sites is being developed to actively observe the signals produced by this vast plumbing system. During August of 2024, the University of Utah Seismograph Stations, U.S. Geological Survey, EarthScope Consortium, and Yellowstone National Park personnel installed a hydrothermal monitoring site (YNB) in the Norris Geyser Basin of Yellowstone National Park to complement the existing 3-component broadband site within the basin (YNM). Station YNB is composed of a 3-channel broadband seismic sensor (sampling at 100Hz), 3-channel infrasound array (sampling at 100Hz), compact weather station, and a full GNSS monument, and it is the most complete monitoring site in the Yellowstone region. In this study we will show seismic, infrasound, and geodetic signals that have been observed in the short time the station has been deployed and how data are being processed to assist in the further understanding of the Yellowstone Volcanic System.

POSTER 16

Improving Earthquake Monitoring Capabilities in Ohio With Low-Cost Robust Posthole Vaults

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The Ohio Seismic Network (OhioSeis) has undergone a significant transformation in instrumentation and vault design over the past decade. The current, modern network has substantially increased the number of earthquake detections across the region and improved our understanding of local seismic hazards and faulting mechanisms. Initially planned and created as a small cooperative network with single-component, narrowband instruments placed indoors, today OhioSeis consists of 29 free-field, broadband stations comprised of a selection of former Transportable Array (TA) vaults, shallow-surface barrel vaults, and more recently, posthole-style vaults. Recent work has focused on improving the viability and lowering the costs of these posthole emplacements. A complete off-the-shelf solution has been developed that can be installed permanently or slightly altered for rapid temporary deployments, such as during aftershock sequences. Depending on emplacement depth, a complete vault can be installed in as little as two hours for less than $100. Vault flooding, instrument damage, and station noise impacting OhioSeis stations have decreased with these new posthole emplacements. Earthquake catalog magnitude of completeness has been lowered to approximately ML 1.5. Today, OhioSeis is better equipped to detect low-magnitude earthquakes across the entire state and better serve the public, researchers, planners, and first responders with high-quality seismic data.

POSTER 17

Near Real-Time Earthquake Catalog for the Endeavour Segment of the Juan De Fuca Ridge: Integrating Community Code Into Ocean Networks Canada's Ocean 3.0 Data Portal

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Ocean Networks Canada's NEPTUNE observatory consists of an 800 km fiber-optic cable loop that provides power and real-time communication to a network of Ocean Bottom Seismometers (OBS) offshore Vancouver Island. The network covers the northern end of the Cascadia Subduction Zone, the abyssal plain of the Cascadia Basin, and extends all the way out to the Endeavour Segment of the Juan De Fuca Ridge. Community members Zoe Krauss and William Wilcock developed a sophisticated software package that includes components programmed in Matlab, Python, and Fortran, which they used to create a long-term micro-earthquake catalog for the Endeavour Segment, constructed from OBS observations spanning nearly three decades. The catalog includes the last rupture of the Endeavour Segment that took place via a sequence of dike emplacements between 1999 and 2005. Since 2016, the earthquake catalog data were obtained from a small network of 3-5 cabled OBS directly on top of the ridge that are connected to the NEPTUNE observatory. The waveform data are publicly available through the Seismological Facility for the Advancement of Geoscience (SAGE/IRIS) under the network code NV and near-real-time updates of the catalog are made available at http://endeavour.ocean.washington.edu by the authors of the code.

This presentation shows how we plan to integrate user community provided code into Ocean Networks Canada's Oceans 3.0 Data Portal and run it in an operational environment. We will use the code to generate the Endeavour earthquake catalog as a test case and provide details about the system requirements, different design options, and compare the approach to our existing catalog of Earthquake Early Warning detections. Once integrated, the real-time catalog will provide context for non-seismologists looking at other measurements of the hydrothermal system that are available through Oceans 3.0. This catalog development is timely since an increase in seismic activity hints to a new rupture in the not too distant future.

POSTER 18

AdriaArray—a Passive Seismic Experiment to Study the Geodynamics and Geohazards in Central Mediterranean

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The densely populated area around the Adriatic Sea is prone to geohazards including earthquakes, tsunamis, landslides, flooding and volcanic activity as the Adriatic Plate is consumed in a tectonically active belt spanning from Sicily, over the Apennines to the Alps, Dinarides and Hellenides, generating earthquakes up to magnitude 7. To identify drivers of associated plate deformation, the plate boundaries, slabs, properties of active faults and of the stress field have to be determined. AdriaArray, a dense plate-scale regional seismic network deployed in the central Mediterranean, provides data for imaging of the crustal and upper mantle structure and for the analysis of seismic activity. The network consists of 1000 permanent and 446 temporary BB stations from 24 mobile pools. 95 % of the planned temporary stations have already been installed. A homogeneous coverage by broadband stations in an area from the Massif Central in the west to the Carpathians in the east, from the Alps in the north to Sicily and the Kefalonia Fault Zone in the south, is achieved. The backbone network (2022–2025) is complemented by locally densified and LargeN networks, e.g. in the western Carpathians (Poland, Slovakia, Hungary), along the Dubrovnik fault (Croatia), in the Vrancea region (Romania), and in Albania. Data recorded by the temporary stations is transmitted in real-time and archived at 9 nodes of the European Integrated Data Archive (EIDA). Regular availability and quality checks ensure high data usability. AdriaArray, the largest passive seismic experiment in Europe so far, is based on cooperation between local network operators, mobile pool providers, field teams, ORFEUS (Observatories and Research Facilities for European Seismology) and EPOS (European Plate Observing System), encompassing 63 institutions from 30 countries. They form the AdriaArray Seismology Group, founded in 2022. Collaborative Research Groups are being established to coordinate the data analysis. We present the maps of the AdriaArray Seismic Network, station properties, coverage, contributing institutions and collaborative research topics.

POSTER 19

Northern California Earthquake Data Now Available in AWS Cloud

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The Northern California Earthquake Data Center (NCEDC) is a permanent archive and distribution center for multiple types of digital data related to earthquakes in central and northern California. The NCEDC is located at the university of California, Berkeley, and has been accessible to users via the Internet since mid-1992. Time series data mainly come from broadband, short period, and strong motion seismic sensors, as well as from other geophysical instruments. Earthquake catalogs include origin time, hypocenter, magnitude, moment tensor, focal mechanisms, phase arrivals, codas, and amplitude data. Metadata and instrument response for seismic sites are accessible in various formats for all data channels archived at the NCEDC. The NCEDC also provides support for earthquake processing and archiving activities of the Northern California Earthquake Management Center, a component of the California Integrated Seismic Network (CISN). Data holdings currently consist of more than 184 TB of data encompassing 29 networks and 2,640 stations. In 2023, the NCEDC archive became part of the AWS (Amazon Web Services) Open Data Sponsorship Program and all of its data are now mirrored in the cloud (s3://ncedc-pds; us-east-2 region). Tutorials (https://ncedc.org/db/cloud/getstarted-pds.html) and data structure (https://ncedc.org/db/cloud.html) are available to facilitate user access to this public data set. This allows the NCEDC to leverage AWS cloud infrastructure and provide users the ability to provision gigabit connections to the archive as well as take advantage of the computational resources offered by AWS.

POSTER 20

Assessment of Data Quality for the Alaska Geophysical Network

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One of the Alaska Earthquake Center's (AEC) core missions is to monitor geophysical events and conditions in the state of Alaska. These events are typically unique, unpredictable, and unrepeatable, so detecting and characterizing these requires AEC to maximize its continuous, real-time geophysical monitoring throughout Alaska. AEC maintains 255 geophysical stations, referred to as the Alaska Geophysical Network (AGN). The environments around Alaska are varied and often create harsh conditions. Maintaining AEC's monitoring capabilities requires constant vigilance to detect, investigate, and troubleshoot problems at stations, and properly document the issues to support short-term repairs and improve the overall network resilience in the long term. Data quality control (QC) at AEC includes established protocols for seismic as well as non-seismic data (meteorological, infrasound, GNSS). We define "QC" broadly as quantitative data that help assess the performance of stations. QC metrics are derived from the raw data and state-of-health channels and the EarthScope MUSTANG website. This includes data on the overall station health (data completeness, clock quality, latency), as well as data specific to individual channels (broadband, strong-motion, weather, infrasound). Standardized QC reports are produced bi-weekly and include percent availability, gaps, and amplitude-related metrics.

In preparation for the next field season, we have conducted a network-wide assessment of the quality of broadband data based on analysis of sensor mass positions and site noise characteristics. Analysis of regional and temporal trends in mass positions of broadband sensors allows us to identify sites with chronic instability issues. Analysis of noise characteristics based on PDF metrics allows us to identify general regional trends and outliers. Additionally, we apply amplitude-based strong motion metrics to identify malfunctioning strong motion sensors. We aim to use this analysis for targeted recommendations for field maintenance that may include sensor replacements and/or improvement to sensor housing.

POSTER 21

A Review of Recent IDA Sensor Performance

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The IDA network, which comprises one-third of the Global Seismic Network (GSN), consists of 40 high-quality seismic stations located around the world instrumented to support high-fidelity recording of very low-amplitude and very long-period seismic signals.

IDA stations are distributed about 50/50 between those having vault and borehole-focused infrastructure. At those with the latter, shallow (~7 m) boreholes complement deep (~100 m) boreholes. Both weak- and strong-motion sensors are included in a standard IDA station instrumentation configuration.

The network-wide upgrade of the no-longer-supported Geotech KS-54000 and Streckeisen STS-1 instruments to modern very-broadband (VBB) STS-6A and T360 seismometers (manufactured by Streckeisen and Nanometrics, respectively) is nearly complete. These "primary" seismometers are complemented with "secondary" instruments---most commonly a Streckeisen STS-2.5 or STS-5A, or a Nanometrics T120---installed on the pier or in the shallow borehole, depending upon station infrastructure.

The ongoing upgrade offers the opportunity to carry out a broad examination of the instrument performance over a period of about a decade. Here we present results of that investigation.

Anomalies in instrument behavior, identified via power spectral density analysis of ambient seismic noise and variation from nominal instrument response, are viewed as general proxies for instrument anomalies and hardware failures. Performance tracking has been conducted since the beginning of the VBB sensor upgrades about a decade ago. The overall performance of VBB instrumentation to date has been somewhat worse than expected, with a significant number of IDA STS-6A complete failures attributed to a faulty electronic component and additional failures due to other problems.

POSTER 22

High Frequency Ground Motion and Electrical Calibrations of Seismometers Used at IMS Stations

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Calibration of seismometers used in nuclear explosion monitoring systems, such as the International Monitoring System (IMS), is important for providing confidence in the measurements of ground motion and the resulting analysis that is performed on the waveform time series data. In this study, six models of seismometers widely used at IMS stations have been calibrated using high precision vertical and horizontal shake tables. The calibration procedure follows the ISO 16063-11 standard for primary vibration calibration by laser interferometry. The sensors are evaluated from 0.1Hz to 50Hz and the calibration results are directly compared to the sensors' nominal response models provided by the manufacturers. Electrical calibrations are then performed on the same sensors which mimics how fielded IMS seismometers are calibrated. The sensors' response to ground motion, measured with the shake tables, is removed from the electrical calibration data so that the performance of the electrical calibration system itself can be determined. This measured calibration system response is then directly compared to manufacturers' specifications.

Results from this study offer insight into the higher frequency performance of seismometers used in the IMS and also demonstrate how primary ground motion calibrations can be used to verify sensor performance and identify issues that relative calibration methods may not detect.

POSTER 23

Machine Learning Earthquake Catalog Performance for Characteristic Alaska Settings

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Globally pre-trained machine learning (ML) earthquake phase-detection algorithms promise broadscale regional transferability in addition to real-time monitoring applications. These algorithms continue to gain research popularity and are routinely used to generate earthquake catalogs with thousands of additional events. We apply a globally pre-trained ML earthquake phase-detection algorithm to four different characteristic regions and sequences to generate a ML earthquake catalog. We compare the ML catalog with the Alaska Earthquake Center's real time (RT) and analyst-reviewed (AR) catalogs. We establish a binary classification framework to compare the RT and ML catalogs to the AR catalog. We visually assess and label additional RT and ML events as earthquakes or other signals. Finally, we apply a minimum catalog inclusion criteria based on Alaska Earthquake Center analyst review standards to additional, visually-confirmed RT and ML catalog earthquakes, establishing a one-to-one performance comparison between catalogs. For each region, we find the ML catalog provides a consistently higher match with the AR catalog than the RT catalog. However, each region's ML catalog introduces additional complications ranging from misidentification of non-earthquake signals to missed detection of large magnitude, felt earthquakes. These discrepancies warrant further training dataset scrutiny and suggest the establishment of a location based training dataset is necessary for consistent and reliable ML phase detection performance across the Alaska seismic network.

POSTER 24

Monitoring Induced Microseismicity (M>-1) With the Local Network at the Utah Frontier Observatory for Research in Geothermal Energy (FORGE)

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The Utah Frontier Observatory for Research in Geothermal Energy (FORGE) is a Department of Energy project to develop technology to help de-risk Enhanced Geothermal Systems (EGS) and eventually make them commercially viable. Part of this technology relates to seismic monitoring for hazard and for mapping geothermal reservoir development. At Utah FORGE a local seismic network serves for near-real-time monitoring. In addition, several temporary seismic experiments were applied including the deployment of nodal geophones and the instrumentation of deep boreholes with strings of geophones and DAS (Distributed Acoustic Sensing). Here, we focus on the local seismic network that has been in operation since November 2016. This network has evolved to the current state that includes: (a) seven surface broadband stations, (b) three surface accelerometers, (c) an ~300m deep borehole instrumented with both a three-component geophone and an accelerometer, and (d) six 30 - 45m deep boreholes instrumented with either collocated broadband and accelerometer sensors or broadband sensors. The horizontal components for the borehole broadband sensors were oriented using teleseismic surface waves. With this network we achieve an Mcomp of ~0.5 for the immediate Utah FORGE study area and have detected events down to M -1.0 within the geothermal reservoir, allowing detailed studies of the injection-induced reservoir response. In addition to meeting the monitoring objectives for the Utah FORGE project, this network provided key information in the analysis of two natural earthquake swarm regions located in proximity to Utah FORGE and has identified a persistent source area (potential swarm zone) characterized by events with magnitudes below the completeness of the Utah Regional Seismic Network.

POSTER 25

Seismic Data Compression and Telemetry Bandwidth Considerations for EEW

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Earthquake early warning systems depend on the prompt, reliable arrival of seismic data at network data centers. Network operators invest significant resources into the design, installation and operation of real-time acquisition systems to ensure maximum data completeness and minimum data latency, to allow EEW processing modules to detect events and issue warnings as quickly as possible.

These mission-critical acquisition systems must perform before, during and after earthquakes, as main shocks are frequently preceded by foreshocks and followed by aftershocks, which are often just as dangerous. As such, a key consideration in the design of these systems is the impact that large earthquakes may have. Seismic data is generally encoded using Steim compression, which is a first difference algorithm. During large events the differences between samples grow, requiring more bits to record and, thus, increasing the data volume. This results in a surge in the throughput required during large events. System designers and network operators must be fully aware of this effect and plan for it accordingly.

This study expands on existing work to further characterize the impact of large events on seismic data compression and the corresponding spikes in throughput which must be supported by real-time acquisition systems. The study will examine the relationship between compression and various factors, including station magnitude, hypocentral distance, sample encoding technique, packet size, sample rate and system sensitivity.

POSTER 26

Sensor Corrections for Multi-Component Monitoring of Seismic Translation and Rotation

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Seismic sensors are used in a variety of applications, such as monitoring of volcanic activity, structural changes in buildings, seismic velocity changes due to anthropogenic activities or seismic ground motion on land or underwater. All applications depend on the sensors reliably recording the motion above the frequency-dependent noise level of the sensors. However, many of the sensors in use are susceptible to errors that derive from the rotational motion that coexists with the translational motion. For example, inertia motion sensors that rely on translational acceleration observations, such as strong motion or broadband sensors, are affected by rotations through changing attitude of the body to the local frame, leading additionally to gravitational errors and inertial effects such as Coriolis, centrifugal, and Euler forces. GNSS sensors, on the other hand, are affected differently and will show errors due to tilting of the antenna pole or phase wind-up from torsional motion. Without a collocated rotational sensor it is impossible to distinguish, which part of the signal is translation and which is due to rotations. Most of these rotation effects can be corrected with appropriate methods if the local dynamic and static rotations are known. However, to correct for inertial effects, additional information on the distance between the point of rotation and the sensor itself is required. This might not be possible in field observations. Unfortunately, the sensor measuring rotations is also falsified by the dynamic tilt and torsion which misorient the sensor and additionally the false projection of the Earth's rotation rate.

Here, we show how the observations from the rotational sensor can not only be used to self-correct for misorientation of the body versus the local system, but additionally correct for the error that derives from the earth's rotation rate being wrongly projected on the channels. The correction scheme will be provided using not only Euler angles but also the more precise quaternion angles. We will present results from the application of different correction schemes on synthetic test scenarios.

POSTER 27

Comparative Analysis of Seismic Instrument Installations: Surface Vaulted Pier Mount, Direct Burial, and Bore Hole, Considering Noise Models

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The study conducts a comprehensive analysis of three seismic instrument installation methods—surface pier mount, direct burial, and bore hole—employing noise models to assess their suitability for seismic monitoring. Surface pier mount installations, though providing convenient access, are susceptible to surface noise such as wind and cultural signals. Direct burial minimizes disturbances, enhancing signal fidelity despite installation complexity and environmental risks. Additionally, bore hole installations effectively isolate instruments from surface disruptions, offering superior data precision at the cost of higher complexity and expense. Moreover, bore hole installations help mitigate thermal variations.

This analysis thoroughly considers factors like cost-effectiveness, accuracy, complexity, and maintenance, outlining the trade-offs between installation ease and data quality across various scenarios. Future research endeavors aim to refine noise models and explore hybrid approaches for optimized accuracy, including deeper installations ranging from 500 to 1000 meters. In conclusion, the study's integration of noise models enhances the understanding of different installations' noise reduction capabilities, facilitating informed decisions in deploying seismic monitoring systems across diverse conditions. The study underscores the importance of considering installation practicality and noise impact on data quality for effective decision-making.

POSTER 28

Applying Machine Learning Salves to Network Build-Out "Growing Pains" at the Pacific Northwest Seismic Network

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The Pacific Northwest Seismic Network (PNSN) is the authoritative network for near-real-time seismic event monitoring and catalog development in Washington and Oregon. The build-out of the PNSN and surrounding networks over the past decade resulted in a roughly eight-fold increase in the number of seismic channels being continuously analyzed by the PNSN. Presently, PNSN's Earthworm system only analyzes vertical component data for automated phase detection and only considers P-wave labels when classifying and associating phase detections. All S-wave characterization is conducted by seismic analysts. The increase in data volume per event, combined with the PNSN's relatively low magnitude threshold (2.95+) for rapid review (less than 10 min post event origin time) produces a substantial increase in workload for PNSN staff.

Machine-learning (ML) seismic analysis tools demonstrate promising accuracy and performance benchmarks for combined phase detection and classification tasks, particularly PhaseNet and EQTransformer. These tools may help soothe growing pains from the PNSN build-out; however, most pretrained models and their applications focus on broadband instrument records, and their performance benchmarks are often based on curated datasets. Data analyzed by the PNSN come from broadband, strong motion, short period, and ocean bottom instruments, have diverse sampling rates and site qualities, and are subject to imperfect data continuity. To bridge this gap, we developed a streaming data workflow that couples SeisBench-hosted ML models to Earthworm's memory rings, the performance of which we test in two pilot studies. The first study assesses the accuracy of picks from pretrained ML models against analyst picks for 7749 PNSN catalog earthquakes. The second study assesses the computational performance of our workflow on modern PNSN data traffic. Our initial results indicate that these models can reasonably replicate analyst characterization of P- and S-wave arrivals and our workflow can attain faster-than-real-time processing, at scale, on modest computational resources.

POSTER 29

System Monitoring, Telemetry Quality Control, and Planning Tools for Scsn

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The Caltech/USGS Southern California Seismic Network (SCSN) is a modern digital ground motion seismic network. It develops and maintains data acquisition and delivery systems for rapid earthquake information products like earthquake origins, magnitude, and ShakeMap as well as for Earthquake Early Warning (ShakeAlert).

We present recent and ongoing innovations in telemetry, system monitoring, and planning tools that keep the network running efficiently and provide timely, high-quality streaming data. We also are developing a quantitative approach to evaluate station locations for the ShakeAlert mission that allows us to calculate station expected contributions in terms of likelihood to detect earthquakes and benefit to people nearby.

Most SCSN sites deliver data continuously to both cloud (AWS) and terrestrial servers located on the Caltech campus in Pasadena. The second data acquisition path allows SCSN to keep processing waveforms during extreme events. Redundant data flows make delivery more disruption tolerant integrating flows for data archiving but requires a special approach to handle arriving duplicate packets.

We also use a bi-axial shake table to test the instrument and telemetry performance during shaking. By recreating past seismic events and analyzing system responses, we can design a more robust seismic site and work with field engineers on the installation improvements.

We are developing tools to monitor the system state of health as well, including regular measurements of data transport latency and telemetry link bandwidth from each datalogger to the data center. Using these results, we analyze performance of new and established connections and track if they meet our latency and bandwidth targets.

POSTER 30

Quick Look at the Reoccupation and Installation of Seismic Stations at the NNSS

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Over the last couple of years, the Nevada National Security Sites (NNSS) has increased the network footprint through the installation of several new seismic stations and by reoccupying historic locations. The overarching goal is to improve our coverage for modern experiments; however, there is also a desire to understand the integration of historic measurements to modern systems. Although some of the historic locations have been easily reoccupied, some locations prove a bit more challenging to locate. Additionally, we have attempted to occupy wells that were not designed for seismic systems. These challenges provide a unique opportunity to compare site and system effects in the modern data. We will discuss the challenges of these installations and compare common signals and noise that are recorded by the modern and historic systems. We have also completed huddle tests in various locations that compare the downhole and surface signals. We show, through modeling, the difference in offset of 100 and 200 m gaps to understand the potential contributions of site effects with re-occupied locations. With the various types of sensors and data recorders, we have a robust data set to help understand some of the issues facing network operators. We are looking at ways to rapidly identify the quality of new stations and ensure that the continuity between historic measurements is maintained in our network.

POSTER 31

A Decade of the Seattle Liquefaction Array

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Completed in February 2012, the Seattle Liquefaction Array (UW.SLA) has now recorded more than a decade of continuous borehole acceleration and pore pressure data at a liquefaction-susceptible site in Seattle's south of downtown (SODO) neighborhood. While the seismically quiescent Pacific Northwest has not produced any earthquakes with appreciable excess pore pressure generation at SLA during the past decade, the urban ambient seismic noise of industrial south Seattle provides a rich dataset for near-surface investigations. Quasi-static surface loading from trains passing by or parking only 5-30 m from SLA drives pore pressure transients as large as 1 kPa at 52 m depth. By computing downhole horizontal-component cross-correlations with overlapping 40-s windows, we can measure perturbations in near-surface velocity from ballistic shear waves ~1-50 Hz generated by the trains. Combining these two datasets, we estimate the nonlinear elastic response of the sediment to poroelastic stress changes, which is as large as +20% dv/v (averaged 0-60 m) per 300 Pa (measured at 52 m). We also apply ambient noise coda wave interferometry to study changes in near-surface velocity and attenuation over seasonal to decadal scales. In the coda of vertical component cross-correlations, we find a decade-long monotonic stiffening trend, with 1-10 Hz Rayleigh wave phase velocity increasing by ~4% from 2012 to 2022. The horizontal-component and cross-component correlations are more complex, showing opposing seasonal trends in dt/t at different windows in the coda and different frequencies, likely representing a depth-dependent phase lag in poroelastic and/or thermoelastic velocity changes.

POSTER 32

Improving Automatic Post-Processing at the Southern California Seismic Network With Machine Learning Algorithms

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During routine seismic network operations, data is automatically analyzed in real-time to identify seismic events and provide initial locations and magnitudes. Additionally, subnet triggers are used to collect unassociated phase picks from the real-time system that may correspond to an undetected event. Automatic post-processing may be applied to small events (M<~3) to add and refine picks and improve the hypocenter and magnitude before analyst review. The Southern California Seismic Network currently employs the Earthworm/AQMS real-time system, which uses a short-term average/long-term average (STA/LTA) phase picker and includes a post-processing module (hypomag).

We aim to improve automatic event picks and hypocenters and to reduce analyst workload by incorporating machine learning algorithms into our existing systems and workflow. Recently, we integrated the deep-learning picker PhaseNet into our event post-processing. This new hypoPN module has produced ~2-3 times more automatic picks of slightly better average quality than the original hypomag, leading to more accurate hypocenters. However, more time and analysis are needed to determine whether this change has reduced analyst workload overall. Following the success of hypoPN, we've begun work on automating subnet trigger processing. Weekly trigger counts can reach a few hundred, with around 10% converted to seismic events. Parsing through these triggers takes time from other analyst work for only a small increase in cataloged events. With modern algorithms, automatic trigger processing should be viable. We plan to apply PhaseNet and the machine-learning event-associator GaMMA to find seismic events in the triggers, with the ultimate goal of eliminating the need for analysts to review triggers.

POSTER 33

Güralp SMART Sensors - A Comparison of Next Generation Mid-Band Seismometers and Traditional Sensor Technologies

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Mid-band seismometer systems usually have shorter period responses and higher noise floors when compared to broadband seismometer sensors. These seismometers have been hugely popular with permanent seismic networks and temporary experiments alike due to their cost-effectiveness, portability, and relative ease of deployment, allowing for network densification and rapid deployments. Güralp have historically led the way with such sensors with the 6T and 40T series, seeing use globally in challenging environments over the last decades.

The Güralp next-generation smart sensor module is designed to be able to operate at any angle, without the use of a mechanical gimbal system. This allows for the entire sensor package to be rotated during installation and deployment without sacrificing data quality and means that all three components of the sensor are manufactured to the same design, eliminating inconsistencies in performance between horizontal and vertical components whilst still maintaining an orthogonal orientation for redundancy. The new generation of sensor makes use of novel materials and techniques to drastically improve the noise performance over traditional mid-band sensors.

The sensor components include digital elements to the feedback loop, allowing for the sensor module to have an onboard serial server. This facilitates greater interoperability with Minimus-based digitizer platforms, including automatic pulling of sensor serial numbers, sensor module SOH channels, and the ability to remotely adjust the long period corner between options of 1s and 120s. This therefore makes the sensor module incredibly easy to deploy and mitigates against previous requirements for multiple instruments of varying responses.

The sensor module has now been successfully developed into a number of different packages for varying deployment scenarios including borehole (the Radian), offshore (Aquarius and Maris), vault (Certimus) and posthole

(Certis) applications. All packages make use of the latest digital technologies to reduce power consumption down to <300mW.

New Insights into the Development, Testing and Communication of Seismicity Forecasts

Oral Session • Thursday 2 May • 4:30 PM Pacific

Conveners: Jose Bayona, University of Bristol (jose.bayona@bristol.ac.uk); Kelian Dascher-Cousineau, University of California, Berkeley (kdascher@berkeley.edu); Leila Mizrahi, Swiss Seismological Service (leila.mizrahi@sed.ethz.c); William Savran, University of Nevada, Reno (wsavran@unr.edu); Max Schneider, U.S. Geological Survey (mschneider@usgs.gov)

Testing Rate-and-State Predictions of Aftershock Decay

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We analyze aftershocks of the 2019 M7.1 Ridgecrest mainshock to test predictions made by the rate-and-state friction model of Dieterich (1994). Rate-and-state friction predicts that the seismicity rate after a stress step follows Omori decay, where the Omori *c*-value, which is the saturation in aftershock rate observed at small times, is larger for smaller stress steps. Put in the context of an aftershock sequence, this predicts that the Omori *c*-value will be systematically larger at greater distances from the mainshock. To our knowledge, this predicted effect has not been observed. In part this may be because the Omori *c*-value is difficult to measure, as it often reflects short-term catalog incompleteness in the mainshock coda rather than true saturation in aftershock rate. Some have even hypothesized that the true *c*-value may be zero, or as Kagan and Houston (2005) argued, negative.

We explore the dependence of the Omori *c*-value on the distance to the mainshock by applying the "*a*-positive" method (van der Elst and Page, 2023) to Ridgecrest aftershocks. This method is insensitive to short-term aftershock incompleteness and allows resolution of the true aftershock rate deep into the mainshock coda.

Time-Dependent Earthquake Forecasts With Pre-Existing Populations of Faults: Application to the Groningen Gas Field, the Netherland

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The Groningen gas field, one of the largest producing onshore gas fields in Europe, is often considered a model test site for induced seismicity. This is due to the open availability of production and detailed structural and field parameters, together with an outstanding effort to monitor shallow, low magnitude seismicity from surface and borehole arrays. A key observation at Groningen is that induced seismicity at depths of about 3 km started with a delay of almost 40 years after the start of production and long after peak production rates were realised. This can be attributed to the fact that the shallow Rotliegend sediments at 3 km depth and pre-existing fault distributions are subcritically stressed. Common seismicity models such as Rate and State (RS) or ETAS do not usually take into account pre-existing fault distributions and pre-stress models.

In this study, we use a recently developed physics-based seismicity model (TDSR) that assumes pre-existing populations of faults that respond to changes in Coulomb stress. In contrast to the traditional Coulomb Failure (CF) model, which assumes instantaneous triggering when stress exceeds a threshold value, the new model replaces instantaneous triggering with an average time to failure that depends exponentially on the absolute stress value. In the new model, the predictions of both CF and RS are special cases for constrained initial and boundary conditions. It is more general and flexible to consider, for example, subcritical initial stress states as commonly assumed for induced or intraplate seismicity. We estimate the pre-stress distribution at Groningen based on the background stress field and the existing fault structure. Using this and the temporal evolution of the 2D stress field in the reservoir, we show that the delayed onset, the peak seismicity rate in 2013-2015 and the decline in observed seismicity today are well explained.

What Drives the Variability in Earthquake Sequence Productivity in California and Nevada?

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It is widely recognized that earthquake sequences exhibit substantial variability in productivity, but the physical mechanisms underlying this observation remain poorly understood. In this work we focus on resolving systematic variations in the productivity of crustal earthquake sequences in California and Nevada, the two most seismically active states in the western US. We apply a well-tested nearest-neighbor algorithm to automatically extract earthquake sequence statistics from a unified 40-year compilation of regional earthquake catalogs that is complete to ~M2.5. We then compare earthquake sequence productivity to geophysical parameters that may influence earthquake triggering processes, including heat flow, temperature at seismogenic depth, complexity of quaternary faulting, geodetic strain rates, depth to crystalline basement, and faulting style. We observe coherent spatial variations in earthquake sequence productivity, with higher values in the Walker Lane of eastern California and Nevada than along the present-day plate boundary fault system in western California. The results illuminate significant correlations between productivity and heat flow, temperature, and faulting that contribute to the understanding and ability to forecast crustal earthquake sequences in the area.

Modernizing Earthquake Forecasts Testing and Experimentation: CSEP Open-Software Contributions

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The Collaboratory for the Study of Earthquake Predictability (CSEP) is an international research community that supports earthquake predictability research through rigorous testing of earthquake forecasting models. Traditionally, CSEP experiments were facilitated by a server infrastructure that autonomously performed model evaluations and whose first implementation used centralized servers tightly coupled to the testing software. Open-science initiatives and open-source software development, however, led CSEP to improve this framework. First, a software toolkit for earthquake forecast users, pyCSEP, was developed to include the core scientific routines for evaluating forecasts, such as: (1) earthquake catalog access and processing, (2) representations of probabilistic earthquake forecast models, both gridded- and catalog-based, (3) statistical tests for earthquake forecast evaluation, and (4) visualization routines. pyCSEP is being continuously developed by a community of researchers who vet its source code and keep up with new testing theoretical methods.

To further improve the experimentation process, CSEP experiments will be redesigned to (i) safeguard an experiment's reproducibility, (ii) facilitate their transparency, accessibility, and persistence, (iii) standardize experimental procedures, and (iv) benchmark experiments for future model developments. To this end, a novel format called Floating Experiment is being developed and managed by the application floatCSEP. The testing process is decentralized from a physical infrastructure, aiming at full reproducibility on any machine, given sufficient computational power. The experiment definition, rules, artifacts, and environment are encapsulated as source code and readily curated in open-data repositories. These Floating Experiments are then live reproducibility software packages able to process, update and deliver results on-demand, both by authoritative institutions and independent users. The CSEP community envisions pyCSEP and floatCSEP as essential elements in a larger software ecosystem that can be used together to quantify earthquake hazards and risk.

Operational Earthquake Forecasting in Japan: A Study of Municipal Government Planning for an Earthquake Advisory or Warning in the Nankai Region

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A team of social scientists from the US and Japan have conducted a study exploring the extent to which municipal governments in Japan have developed plans for response to an operational earthquake forecast (OEF) from the Japan Meteorological Agency (JMA) indicating that seismic activity in the Nankai Trough region has elevated the short-term probability that a major earthquake may occur. Employing both survey research and in-depth interviews, the team explored various aspects of the history and science behind the alerting system, guidance from the national government of Japan and planning by local jurisdictions for a possible future Nankai Trough major earthquake. The survey included questions regarding planning actions included in a response plan for receipt of "special earthquake warning information (SEWI)" as well as questions regarding challenges in the planning process, expectations that an earthquake would follow the issuance of an alert and whether planning would reduce the number of fatalities and injuries. We also conducted in-depth interviews that explored the scientific basis for the alerting system and asked working disaster managers in the Nankai region what they had done to plan and if plans had not been developed, the reasons for not planning. Our survey netted 469 responses from a total of 736 jurisdictions in the Nankai region, a response rate of 63.7%. We conducted a total of 17 in-depth interviews. In general, we found that a majority of jurisdictions have response plans for receipt of an alert from the Japan Meteorological Agency (JMA); however, the plans lacked a number of planning elements considered important from a disaster management perspective. In addition, many smaller jurisdictions lacked the staffing, resources and guidance to form comprehensive response plans. Our report identifies both the strengths and weaknesses of existing plans and outlines a program for improving planning in the region.

New Insights into the Development, Testing and Communication of Seismicity Forecasts [Poster Session]

Poster Session • Thursday 2 May

Conveners: Jose Bayona, University of Bristol (jose.bayona@bristol.ac.uk); Kelian Dascher-Cousineau, University of California, Berkeley (kdascher@berkeley.edu); Leila Mizrahi, Swiss Seismological Service (leila.mizrahi@sed.ethz.c); William Savran, University of Nevada, Reno (wsavran@unr.edu); Max Schneider, U.S. Geological Survey (mschneider@usgs.gov)

POSTER 39

The Pattern of Earthquake Magnitude Clustering Based on Interevent Distance and Time

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The clustering of earthquake magnitudes is poorly understood compared to spatial and temporal clustering. Better understanding of correlations between earthquake magnitudes could provide insight into the mechanisms of earthquake rupture and fault interactions, and improve earthquake forecasting models. In this study we present a novel method of examining how seismic magnitude clustering occurs beyond the next event in the catalog and evolves with time and space between earthquake events. We first evaluate the clustering signature over time and space using double-difference located catalogs from Southern and Northern California. The strength of magnitude clustering appears to decay linearly with distance between events and logarithmically with time. The signature persists for longer distances (more than 50km) and times (several days) than previously thought, indicating that magnitude clustering is not driven solely by repeated rupture of an identical fault patch. The decay patterns occur across different magnitude ranges of the catalog and can be demonstrated across multiple methodologies of study. These patterns are also shown to be present in laboratory rock fracture catalogs but are absent in ETAS synthetic catalogs. Incorporating spatial and temporal decay of magnitude clustering into earthquake forecasting approaches that currently use ETAS models would likely improve their accuracy.

POSTER 40

ETAS-positive: An Epidemic-Type Aftershock Model That Is Insensitive to Catalog Incompleteness

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Earthquake catalogs provide incomplete records of the earthquakes that occur, due to saturation of the network during periods of high activity. Incompleteness typically manifests as an early-time plateau in the aftershock rate, during which the rate exceeds the maximum detection rate of the seismic network. This complicates the generation and testing of aftershock forecasts, which need to consider all of the earthquakes that occur, not just those that make it into the catalog. Traditional attempts to recover unbiased statistics involve modeling the time-dependent completeness magnitude, but such models are non-unique and introduce their own biases and uncertainty.

In previous work, I demonstrated how to set up the estimation of common seismicity parameters in a way that minimizes sensitivity to incomplete data. Using the 'positive' statistics approach, parameters are estimated within nominally complete intervals, defined by pairs of earthquakes where the second is larger than the first. The first earthquake in the pair sets a reference magnitude above which subsequent earthquakes are likely to be detected, and a small positive magnitude adjustment ensure arbitrarily high detection probability. This definition makes no reference to an absolute magnitude of completeness. I previously applied this method to the estimation of the *a* and *b*-value of the Gutenberg-Richter distribution; here I extend the approach to the epidemic-type aftershock sequence (ETAS) model. I define pairs following the same scheme used for *a*-positive, where every earthquake defines the start of a 'complete' interval terminated by the next larger earthquake. In situations where there is no next larger earthquake, the open interval is used. The ETAS+ likelihood is then maximized only over these complete intervals.

Applying ETAS+ to global aftershock sequences reveals little evidence for an early-time plateau in rate, with an Omori c-value of 60 seconds following magnitude 6.5 and larger mainshocks. This is coincident with the times of the earliest cataloged aftershocks.

POSTER 41

Correlations of Deep Low-Frequency and Crustal Earthquake Activity in Parkfield, Ca, and Implications for Their Joint Use in Forecasting Frameworks

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Faults exhibit a wide spectrum of slow slip behaviors that shape the distribution of forces on a fault network, thus informing when and where seismicity occurs. Although it is well documented that large (M>6) slow slip transients can both trigger seismicity swarms and be influential in the nucleation of larger earthquakes, the contribution of smaller-magnitude (M<5) slow slip events to shaping nearby seismicity is still elusive. At the edge of the creeping section of the San Andreas fault near Parkfield, deep slow-slip events are small enough that they are mostly detected indirectly through the activity of low-frequency earthquakes (LFEs). Using them as a proxy for deep slip, our objective is to understand the inter-dependence of deep slow-slip and seismicity in the upper crust, to assess if LFEs could help forecast shallow seismicity changes.

In this work, we show that a significant increase in seismicity occurs both before and after days of high LFE activity. It is consistent with a systematic interaction of deep slow-slip and shallow seismic release. The signal we detect may very well be a sign that the two catalogs are correlated for other reasons. We therefore evaluate possible external sources of correlation, including dynamic triggering of both populations from distant earthquakes and inter-dependent detection thresholds for both catalogs. Such effects would systematically bias any seismicity forecast using LFEs, by interpreting activity correlation as causal interaction between the populations during the learning phase. We finally assess the added value of incorporating LFE activity as additional information to predict seismicity using a deep-learning forecasting model (RECAST, Dascher-Cousineau et al., 2023). The model learns how to predict the timing of the next event based on timing and magnitude and is flexible enough to integrate additional observables to describe the history of activity. We therefore train the model to learn from the number of LFEs in a short period before each earthquake, evaluate the change in forecasting performance and discuss the added-value to the forecasting problem.

POSTER 42

Stress Shadows: Insights into Physical Models of Aftershock Triggering

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Why some aftershocks appear to occur in stress shadows, regions of Coulomb stress decrease due to a mainshock, is an open question with implications for physical and statistical aftershock models. New machine-learning focal mechanism catalogs make it possible to study the fault orientations of aftershocks occurring in the stress shadows, and test competing hypotheses about their origins. There are three main hypotheses: (1) Aftershocks appear in shadows because of inaccuracy in the computed stress change. (2) Aftershocks in the shadows occur on faults with different orientations than the model receiver faults, and these unexpected fault orientations experience increased Coulomb stress. (3) Aftershocks in the shadows are triggered by dynamic stress changes. We test these three hypotheses on the 2016 Kumamoto and 2019 Ridgecrest sequences. We test Hypothesis 1 through many realizations of the stress calculations with multiple mainshock models, multiple receiver fault orientations based on background events, and a range of coefficients of friction. We find that numerous aftershocks are consistently in the stress shadows. To test Hypothesis 2, we consider whether the individual event focal mechanisms receive an increase of Coulomb stress. Again, we perform many realizations of the stress calculation, this time with receiver fault orientations based on the focal mechanism and its uncertainty. Many of the aftershocks in the shadows consistently show a Coulomb stress decrease on the planes of their focal mechanisms. These results imply that aftershocks do occur in stress shadows, many on fault planes receiving a decrease in static Coulomb stress, contrary to Hypotheses 1 and 2. We test Hypothesis 3 by investigating the modeled dynamic stress changes on the individual event focal mechanisms. Preliminary results show that while the amplitude of the dynamic Coulomb stress change is generally lower on the aftershock nodal planes than on the planes of background events, the amplitude of the dynamic normal stress change is often 20%-100% higher. This suggests a dynamic triggering mechanism related to changing fault strength.

POSTER 43

The Generalized Long-Term Fault Memory Model and Applications to Paleoseismic Records

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Paleoseismic studies show large variability in earthquake inter-event times along a fault, with short intervals often separated by long quiescent periods. Some paleoseismologists have interpreted this variability as a product of an earthquake's partial strain release with the next earthquake occurring sooner than expected because of the remaining residual strain. However, commonly used probabilistic large earthquake recurrence models attribute this variability purely to chance, not the state of strain on the fault. Here, we present an alternative probabilistic model, built on the Long-Term Fault Memory model framework that better reflects the strain accumulation and release process. This Generalized Long-Term Fault Memory model (GLTFM) predicts that this inter-event time variability arises from both chance and the state of strain on the fault. Specifically, it estimates when residual strain is likely present and its impact on the timing of the next earthquake in the sequence. Additionally, GLTFM assumes that additional accumulated strain always increases earthquake probability. In contrast, the commonly used lognormal and Brownian Passage Time models predict that the probability of a large earthquake stays constant or even decreases after it is "overdue" (past the observed average recurrence interval) so additional accumulated strain does not make an earthquake more likely. GLTFM's simple implementation and versatility should make it a powerful tool in earthquake forecasting.

POSTER 44

Prototyping Aftershock Forecast Maps and Products Based on User Needs

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After large earthquakes, aftershock forecasts are released by science agencies and can inform decisions on earthquake response and recovery by diverse users (e.g., emergency managers, critical infrastructure operators, and public information officials, among others). Visual design choices for forecast products can affect how the forecasts are used and understood by such varied groups. We recently held several user workshops in the United States, Mexico and El Salvador and found that user needs for aftershock forecast information may vary by profession, use case, country, and with time since the mainshock. In this study, we prototyped aftershock forecast products to support the distinct user needs found in our workshops by translating user needs into design choices for the product. Design choices were also based on literature-backed best practices in data visualization and cartography for natural hazards. We developed multiple versions of probabilistic shaking forecast maps, where we varied such design choices as color palette, discretization of the data, additional map layers and whether to animate the map. Each prototype corresponded to a version of the forecast map aligned with specific user needs. Additionally, we created non-spatial forecast products around user needs, such as tables or graphics for the forecasted probability or number of aftershocks and how this is forecasted to decrease with time. We carefully considered how to communicate uncertainty across the huge ranges (orders of magnitude) often provided by these forecasts. We assessed these forecast product prototypes with a focus group of our workshop participants from the United States, Mexico and El Salvador, revising products based on their feedback. We discuss implications for the visual communication of earthquake and aftershock forecasts to wide-ranging audiences. Ideas for future testing of our product prototypes include task-based online experiments where participants use candidate forecast products to perform tasks based on common use cases for aftershock forecasts.

POSTER 45

Observations of the Aftershock Sequences of Intermediate-Depth Earthquakes Beneath Japan

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The increasing pressure and temperature with increasing depth in the Earth should prevent earthquakes from occurring >50 km depth, yet they are observed occurring down to ~700 km. At intermediate depths, the two most commonly proposed mechanisms are dehydration embrittlement and thermal shear instability. These two mechanisms have different implications for aftershock production — dehydration embrittlement would lead to aftershock patterns similar to those observed for shallow earthquakes whereas thermal shear instability would result in few aftershocks — so observing and quantifying the temporal decay of intermediate-depth aftershock sequences can help distinguish the causative source mechanism. Japan's high earthquake activity, earthquake catalog with a low magnitude of completeness, and contrasting properties of the subducting Pacific and Philippine Sea Plates make it an excellent location to study intermediate-depth aftershock sequences and how different factors contribute to aftershock productivity. We analyze the 199 earthquakes in the JMA Unified Earthquake Catalog from 1985-2021 with $M_J \geq 5.7$ at 70-350 km depths and are able to fit the modified Omori's Law to quantify the temporal decay for 21 of the aftershock sequences. The aftershocks tend to be clustered around the mainshock, so an aftershock zone can be drawn that separates the aftershocks from the surrounding background seismicity. Earthquakes within this subjective aftershock zone are used to characterize the aftershock sequences. In comparison with shallow aftershock sequences, the characterized aftershock sequences have a similar temporal decay exponent $p \cong 1$ but much lower productivity. Preliminary results suggest that productivity is higher in the Pacific Plate than in the Philippine Sea Plate, in the upper plane of the double seismic zone than in the lower plane, and for shallower earthquakes. The characterized sequences last from ~40 days to >30 years. The characterized aftershock sequences are closer to our expectations for dehydration embrittlement than thermal runaway. Variations in productivity may relate to the amount of fluid available.

Numerical Modeling in Seismology: Developments and Applications

Oral Session • Wednesday 1 May • 8:00 AM Pacific

Conveners: Alice-Agnes Gabriel, University of California, San Diego (algabriel@ucsd.edu); Martin Galis, Comenius University Bratislava (martin.galis@uniba.sk); Jozef Kristek, Comenius University Bratislava (kristek@fmph.uniba.sk); Peter Moczo, Comenius University Bratislava (moczo@fmph.

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Reflection and Transmission of Inhomogeneous Plane Waves in Thermoporoelastic Media with Two-temperature Equations of Heat Conduction

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Elastic wave propagation analysis in fluid-saturated high-pressure, high-temperature fields is among the most important and effective methods for georesource exploration. Successful explanation and interpretation of deep resources requires a valid and simple rock physics model that combines rocks' porous properties and thermal nature.

The theory of thermoporoelasticity introduces mechanical-thermal coupling in poroelasticity. We develop a modified thermoporoelastic model with fluid-saturated by introducing two temperature equations to account for the temperature differences between the solid skeleton and the pore filling. The modified two-temperature-generalized thermoporoelastic (TTG) equation is an extension of the classical single-temperature LS, GL, and generalized LS theories. It predicts four compressional waves and one shear wave, i.e., fast P (P1), slow P (P2), thermal (T1), slow thermal (T2), and S waves, based on the analysis of inhomogeneous plane waves. We derive the reflection and transmission coefficients of a plane wave with the inhomogeneity angle incident on the interface separating two half-spaces based on the TTG equation. The coefficients as a function of incidence angle and porosity are presented. We also develop the corresponding AVO approximation to compare with that of the Biot poroelastic model and study the fluids' effects.

The inhomogeneity angle is found to affect the attenuation values of the P1 and S waves more strongly, with an increase in the angle leading to enhanced attenuation, especially in the range caused by Biot dispersion, while the dispersion for the other three waves shifts to the high frequencies. The critical angle of P1 waves increases with porosity until it vanishes, where the velocity of the P1 wave in the transmission medium is equal to the incidence. Comparison with the Biot poroelastic case of the water/oil contact shows that the TTG model reproduces the exact R/T results. The AVO response of oil and gas reservoirs illustrates the practical applicability of the proposed model and provides the theoretical basis for the exploration of high-temperature resources.

Dynamic Rupture Simulation of Caldera Collapse Earthquakes: Effects of Wave Radiation, Magma Viscosity, and Evidence of Complex Nucleation at Kīlauea 2018

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All instrumented basaltic caldera collapses generate $M_w > 5$ very long period earthquakes. However, previous studies of source dynamics have been limited to lumped models treating the caldera block as rigid, leaving open questions related to how ruptures initiate and propagate around the ring fault, and the seismic expressions of those rupture dynamics. We present the first 3D numerical model capturing the nucleation and propagation of ring fault rupture, the mechanical coupling to the underlying viscoelastic magma, and the associated seismic wavefield. We demonstrate that seismic radiation, neglected in previous models, acts as a damping mechanism reducing coseismic slip by up to half, with effects most pronounced for large magma chamber volume, high magma compressibility, or large caldera block radius. Viscosity of basaltic magma has negligible effect on collapse dynamics. In contrast, viscosity of silicic magma significantly reduces ring fault slip.

We use the model to simulate the 2018 Kīlauea caldera collapse. Three stages of collapse, characterized by ring fault rupture initiation and propagation, deceleration of the downward-moving caldera block and magma column, and post-collapse resonant oscillations, in addition to chamber pressurization, are identified in simulated and observed (unfiltered) near-field seismograms. A detailed comparison of simulated and observed displacement waveforms corresponding to collapse earthquakes with hypocenters at various azimuths of the ring fault reveals a complex nucleation phase for earthquakes initiated on the northwest. Our numerical simulation framework will enhance future efforts to reconcile seismic and geodetic observations of caldera collapse with conceptual models of ring fault and magma chamber dynamics.

What Is the Principal Accuracy Limit of a Seismic Wavefields Simulated by a Finite-Difference Method?

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The finite-difference method is based on spatial discretization of a medium for which seismic wave propagation and earthquake motion are to be simulated. Moczo et al. (2022) systematically analyzed equations of motion in the wavenumber domain and found that the discrete (grid) representation of the heterogeneous medium must be wavenumber band-limited up to the Nyquist frequency. Mittet (2021a) reported that if the discrete grid model of medium coincides with the true medium up to some wavenumber, the simulated wavefield is accurate only up to a half of this wavenumber.

We present results of the comprehensive analysis focused on the principal limits of accuracy of numerically simulated wavefields. The analysis includes A. wavenumber spectra of a) exact wavefields in a heterogeneous elastic medium, b) wavenumber band-limited wavefields, c) spatially discretized wavefields, B. spatial dependence of the frequency spectrum of waves generated by a finite source, C. perturbing wavefields due to a small perturbation of the medium and due to a small wavenumber band-limited perturbation of the medium, D. interaction of an incoming wave with the medium perturbation through phase difference and wavenumber spectra.

In the synthesis of partial findings, we draw conclusions on the wavenumber limitation of wavefields in the wavenumber band-limited heterogeneous medium, and the principal consequence for the numerical modeling based on spatial discretization of the computational domain.

Modeling the Seismic Noise Horizontal-to-Vertical Spectral Ratio in Laterally Irregular Configurations Using the Diffuse Field Assumption

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The horizontal-to-vertical spectral ratio (HVSR) of ambient seismic noise (ASN) is a current measure to assess the predominant soil frequency of a given site. We assume that ASN field comes from equipartioned, uniform illumination of random sources and the scattering by heterogeneities leads to some equilibration that makes a field diffuse. Besides, diffuse fields are closely related with the Green's function. Under the diffuse field assumption (DFA) theory asserts that the average directional energy densities (DED) are related to Green's function. Therefore, using ASN and under the DFA, the HVSR is computed with the imaginary parts of the Green's function. That fact made the inversion of soil properties in depth feasible for horizontally layered media. However, this is not completely free of uncertainties about the diffuse character of the wavefield and the non-uniqueness of the inversion, subjects that require further scrutiny. In practice, lateral variations are ignored or integrated with some interpolation. Their study may add physical meaning to the quest because HVSR in irregular layered settings has significant lateral and azimuthal variability. In this work, we model HVSR under the DFA and use the 3D indirect boundary element method (IBEM) to study an irregular layer and use an adaptive mesh scheme by accounting for the locality of problem and the wave diffraction properties. Our preliminary results show that layer irregularities may lead to "spots" of enhanced wave excitation and suggest the need for denser field measurements to study lateral variations and azimuthal variability. Clearly, the potential variations of possible substructures greatly exceed any information present in HVSR. As ever, one must supplement with extra information, possibly non-seismic, and learn to live with some uncertainty. We discuss results and examine the implications for seismic hazard assessment.

The Ongoing Development of Distributional Finite-difference Modeling in Global Seismology

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DFDM was recently introduced as a new numerical simulation approach that combines advantages from classic finite difference and finite element methods for solving the elastic wave equation (Masson, 2022). Through two/three-dimensional benchmarks against the well-established spectral element method (SEM) in Matlab, we have demonstrated this algorithm's high level of precision, at reduced computational cost with the flexibility to describe the meshing. We recently started a collaboration with the Application Performance Group at NERSC to develop a distributed version of the solver in C++ optimized for use on HPC platforms.

Numerical Simulation of Strong Ground Motion for the Mw 6.0 Jishishan Earthquake of 18 December 2023 in Gansu Province, China

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The Mw6.0 Jishishan earthquake on December 18, 2023 occurred along the eastern edge of the Tibetan Plateau and resulted in significant human casualties. To gain a better understanding of earthquake source properties and wave-propagation effects, we conducted simulations of the strong ground motion in the near field of the fault, incorporating 3D earth structure, finite-fault rupture, and realistic surface topography. In this study, the topography elevation from SRTM90, a global digital topography dataset is adopted. We utilized a 3D velocity model of the continental China lithosphere, USTClitho2.0, to simulate wave propagation in a box-like volume with a dimension of 300 km × 300 km at the surface and 30 km in depth. Our primary focus lies in the impact of the slip model on the simulated ground motions. The finite fault-slip models employed in this study include Zhang's preliminary rupture model obtained through iterative deconvolution and stacking of high-rate GPS and strong motion seismogram data, Zhang's rupture model obtained through joint inversion of teleseismic and strong motion data, Wang's rupture model and the GP source model. We apply a hybrid broadband method to simulate the ground motions within the frequency range 0.1–20 Hz. The low-frequency seismograms (<1hz) are simulated by 3D non-staggered grid finite-difference method, which incorporates boundary-conforming grids in the presence of an irregular free surface.The high-frequency seismograms are calculated using the stochastic approach. Then, we combine the high- and low-frequency seismograms to obtain broadband seismic motion by considering both amplitude and phase matching. We compare the simulated ground motions based on different finite fault models with the observed near-field records and the corresponding peak values. Furthermore, an analysis of the differences in strong ground motion calculated from different rupture models is presented. The results demonstrate the effectiveness of hybrid broadband method in predicting strong ground motion parameters, provided that appropriate Earth structure and earthquake rupture models are utilized.

A Detailed Analysis of Body Waves Simulated in Homogenized Media

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Non-periodic homogenization has proved to be an accurate asymptotic method for computing long-wavelength equivalent media for the seismic wave equation, turning small-scale heterogeneities and geometric complexity into smooth elastic properties. Using homogenized media allows i) decreasing the computation cost of wave propagation simulation and ii) studying the apparent, small-scale-induced anisotropy. After illustrating these two aspects briefly, we propose to analyze in great detail the accuracy of body waves simulated in homogenized 3D models of the subsurface. First, the behaviour of head-, reflected and refracted waves with respect to source-receiver offset, maximum frequency and velocity contrast across a planar interface, is investigated. Then, we consider the SEG-EAGE overthrust model to exemplify how the accuracy of simulated body waves anti-correlates with the distance to seismic source and the amount of apparent anisotropy. In high apparent anisotropy regions, we show that the first-order correction provided by the homogenization theory significantly improves the computed wavefield. The overall results of this analysis better frame the use of homogenized media in seismic wave simulation.

Efficient Lossy Compression of Simulated 4d Seismic Wavefields

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State-of-the-art inversion and imaging technologies, such as Full Waveform Inversion (FWI) and Reverse Time Migration (RTM) require the ready availability of the forward simulated wavefields or Green function wavefields during gradient calculation. As storing all the wavefield of all time steps, which a 4D volume, in computer memory is impractical for 3D problems, the most intuitive strategy would be to store the 4D simulated wavefield data on disk. However, this will introduce an important bottleneck because of the significant I/O overhead and decrease in performance. To overcome this bottleneck, we incorporate the efficient lossy compression techniques based on Tucker tensor decomposition into waveform inversion workflow by storing the compressed 4D simulated wavefield onto the disk instead of reconstruction on-the-fly. For Tucker tensor decomposition, the simulated seismic wavefield sequence with three spatial dimensions and a time dimension can be naturally represented as a 4-way tensor, and then detects the global structure of the tensor and removes redundant information, resulting in a low-rank representation of the data. We compared the Tucker-based compression with other common compression schemes on compression ratio, accuracy, and compression/decompression time, and the results show that Tucker-based compression is a good choice for real-time online compression of 4D simulated wavefield data since it can efficiently compress the wavefield by more than 100x with less than 40% time overhead in our tests. To verify the effectiveness of the method in FWI workflow, we use the 3D collocated-grid finite-difference algorithm on curvilinear grids to simulate seismic wavefield in the presence of surface topography (CGFD3D). The efficient lossy compression is applied in the ambient noise waveform inversion of seismic data in the Longmenshan area, which greatly speeds up the computation compared with directly outputting the forward wavefield and strain Green tensor without compression.

Effects of Dip Angle on Rupture Propagation Along Branch Fault Systems

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An important consideration in assessing seismic hazards is determining what is likely to happen when an earthquake rupture encounters a geometric complexity such as a branch fault. Previous studies showed parameters such as branch angle, stress-orientation, and stress heterogeneity as key factors in the self-determined rupture path on branch faults. However, most of these studies were conducted in 2-D space or in 3-D with perfectly vertical faults. Many natural strike slip faults do not form perfectly vertical and have some dipping angle. In this study, we investigate the effects of dipping angle on rupture propagation along a branch fault system. We construct 3-D finite element meshes where we vary the dip angles (9 geometries in total) of the main and secondary faults, the stressing angle ($\Psi = 20°$, $40°$ and $65°$) and the hypocenter location with nucleation on both the main and secondary segments. We find that for intermediate stressing angle ($\Psi = 40°$), a rupture on the main fault is most likely to propagate across the branch intersection when the secondary fault is dipping. Also, for high stressing angle ($\Psi = 65°$), a rupture on the secondary fault is most likely to propagate to the main fault when the secondary fault is shallowly dipping. This is caused by a fast rupture speed on the secondary fault and the dynamic stress effect that develop with the interaction of the free surface and the dipping secondary fault. These results indicate that dip angle is an important parameter in determination of rupture path on branch fault systems, with potentially significant impact for seismic hazard and should be taken into account in future earthquake modeling.

Insight From 3D Deterministic Ground Motion Simulations in Central Italy

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Starting on August 24, 2016, with the M6.2 Amatrice earthquake, a sequence of earthquakes has resulted in numerous casualties and significant damage to buildings in central Italy. Following the Amatrice mainshock (Mw6.2), the Visso (Mw5.9) and Norcia (Mw6.5) events occurred two months later. The seismic activity has been meticulously recorded by a dense network of strong motion stations, with over 40 stations located within 50 km from the fault rupture. Considering the persistent seismic activity in this region, our objective was to develop a tool using a fully deterministic 3D approach to calculate strong ground motions at higher frequencies, intended for use in seismic hazards and engineering applications. We also examined the impact of the source rupture model in the near-source area. We tested an end-to-end modeling capability for strong ground motion simulations, utilizing the extensive recorded data and predictions from regional Ground Motion Models (GMMs). The simulations were conducted in the frequency range of 0-3Hz and 0-5Hz using a physics-based deterministic technique to model earthquake rupture and elastic wave propagation for the Amatrice and Norcia earthquakes. We employed SW4, a finite difference code designed to use a topography-conforming curvilinear mesh for modeling surface topography with high numerical accuracy. Incorporating several rupture scenarios, our simulations demonstrated a direct correlation between the pattern of near-fault ground motion amplification and the slip distribution over the fault. We found that large slip patches have a pronounced impact not only on the intensity of ground motion but also on , the inter-event variability of the PGV. In our simulations, ground motions computed with and without surface topography showed an average PGV that is 30% higher for models incorporating surface topography in the case of Norcia event. We believe that our results provide a valuable framework for understanding the physical parameters and how they contribute to the amplitudes of ground motions observed during earthquakes in Central Italy.

The 2022 Mw 6.6 Menyuan Earthquake, Qinghai, China: An Early-terminated Runaway Rupture Revealed by the Dynamic Rupture Simulations

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The 2022 Mw 6.6 Menyuan earthquake is one of the best-recorded strike-slip events in the northeastern Tibetan plateau. There is still a puzzle about this event: why did it generate unexpectedly large surface dislocations (about 2.6–3.5 m) relative to its seismic magnitude? To explore the mechanism, we conducted numerous dynamic rupture simulations with a grid search method to screen out a preferred dynamic model that fits the geodetic, seismic, and geological observations well. The results show that the average stress drop of the nucleation part of the seismogenic fault is relatively high (11 MPa), which indicates that this event might nucleate with high initial energy as a runaway rupture and be capable of growing into a large earthquake (≥Mw 7.0). However, the rupture propagating eastward is slowed and terminated by two consecutive fault bends of about 10º each, and the westward propagating one might self-arrest on the south secondary fault after it jumps over the stepover. Thus, the fault bend and stepover terminate the rupture propagation early. That's why the observed magnitude (Mw 6.6) is smaller than the estimated one (Mw 7.1–7.2) based on surface offsets. Our study shows that, due to advances in computational power and observations (coverage and quality), physics-based dynamic rupture simulations have entered an era where it is possible to fit the wide variety of observations well, which is vital for further understanding the complex earthquake rupture mechanics. More importantly, our results imply that some moderate-to-strong earthquakes, which can grow into large ones, fail to develop into large earthquakes because their rupture propagations are terminated early by stress barriers. This new understanding of earthquake ruptures can provide theoretical guidance for future seismic risk assessments.

Using a Dynamic Earthquake Simulator to Explore Three-Dimensional Multicycle Dynamics of Stepover Faults

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Classical earthquake simulators such as RSQsim do not capture spontaneously dynamic rupture propagation, which calls into questions about robustness of rupture extent and path from these simulators on geometrically complex faults from these simulators. We have been developing a finite element method (FEM) dynamic earthquake simulator to capture both spontaneously dynamic rupture propagation and other quasi-static processes of earthquake cycles. The dynamic earthquake simulator is based on EQdyna, an explicit FEM dynamic solver originally developed for spontaneous rupture propagation along geometrically complex faults and seismic wave propagation in heterogeneous media. We adopt a dynamic relaxation technique to solve quasi-static problems of earthquake cycles using the dynamic solver. Therefore, the EQdyna-based dynamic earthquake simulator solves both dynamic and quasi-static processes of earthquake cycles in the same FEM framework.

Previous studies on dynamics of stepover faults are primarily in two dimensions. In this research, we apply the dynamic earthquake simulator to explore three-dimensional dynamics of stepover faults over multiple earthquake cycles. To our knowledge, this is the first of fully dynamic earthquake cycle simulations on geometrically complex faults in the scientific community. In this study, we specifically examine effects of different depth profiles of the effective normal stress and different loadings on earthquake patterns and rupture behaviors of stepover faults over many earthquake cycles. Our preliminary results show that the depth-dependent effective normal stress results in more complex event patterns and rupture behaviors than the depth-independent case. For the depth-independent case, different loading rates do not affect the event pattern much, though faster loading rates result in shorter recurrence intervals. Our results also suggest that jumping ruptures are more difficult to occur in three dimensional models than in their two-dimensional counterparts over many earthquake cycles.

Entropy Approach to the 2021 Alaska 8.2 Earthquake

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The year 2021 was abundant in large earthquakes worldwide and the most important was the one of Alaska, Mw 8.2, which generated important aftershock activity. In this paper, we use Tsallis Entropy, Shannon Entropy, and Mutability to categorize the various stages of the phenomenon: a) random seisms; b) increase (decrease) of Tsallis entropy (mutability) years/months before the big earthquake; c) several seisms with magnitude close or over 7.0; d) a long aftershock regime lasting to present days. From the entropy point of view, we find similarities and differences in this behavior compared to that of the recently reported analysis of the Mw 8.1 earthquake of Iquique on April 1, 2014 [1].

We mainly conducted the analysis on the magnitude sequence from 2000-01-01 to 2023-12-31 obtained from the USGS web page. It is clearly appreciated how Tsallis entropy raises during 2019 in parallel to the decrease in mutability. Then, they abruptly reverse this behavior on the occurrence of the large earthquakes of 2020. However, Tsallis entropy (mutability) quickly increases (decreases) its value to the levels previous to this earthquake within a matter of months, only to sharply collapse (raise) for the 8.2 earthquake of 2021. It soon recovers, reaching the levels previous to the 2020 seisms, which is a worrisome sign. Shannon entropy heels the results for mutability, which is preferred because of its clearer results in perfect agreement with those got by Tsallis entropy. We can also do the analysis using the interval sequence (time between successive seisms) which is complementary to the one based on magnitudes. The combination of these results define a powerful technique able to shine light on the seismic activity years prior to major quakes and could be a potential indicator for categorizing seismic risk areas.

[1] *Tsalllis Entropy and Mutability to Characterize Seismic Sequences: The Case of 2017-2014 Northern Chile Earthquakes*. Denisse Pasten, Eugenio E. Vogel, Gonzalo Saravia, Antonio Posadas, and Oscar Sotolongo, *Entropy* 25 (2023) 1417 (https://doi.org/10.3390/e25101417).

On the Dynamic of Peierls Creep at Subduction Zones: Implication for Intermediate-Depth Lower Plane Earthquakes

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Most earthquakes occur within Earth's subduction zones, where oceanic plates, possessing negative buoyancy, descend into the underlying asthenosphere mantle at trench boundaries. The interactions between the subducting slab and the surrounding mantle generate substantial deformation, resulting in double zone seismic in subduction regions, but the controversy of earthquakes in the lower plane persists. The occurrence of seismic events is intricately linked to the strength of tectonic plates. Olivine is presumed to influence plate strength through its rheological properties. Previous studies predominantly focused on dislocation and diffusion creep, neglecting the significance of Peierls creep. The wide variance in experimental approaches and flow laws used yields a diverse range of parameters related to Peierls creep.

To examine the impact of Peierls creep on deformation mechanisms and stress states within subducting slabs, pseudo-two-dimensional numerical models were developed using LaMEM. Systematic exploration of parameters including activation energy, activation volume, and Peierls stress categorizes model outcomes into three regimes, delineating the effects of Peierls creep on slab deformation patterns. When Peierls stress or activation energy is low, signifying strong Peierls creep effects and a weak slab, the subduction angle becomes substantial, eventually leading to a flat lying slab at the base. Conversely, higher activation energy with the inclusion of activation volume indicates diminishing Peierls effect and a stronger slab, potentially causing slab retrogradation. Increasing activation energy, Peierls stress, and critical activation volume tend to segment the slab, resulting in a moderate subduction angle. Additionally, given the Peierls creep's alignment with the lower plane seismic zone within the subduction double seismic zone, there is speculation regarding a potential correlation between lower plane seismic activity and Peierls creep, offering a novel perspective on seismic origins.

Quadrangular Adaptive Mesh for Elastic Wave Simulation in Smooth Anisotropic Media

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The management of smooth anisotropic media holds significant importance for seismic wave simulation and imaging. In such media, adaptive meshes constitute, in principle, an attractive representation to maximize simulation accuracy while minimizing computational cost. However, creating such meshes can be difficult, because the optimal local size of the elements is not clearly defined in the case of smooth anisotropic media.

In this work, we present a two-step algorithm to efficiently mesh 2D these media for spectral element method (SEM) simulations. Our algorithm yields quadrangular meshes which adapt the size of the elements to the local effective and directional S-wave velocity. It first relies on the octree decomposition introduced by Maréchal (2009) to divide the mesh until the size of each element edge is adapted to the local minimum wavelength that will be propagated. Then, a smoothing is applied to further optimize the size and shape of the elements, which increases the global time-step and, consequently, makes SEM simulations faster while keeping a good accuracy or even improving it in some cases. The application of our method on a section of the homogenized Groningen area shows that simulation time can be reduced by a factor up to 3.

Numerical Modeling in Seismology: Developments and Applications [Poster Session]

Poster Session • Wednesday 1 May

Conveners: Alice-Agnes Gabriel, University of California, San Diego (algabriel@ucsd.edu); Martin Galis, Comenius University Bratislava (martin.galis@uniba.sk); Jozef Kristek, Comenius University Bratislava (kristek@fmph.uniba.sk); Peter Moczo, Comenius University Bratislava (moczo@fmph.uniba.sk); Arben Pitarka, Lawrence Livermore National Laboratory (pitarka1@llnl.gov); Wei Zhang, Southern University of Science and Technology (zhangwei@sustech.edu.cn)

POSTER 114

Utilizing Metaheuristic Algorithms for Ground Motion Selection and Scaling in Structural Time History Analysis

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This study proposes two Metaheuristic Algorithms for structural time history analysis to optimize the selection and scaling of ground motion (GM) records. The primary goal is to preserve the phase and shape of the response spectra in the selected records. The methodology efficiently navigates through a vast database of earthquake records, proposing a set of 11 record pairs and corresponding scaling factors. The outcome is a mean spectrum that closely aligns with the target spectrum. The application of our research is demonstrated at two distinct sites in the United States: the first in Memphis and the second in San Francisco, following the ASCE 7-22 procedure. Selected ground motions undergo scaling adjustments represented by scalar values within a user-defined range. Additionally, we present error metrics, comparing the target spectrum with the mean spectrum derived from the selected records. To validate the effectiveness of our approach, a comparative analysis is conducted against results obtained from the PEER-NGA web application methodology. The results highlight our model as a robust and reliable approach for acquiring suitable GM records for structural time history analysis.

POSTER 115

Building Geologically Realistic Initial Conditions for Geodynamic and Seismological Models With the Geodynamic World Builder

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Global and location specific geodynamical or seismological forward models are based on a variety of geological and geophysical data used to determine the often complex geometry of three-dimensional volumes representing structures such as layers within tectonic plates, crustal and lithospheric terranes, faults and subducting slabs. Creating such complex geological settings in 2D, but especially in 3D can be very challenging. Here we present the latest version of the open source code library, the Geodynamic World Builder (GWB). The GWB is designed to greatly enhance the speed of setting up and modifying such models by parameterization of the problem. The user defines inputs in a JSON-style parameter file, which is a structured nested list describing tectonic features, e.g. a continental, an oceanic or a subducting plate. Each of these tectonic features can be divided into layers (which can have variable thickness) and assigned a specific temperature model (e.g. linear or a plate model), a compositional label (e.g. uniform) and/or a grain size and orientation model. Complex models are developed by sequentially adding structures within a 3D domain. For each point in the domain, the GWB can be queried for the temperature, composition and/or grain size and orientation in that point.

The GWB is written in C++, but can be linked to either geodynamic or seismological models that require complex model setups in almost any programming language through its C, C++, Python and Fortran wrappers. It has already been coupled with the C++ code ASPECT and with the Fortran codes ELEFANT and SEPRAN. The GWB can also be used as a stand-alone application for visualization purposes. We will show various examples in both 2D and 3D and in Cartesian and spherical domains. We will share a range of examples from building regional subduction models using Bird (2003), Slab 2.0 and Litho1.0 to global mantle models. The GWB has an extensive online user Manual and a well documented API through Doxygen available through http://geodynamicworldbuilder.github.io and can be used with Linux, OSX and Windows operating systems.

POSTER 116

Passive Source Detection Technology Based on Short-Period Dense Seismic Array

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In the past decade, passive source detection technology based on short period dense array has increasingly become a domestic and international significant tool in the field of deep structure exploration. Compared with the traditional broadband seismic method, this technology has the advantages of high resolution, efficiency, cost saving, and minimal environmental impact. Despite the low-frequency signals being too weak to detect the deep structures within the lithospheric mantle, the dense station distribution allows imaging of detailed structures within Earth's crust. Furthermore, taking advantage of the dense ray crossing coverage from different directions beneath the array, a stable image of crust-mantle structures can be imaged by inversion and stack migration. Therefore, the short period dense array detection technology has been widely used in different fields, such as imaging of deep velocity and interface structure, mineral resources exploration, volcanic activity monitoring, microseismic high-precision Locations, and geometry and kinematic characteristics: key aspects of seismogenic faults. With the research progress of short period dense array in the field of imaging study on crustal structures and microseismic location monitoring. Looking into the future and guided by scientific questions, joint inversion and imaging could be carried out using a variety of geophysical data such as natural earthquake, ambient noise, gravity, InSAR, GPS and magnetotelluric measurements to acquire the multi-attribute characteristics of the interested targets, and this method is increasingly developing to an effective way to reduce the non uniqueness of solutions and reveal the real state of geological bodies. The rapid development of the detection methods in this area is expected to greatly promote the research of seismology and geodynamics, and has a broad application prospect in the fields of deep structure imaging and mineral resources exploration. As the world's leading manufacturer of short-period seismic equipment, SmartSolo provides highly reliable, consistent, and cost-effective short-period seismometer solutions.

POSTER 117

Effects of Bimaterial Interface on Rupture Along Strike-Slip Branch Faults

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Crustal faults often separate material with differing elastic properties. Dissimilar media around faults has been shown to cause substantial effects on the rupture process along vertical strike-slip faults. Some previous studies suggest that asymmetry in wave propagation across a bimaterial interface can introduce normal stress perturbations on the fault around the rupture front that can lead to asymmetric bilateral or even unilateral rupture propagation. Furthermore, a bimaterial interface can also lead to differences in strain release across a fault interface for a fixed stress drop. Considering the effects caused by bimaterial interface on rupture propagation and also the fact that natural fault systems can be composed of numerous segments, it is worth understanding whether these effects can be significant enough to impact throughgoing rupture across a geometric complexity. Therefore, in this work we use dynamic rupture simulations with uniform tractions to investigate the effects of a bimaterial interface on rupture propagation along branch faults. To do this we construct a planar branch system which consists of a 40 km long main fault bisected by a 20 km secondary segment, at a branching angle of 50°. We assign a zone of stiffer material to one side of the fault system, such that both the main and secondary fault separate dissimilar media. We vary the material contrast (γ) from 0-0.20 in the zone of stiffer material such that the p-velocity in the stiffer material is $Vp^*(1+\gamma)$, where Vp is the p-velocity in the rest of the elastic medium. The results show that when rupture is nucleated on the main fault it is less likely to rupture the secondary segment as the material contrast increases if the main fault and secondary faults have the same sense of slip. If the faults have opposite senses of slip, we find that a larger material contrast promotes rupture propagation on the secondary fault. This could have implications for assessing seismic hazard in regions with complex fault systems which separate dissimilar media, in particular which direction seismic energy may be directed during an earthquake.

POSTER 118

New Constraints on the Seismic Crustal Structure of the Southern Apennines (Italy): Numerical Modeling of P- and S- Body Waves for Moderate Earthquakes at Regional Scale

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The Apennines mountain range and the Tyrrhenian back-arc basin originated in the central Mediterranean area, due to the convergence and collision of the Eurasia and the Africa-Adria plates. Geological and geophysical studies reveal variations in structural, tectonic and seismogenic patterns along the chain axis, and across the western Tyrrhenian and eastern Adriatic domains (Di Luccio et al. 2022).

Our focus lies on the southern Apennines, where the Adriatic plate subducts westward under the thinner Tyrrhenian plate, forming a complex "overlapping-Moho" setting. This area exhibits high seismic activity and heterogeneous CO_2 gas emissions at the surface. Notably, these emissions cease to the east, where high-pressure fluids are trapped in the crust, influencing the seismogenic cycle (Chiodini et al. 2004).

Our approach involves P- and S-body waveform analysis and numerical modeling of moderate magnitude crustal earthquakes, at the regional scale. We concentrate on a SW-NE oriented transect cutting across the southern Apennines chain. Along this path the observed waveforms exhibit significant variations in frequency content and pulse shape, depending on both distance and azimuth. We analyze the 2018 Montecilfone (Mmax 5.1) and the 2013 Sannio-Matese (Mmax 5.0) seismic sequences, to examine the characteristics of westward and eastward wave propagation respectively.

We explore the trade-off between velocity and geometry perturbations starting from a 1D velocity model (Di Stefano et al. 1999). We upgrade the reference EPcrust model (Molinari et al. 2011) by incorporating external information on Moho and sedimentary layer structures (Spada et al. 2013, Nicolai and Gambini 2007). By employing the finite difference modeling code from Li et al. (2014), we generate synthetic waveforms to better fit the observed data, in terms of arrival time, pulse shape and waveform complexity on the three-component seismograms. Our results contribute to the understanding of the interplay between fluids and seismicity in the region, by providing higher resolution constraints on the structure of the southern Apennines.

The OSIRIS-REx Sample Return Capsule Re-entry: Geophysical Observations

Oral Session • Wednesday 1 May • 4:30 PM Pacific

Conveners: Chris Carr, Los Alamos National Laboratory (cgcarr@lanl.gov); Brian Elbing, Oklahoma State University (elbing@okstate.edu); Charles Langston, University of Memphis (clangstn@memphis.edu); Richard Lewis, The Defense Threat Reduction Agency (richard.d.lewis1.civ@mail.mil); Yasuhiro Nishikawa, Kochi University of Technology (nishikawa.yasuhiro@kochi-tech.ac.jp); Elizabeth A. Silber, Sandia National Laboratory (esilbe@sandia.gov)

First-Ever Detection of a Re-Entry Capsule With Distributed Acoustic Sensing (DAS): Initial Results and Data Comparison With Co-Located Seismic and Infrasound Sensors

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On 24 September 2023, the OSIRIS-REX sample return capsule re-entered Earth's atmosphere, generating infrasonic and seismic signals. The re-entry provided an ideal experiment for rapid deployment of fiber-optic cables to be sensed with distributed acoustic sensing (DAS) interrogator units (IUs). We deployed 12 km of fiber at two locations in Nevada, chosen for their proximity to the portion of the trajectory with anticipated maximum infrasound generation. At each fiber location, we deployed three co-located seismometers and infrasound sensors to inform interpretation of DAS data. For nearly the entire fiber length, we placed the fiber directly on the ground without any trenching or weights to increase ground coupling. We used three different IUs to sample the fibers at the two locations: an AP Sensing IU sampled 4.5 km of fiber at the Eureka Airport and a Silixa IU and an Optodas IU sampled 7.5 km of fiber in nearby Newark Valley. While seismometers and infrasound sensors have recorded previous space capsule re-entry events, our deployment represents the first DAS recording of a re-entry.

All our instruments recorded the signal generated by the sample return capsule. All seismometers and infrasound sensors recorded high SNR signals. The Silixa DAS data recorded a move out of the signal as it propagated along the 7-km fiber that can be seen without any pre-processing. We estimate back-azimuths to the infrasound-generating source using beamforming techniques for the Newark Valley data. Finally, we use arrivals recorded with the seismometers and infrasound sensors to interpret the DAS signals.

Array Data From the University of Memphis Seismo-Acoustic Coupling Experiment Fielded at the Eureka County Airport, Nevada

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In collaboration with Sandia National Laboratory, the University of Memphis fielded a seismo-acoustic array experiment at the Eureka County airport to record the sonic boom from the capsule return of NASA's OSIRIS-REx mission to the asteroid Bennu. Eureka airport is nearly under the expected trajectory of the incoming capsule that landed in the western Utah desert early Sunday morning, September 24. The University of Memphis portion of experimental observations consists of fielding a 1 km aperture, 3x6 Golay array, composed of 18 three-component Magseis-Fairfield 5 Hz nodal seismometers, with two sub-arrays of the Golay array each containing an extra seismic node and a 4-element infrasound array. The infrasound instruments were built by VLF Designs expressly for use with a REFTEK 130 DAS. The Golay array is designed to characterize the slowness and azimuth of the descending Mach cone that are needed parameters in modeling the conversion from the acoustic wave into P and S waves in the Earth. The Golay array also makes it possible to analyze any secondary seismic waves that may be generated by the acoustic N-wave through frequency-slowness analysis. Small-scale (94m), P and S wave refraction and MASW surveys were performed near each acoustic array to determine near-surface structure to constrain models of the seismo-acoustic interaction. All seismic and acoustic array instrumentation recorded the audible, "double", sonic boom from capsule reentry. The incident acoustic wave impinged on the arrays with an apparent velocity of 2.9 km/s from an azimuth of N02ºE. The infrasound observations show changes in the N-wave waveform over a distance scale of 1km with smaller secondary coda that may be related to near-surface seismic reverberations. The seismic data also show significant later arrivals in the first 1s that indicate conversions and reverberations within the lakebed sediments of Diamond Valley.

Infrasound From the Osiris-Rex Src Re-Entry Observed Near the Nevada-Utah Border

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The OSIRIS-REx Sample Return Capsule (SRC) re-entered the Earth's atmosphere on the morning of 24 September 2023. The SRC entered the atmosphere over the Pacific Ocean at a speed of over 43,000 km/hr and a few minutes later landed in Utah. Our team had microbarometers deployed on the ground near the border between Nevada and Utah to detect the infrasound (i.e., sound a frequency below human hearing) waves produced by the OSIRIS-REx SRC re-entry. Most of the sensors were deployed at the Wendover Airport, which was nominally 58 km to the north of the SRC trajectory. Our team deployed 15 sensors at the Wendover Airport, which some were co-located with sensors deployed by the University of Hawaii. Our team deployed three different sensor models (Chaparral Physics, GEM, and WERD) in close proximity to each other. The Chaparral Physics sensors formed a 4-sensor array with an aperture of 112 m. The additional sensors were arranged to form smaller arrays around the Chaparral Physics sensors. In addition, two GEM sensors were deployed between the airport and the SRC trajectory. All the sensors observed an N-wave arrival followed by broadband coherent rumbling after the initial arrival. This presentation will present the details of this deployment as well as preliminary results.

Direction-Finding Observation of Vlf Radio Emission Upon the Reentry of Osiris-Rex Sample Return Cuspule on 24 September 2023

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After the detection of peculiar VLF radio noises upon the reentry of Hayabusa-2 SRC in 2020 (WGN, the Journal of the IMO 51:3, 2023), direction-finding radio observations were performed at Pinto Summit, Eureka, Nevada upon the reentry of the OSIRIS-REx SRC on 24 Sep. 2023 (UTC) in the frequency region of 100 Hz - 96 kHz. Crossed loop aerials were employed to estimate the azimuthal angle (Az) of an observing radio source. The expected accuracy of the measurement is +/- 10 degrees. One vertical rod antenna was also used to measure the vertical component of the electric field of the radio wave. The initial polarity of Ez can eliminate the ambiguity in the Az estimation. We employed a simplified method to estimate the altitudinal angle (Alt) of the radio source by assuming the directivity of the vertical antenna, but an error of +/-20 degrees or more is expected near the zenith. We checked the consistency between the estimated (Az, Alt) and those of SRC predicted by a simple model of its trajectory (based on the nominal parameters given in NTRS-20150000809). This model is only applicable in the interval before the onset of significant deceleration of the SRC. The SRC's Entry Interface (EI) epoch was finally adjusted to 14:42:00 UTC, after an announcement from NASA. More than 20 weak non-impulsive radio noises, having similar values of (Az, Alt) to those predicted by the trajectory model, were detected during the interval of about +/- 25 sec around the peak-heating phase of the reentry (+51 sec from EI). These signals showed relatively wider frequency spectra than those of daytime long-distance sferics. Although the actual trajectory of the reentry has not been available at this stage, the presence of VLF radio emission upon the reentry of the SRC is plausible within the level of uncertainty. Intermittent electric discharges in the environmental plasma of SRC in the fireball phase of the reentry are suggested to be the sources of observed radio noises.

Airborne Acoustic Observations of the OSIRIS-REx Reentry

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Natural and artificial objects arriving from interplanetary space create powerful acoustic arrivals that contain information about its speed and shape. In the past, these sound waves were captured solely on ground-based recorders. However, elevated platforms may be able to sample elements of the acoustic wavefield unavailable on the Earth's surface, such as a cleaner source signal, transmission through elevated wave guides (e. g. the 'atmoSOFAR' channel), and reflections from the ground. Here we report acoustic arrivals from the 24 September 2023 reentry of the OSIRIS-REx space capsule recorded on balloon-borne platforms ranging from 1.7 to nearly 20 km above ground level. We compare the amplitude and frequency content of the balloon-recorded signals to those captured on nearby ground stations. We investigate the propagation path from the source to the elevated receiver. Finally, we assess the origin and properties of suspected ground reflections observed after the main arrival passed. Our results have implications for the detection and characterization of incoming objects on Earth and other planets such as Venus. The reflection signatures also shed light on the properties of lateral sound transmission through surface-bound acoustic ducts. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

The OSIRIS-REx Sample Return Capsule Re-entry: Geophysical Observations [Poster Session]

Poster Session • Wednesday 1 May

Conveners: Chris Carr, Los Alamos National Laboratory (cgcarr@lanl.gov); Brian Elbing, Oklahoma State University (elbing@okstate.edu); Charles Langston, University of Memphis (clangstn@memphis.edu); Richard Lewis, The Defense Threat Reduction Agency (richard.d.lewis1.civ@mail.mil); Yasuhiro Nishikawa, Kochi University of Technology (nishikawa.yasuhiro@kochi-tech.ac.jp); Elizabeth A. Silber, Sandia National Laboratory (esilbe@sandia.gov)

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Infrasound Analysis of the OSIRIS-REx Reentry at the NVIAR Array

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The OSIRIS-REx capsule, returning collected samples from the Bennu asteroid, passed near a permanent infrasound array, NVIAR, in western Nevada on September 24, 2023. Southern Methodist University operates NVIAR composed of a four-element triangular array with an aperture of 1-3 km and a seven-element, circular infrasound array with a 70-m aperture at the center element of NVIAR. The return capsule traveled within 98 km of the NVIAR array, which recorded multiple infrasound arrivals from the source. The capsule traveled approximately 12 km/s at its nearest point to NVIAR, 98 km away, resulting in direct, N-wave type records caused by shockwaves. Beamforming analysis confirms a moving source as the return capsule travels from west to east past the array. Array processing results indicate three coherent arrivals within a 20-minute record section. Ray tracing analysis using the projected return path also predicts arrivals from multiple stages of the capsule reentry, not only direct sonic boom arrivals from the closest proximity location to NVIAR. Other predicted arrivals may be from the maximum heating point, refractions through the thermosphere, and ground-level reflections. This study provides insight into the infrasound characteristics of a moving, elevated, hypersonic source from bolides and other hypersonic objects.

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Observation of Osiris-Rex via Shock Wave: Temporary Observation Network Utilizing Portable Infrasound Sensors and Comparative Analysis With Hayabusa and Hayabusa2

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On September 24, 2023, National Aeronautics and Space Administration's OSIRIS-REx sample return capsule (SRC) re-entered Earth's atmosphere. The capsule flew over Nevada, creating a shock wave around it, before landing in Utah. The Kochi University of Technology team was part of the infrasound/seismic observation team and installed someinfrasound sensors and microphones at Eureka airport in Nevada to capture the atmospheric pressure perturbations (infrasound and sound) generated by SRC. We successfully captured infrasound and sound generated from OSIRIS-REx. Our previous experience with observing HAYABUSA and HAYABUSA 2 (Japan Aerospace Exploration Agency's sample return mission) led us to employ the same portable infrasound sensor for this task. In this presentation, we will share the results of our OSIRIS-REx observations and compare them with our earlier findings from studying HAYABUSA and HAYABUSA2.

POSTER 70

Leveraging Infrasound Detections of Sample Return Space Missions Towards Characterization of Meteors: A Review

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Upon entering the Earth's atmosphere at hypervelocity (11.2–73 km/s), large meteoroids (> ~10 cm) and asteroids (>1 m in diameter) undergo complex processes as they plunge into dense regions of the atmosphere. These objects also generate powerful acoustic waves with dominant frequencies below human hearing, known as infrasound. Depending on atmospheric conditions, infrasound could be detected by ground-based or airborne microbarometers. Well-documented encounters with asteroids are rare because impacts in that size-range are sporadic and largely unpredictable, making dedicated observational campaigns impractical to plan. Unless there are multi-modal detections as well as the presence of physical material (i.e., meteorites), there will be notable uncertainties pertaining to the derived object parameters. In the quest to better characterize extraterrestrial objects and accompanying physical phenomena, it is possible to leverage space mission sample return capsules (SRCs). SRCs can serve as 'artificial meteors' given that they re-enter from interplanetary space at speeds corresponding to slow meteoroids. We will discuss infrasound observations of SRCs since the end of the Apollo era, emphasizing efforts between 2004 and 2021.

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The Utility of Infrasound Towards Detection and Characterization of Bolides

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Very bright meteors, also known as fireballs and bolides, are produced when extraterrestrial objects larger than approximately 10 cm in diameter enter dense regions of the Earth's atmosphere. Besides the luminous phenomenon, bolides also generate shock waves, which decay to low frequency acoustic waves or infrasound. Depending on initial conditions, atmospheric propagation paths, and the mode of shock production, infrasound emanating from a bolide can be detected by microbarometers hundreds and even thousands of kilometers away. Unlike other sensing modalities that might have geographic (e.g., inaccessible regions), time-of-day (e.g., optical) or other limitations, infrasound can be utilized continuously (day and night) on a global scale. Hence, infrasound can be leveraged towards detection and localization of bolides, as well as estimating their explosive yield. Bolide infrasound detections date back to the early 20th century. On June 30, 1908, an extraterrestrial object exploded over Tunguska, Siberia, generating low frequency acoustic waves that mark the first known instrumentally observed bolide infrasound. During the mid-20th century, ten large bolides were detected by infrasound stations meant for explosion monitoring. Since the mid-1990s, many more events have been detected via infrasound. However, characterization of bolides through infrasound is not without its challenges, mainly because no two bolide events are alike. Systematic studies and data fusion can aid in better constraining some important parameters. Here, a brief primer on bolide infrasound accompanied by notable examples will be presented.

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Infrasound Detection of the OSIRIS-REx Re-Entry: Signal Characteristics

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Sample Return Capsules (SRCs) enter Earth's atmosphere with energies equivalent to decimeter-scale meteoroids. Upon entering dense regions of the atmosphere, these objects generate shockwaves, which decay to low frequency sound. These acoustic waves can be detected by sensitive instruments positioned on the ground and on high-altitude platforms. Since SRCs are well-characterized objects with known parameters (speed, mass, size, etc.), their re-entries can be leveraged towards studying meteor phenomena, characterizing high-altitude shockwave dynamics, improving entry and propagation models, and advancing global monitoring efforts. On September 24, 2023, NASA's OSIRIS-REx sample return capsule (SRC) successfully brought particles of the nearby asteroid Bennu to Earth. The sample return capsule generated shockwaves as it entered the atmosphere, traversing California, Nevada and Utah before landing at the UTTR. We deployed infrasound and seismic sensors in Nevada and Utah to capture the signals as a function of distance from the trajectory and from different parts of the trail. We will discuss signal characteristics different stations, and how these might relate to SRC altitude and point(s) along the trajectory. The results have implications for future observational efforts on Earth as well as capturing shockwave signatures on other planetary bodies with atmospheres (e.g., Mars, Titan, Venus). SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

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The OSIRIS-REx Sample Return Capsule Re-Entry: Initial Results From a Historic Geophysical Recording Campaign Against an 'Artificial Meteor'

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Artificial and natural objects entering Earth's atmosphere at hypervelocity generate powerful acoustic waves, but well-characterized observations of entries are exceptionally scarce. This is because impacts by small asteroids (1 m in diameter and greater) are rare and random, making it impractical to plan dedicated observational campaigns. Artificial objects arriving from interplanetary space have the parameters well known a priori and can serve as ideal proxies for studying meteoric phenomena and are critical for improving global monitoring; however, only a handful of spacecraft have re-entered since the end of the Apollo era. The most recent opportunity presented itself with the re-entry of NASA's OSIRIS-REx sample return capsule (SRC) on September 24, 2023. A multi-institutional effort resulted in the largest to-date observational campaign to capture geophysical signals generated by an object as it re-entered the atmosphere from interplanetary space. We will describe the observational campaign, instruments, and the geographical coverage. We will also discuss field observations and present initial results. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

POSTER 74

The First Detection of an 'Artificial Meteor' by a Large N Acoustic Array

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On September 24, 2023, NASA's OSIRIS-REx sample return capsule (SRC) landed in Utah, bringing delicate particles of the nearby asteroid Bennu to Earth. SRC are considered 'artificial meteors' since they are analogous to natural extraterrestrial objects impacting Earth. The SRC entered the atmosphere at hypervelocity over California and flew over Nevada, before slowing down and landing at the Utah Test and Training Range (UTTR). Dense nodal acoustic arrays, like their seismic cousins, can provide detailed signal information that is otherwise unavailable using standard array installations. A large N-array with 118 recently developed nodal sensors was deployed in Eureka, Nevada enclosing a 100 x 100 m square. The location was near the nominal ground track and approximately 60 km beneath the trajectory. The large N-array readily detected infrasound signatures related to the ballistic shockwaves generated by the SRC. We will discuss the utility of dense array installations towards similar applications. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Physics-Based Ground Motion Modeling

Oral Session • Friday 3 May • 8:00 AM Pacific

Conveners: Evan Hirakawa, U.S. Geological Survey (ehirakawa@usgs.gov); Kim B. Olsen, San Diego State University (kbolsen@mail.sdsu.edu); William Stephenson, U.S. Geological Survey (wstephens@usgs.gov)

Evaluation of Seismic Community Velocity Models With Simulations of Small Earthquakes

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Seismic community velocity models (CVMs) are foundational for many basic and applied topics ranging from derivations of earthquake source properties to simulations of ground motions. CVM accuracy directly impacts the epistemic uncertainty of synthetic wave fields generated by earthquakes or 3D physics-based simulations. We present an innovative methodology to evaluate the epistemic uncertainty reflected in key intensity measures of ground motions related to seismic hazard analysis. This methodology involves simulating point source approximation wavefields from small historic earthquakes located in different parts of the crustal volume of interest and comparisons of results to observations. Using small events and the point source approximation facilitates a focus on properties of the CVM rather than finite source ruptures. Evaluation of differences between observed and synthetic data in spectral amplitude, phase matching, and signal duration allows us to estimate epistemic uncertainties and identify features and subregions of the CVM to improve. Here, we apply this framework to evaluate the performance of CVMs developed for southern and northern California. The evaluation employs three-dimensional physics-based ground motion simulations of sets of local small earthquakes with magnitudes ranging from 3.5 to 4.5. Because of the relatively low ground-motion amplitude induced by these earthquakes, the soil response is expected to be well-represented as linear at all recording sites. Therefore, the misfit between observed and synthetic waveforms can be mainly attributed to structural complexities not fully represented in the examined CVMs and, to a lesser extent, the source parameterization (location, depth, focal mechanism, source time function). Maps displaying the spatial distribution of residuals in the spectral domain facilitate the recognition of areas where each model performs better than the others and provide important guidance for future refinements of the CVMs.

Waveguide or Not? Expected Ground Motions in the Greater Los Angeles Area From the ShakeOut scenario

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Since its introduction in 2008, the ShakeOut scenario of a M7.8 northwestward rupture on the southern San Andreas fault (SSAF, Jones et al., 2008) has been widely used as a basis for a world-wide earthquake drill as well as for estimation of seismic hazard and potential economic losses in Southern California. Previous ShakeOut studies predicted significant long-period ground motion amplification in the Los Angeles areas, caused by a waveguide from interconnected sedimentary basins (Olsen et al., 2008, 2009; Graves et al., 2008). However, the original ShakeOut simulations omitted surface topography, and subsequent studies have refined the velocity structure of southern California as well as the SSAF. In this study, we conduct 0-1 Hz 3D numerical wave propagation simulations for the ShakeOut scenario in the Statewide California Earthquake Center (SCEC) Community Velocity Model (CVM) version 4.26M01, including updated high-resolution velocity structure of the Imperial and Coachella Valleys from reflection seismic imaging (Ajala et al., 2019; Persaud et al., 2016) and the northern basins (San Gabriel, Chino and San Bernardino Basin) from ambient noise imaging (Li et al., 2023), and detailed geometry of the SSAF (Fuis et al., 2017). We find a reduction of long-period ground motion levels (measured by spectral accelerations at a period of 3s, 3s-SA) by up to 55% along the waveguide into the Los Angeles basin, caused by stronger scattering effects from spatial complexity introduced by the updated CVM in areas outside the basins. Topographic scattering further decreases the 3s-SA values by another 40% due to the loss of coherency in the surface wave train. The addition of high-resolution near-fault models slightly increases the long-period (6s and longer) ground motion in the basins. The combined effects of the updated velocity models and surface topography reduce the maximum peak ground velocities in the waveguide from 250 cm/s to 100 cm/s. The significantly different ground motion pattern in the densely populated Los Angeles metropolitan area implies the need to revise seismic risk accordingly.

Effect of Soil Nonlinearity on Physics-Based Ground Motion Simulations

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Nonlinearity can dramatically affect soil behavior, especially for the soft soils within the shallow crust and under complex cyclic loadings induced by strong earthquakes. In the past few decades, numerous constitutive models of soils have been developed and applied to the analysis of soils and soil-structure systems. However, few physics-based ground motion simulations consider soil nonlinearity, mainly due to a significant increase in computational cost when nonlinearity is included and a lack of data to calibrate a constitutive model for a large region. In this study, we adopted a 3D bounding surface plasticity model, calibrated it using stiffness degradation (G/G_{max}) curves for multiple geology formations, and performed a large-scale broadband (up to 8 Hz) fully nonlinear physics-based ground motion simulation for a district in Istanbul, Turkey. In addition, by utilizing the simulated ground motions, we conducted one-dimensional nonlinear site response analyses (SRA) for a total of 2912 sites. For each site, we compared the time histories and surface shaking intensities, such as PGA, PGV and spectral accelerations, between linear and nonlinear 3D simulations, 1D nonlinear SRAs and an empirical ground motion model. Results indicate that soil nonlinearity can both significantly amplify and slightly de-amplify site responses, depending on the soil parameters (e.g., Vs30, G/G_{max} curves, bedrock depth) of the sites.

3D 0-10 Hz Physics-based Simulations of the 2020 Magna, Utah Earthquake Sequence

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The Salt Lake City Segment of the Wasatch fault (WFSLC), where the probability of a M7 earthquake in the next 100 years is estimated to be 16% (McCalpin and Nelson, 2000), is a primary seismic hazard to the Salt Lake Valley, populated by 1 million+ people. The 2020 Magna, UT, earthquake, which likely occurred on the WFSLC, generated Peak Ground Accelerations (PGAs) as large as 0.55 g, and was a stern reminder of the seismic hazards for the area. Here, we present 3D wave propagation simulations of the Magna earthquake sequence in the Wasatch Front Community Velocity Model (WFCVM, Magistrale et al., 2008) up to 10 Hz to better constrain both linear and nonlinear parameters in the soils of the Salt Lake Valley. We first validated the WFCVM via linear simulations of a M4.5 aftershock in the Magna sequence. By adding a geotechnical layer outside the basin, a statistical distribution of small-scale velocity heterogeneities with 10% standard deviation, and using frequency-dependent anelastic attenuation as $Q_s=0.05*V_s$ (f<1 Hz) and $Q_s(f)=0.05*V_s*f^{0.4}$ (f>1 Hz, V_s in m/s), we obtained an overall satisfactory fit to the seismic recordings for the aftershock. Our simulations of the 2020 Magna main shock use finite-fault source models from the Graves-Pitarka rupture generator, and a preferred source model is chosen with minimal bias to data at f<1 Hz, where nonlinear effects are expected to be negligible. Although different plausible source realizations result in factor-of-ten variations in high-frequency synthetic ground accelerations, they generally overestimate those of the recordings, in particular at stations with the largest PGAs, suggesting the presence of nonlinear soil effects. Then, using a fully hysteretic multi-yield-surface 3D method (Roten et al., 2023) we find that Darendeli's (2001) proposed reference strain-depth relations provide excessive damping of the high-frequency synthetics in the Magna area, with an optimal fit to observations for reference strains 3 standard deviations larger. Our findings provide a basis for improved seismic hazard analyses of the greater Salt Lake City region.

Spe Rock-Valley-Direct-Comparison Chemical Explosions Near-Field 3-D Ground Motion Simulations and Predictions

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Rock Valley Direct Comparison (RV/DC) is Phase III of the Source Physics Experiment (SPE) series. The first explosion, RVDC-1, is a 1-ton equivalent TNT located at 1.8km depth, while the second, RVDC-2, is a 10-ton equivalent TNT located at 1.7km depth. The local geology of the site is complex and encompasses a deep hard-rock (dolomite starting at 1km depth) and the shallow 1km is a mixture of tuff and sedimentary layers, deposited under a rugged topography. The water table is located nearly 500m deep. The layered beds are crosscut by a series of faults. The source package is sized to be 3.5 to 4.5 feet diameter emplaced in a 4 to 5 feet diameter ground-zero (GZ) borehole RV/DC includes two chemical explosion experiments. The characterization of the geology is limited and includes one straight continuous core-hole (CH), and two directional observation boreholes (OB) cored as needed sporadically. Based on this complex geological conceptual setting, we have conducted 3-dimensional non-linear numerical simulations of the ground motions generated from both explosions. First, we used deterministic geophysical properties of the layered model and assessed the response of the system with and without the faults to assess their effect on the anisotropic radiation of the ground motions. Second, because of the limited characterization of the site, we have included stochastic variations in the geological layers. We adopted a scheme of including stochastic discrete fractures in the deep dolomite layer (analogue to SPE Phase I), while a continuous stochastic variation of lenses in the shallow geological layers (analogue to SPE Phase II). Assessing the effect of those stochastic parametrizations on the overall response of the system were obtained using a sophisticated interval Monte Carlo method. Material models have been calibrated to laboratory experiments and assessed under variably saturation conditions. Differentials of ground motion under different conditions of physical and structural uncertainties are then derived for both RVDC-1, RVDC-2, and a hypothetical earthquake.

Modeling Topography and Fault Geometry Effects on Earthquake Ruptures and Ground Motions Along Double Compressional Bends

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Fault geometry is known for affecting the endpoints of earthquake ruptures. Recent studies suggest that ground surface topography also affects earthquake ruptures and ground motion, but they do not offer much physical explanations. This project is a dynamic rupture modeling geometrical parameter study that explores the effects of fault geometry and topography on earthquake ruptures and ground motion on double compressional bends in strike-slip faults. Our primary variables are fault bend angles, and mountain height and width. Our results show that bend angle has a larger role in controlling earthquake ruptures than topography does. For bend angles >= 23°, earthquakes stop within the linking segment, while faults with bend angles =< 22° ruptured entirely, regardless of topography. Higher or lower initial stresses shift this transition point by only 2° and 1°, respectively. Mountains allow more of the fault to slip compared to the flat models and produce tails and patches of slip along the surface. In models with topography, both supershear and subshear rupture fronts occur. Shallow normal stress perturbations occur at and behind the subshear rupture front, which increase in length and depth for taller and wider mountains and increase in number for narrower ones. Seismic wave reflections within the topography along the linking segment, and associated normal stress perturbations, produce the tails and patches of slip along the surface. This effect is largest when the mountain height is larger than the mountain width. Fault-adjacent topography also increases maximum ground motions in the near field, particularly directly on the hills.

The Effects of Surface Topography and Basin Layering on the Earthquake Ground Motion Intensities in Intermontane-Basin Settings

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Many densely populated intermontane sedimentary basins in collisional tectonic settings possess high seismic risk due to widely observed basin-specific ground motion amplifications. The documented observations show that ground motion predictions in these basins are often poorly constrained due to

oversight of surrounding surface topography and the absence of sub-surface information about deeper basin layering, leading to inaccurate hazard assessment. In this study, we systematically evaluate the implications of these two factors on high-frequency ground motion characteristics, which is crucial for earthquake engineering practices.

Using the Kathmandu sedimentary basin as our case-study area, we extract a 2D east-west cross-section of length 80km containing high relief surface topography on either side of the 20km-wide basin. We simulate the eastward travelling Rayleigh waves in a high-resolution domain allowing us to resolve frequencies up to 5Hz. Our results indicate that the topography reduces peak ground acceleration (PGA) in the basin by 40% as compared to scenarios when the topography is neglected, particularly shielding frequencies above 2 Hz. We also perform 3D simulations of a shallow thrust-faulting moment tensor source in the west of the Kathmandu basin to confirm the high-frequency attenuation of waves entering the basin area due to the surface topography. In a simultaneous analysis for basin-specific properties, we find that the deeper Kathmandu basin layers control the spatial variability in the observed amplification that has an order of magnitude difference within the basin compared to the scenarios excluding the deeper basin layers.

We conclude that neglecting topography in ground motion predictions may lead to an overestimation of ground motion amplification in the basin, particularly for higher frequencies. A strong emphasis must also be given to maximise the understanding of deeper basin layers to capture the spatial variability in the ground motions. This is particularly relevant to microzonation studies where high spatial resolution is needed for risk-mitigation measures.

Analysis of Anomalously Large High-Frequency Amplification in Chugiak, Ak, From the 2018 Anchorage Earthquake and Aftershocks

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A dense, pseudo-linear nodal ~3km long array was deployed in Chugiak, Alaska (30 km NE of Anchorage, AK) by the USGS from 2021-08-09 to 2021-09-08 around the permanent NetQuakes station ARTY where an anomouslously large peak-ground acceleration (PGA) of 1.98 g was recorded during the 2018 Mw 7.1 Anchorage, AK earthquake, as compared to ~0.3 g at a nearby site. The nodal array data for aftershocks with different magnitudes (M_L 1.8 - 4.3) and azimuths confirm the anomalously large ground motions recorded at the permanent station and show similar PGA amplification at stations up to ~1 km further to the east of ARTY. The topography and Quaternary geology along the transect are characterized by a series of flat surfaces and steep slopes, interpreted as kame terraces and outwash fans, which formed during deglaciation prior to 14 kya. In this study, we perform 3D finite-difference simulations up to 10 Hz, including the 1m-resolution surface topography, to explore the cause of these unexpectedly large amplifications. The simulations, computed with a near-surface geotechnical layer (GTL) tapered to 350 m depth, match the nodal data reasonably well at stations west of ARTY as well as those near the eastern end of the array towards the mountains, while this model underpredicts in the area covered by glacial sediments. The addition of a layer of glacial sediments near the surface along the array and surroundings with depth-to-bedrock constrained by water wells and assuming a Vs30 of 400 m/s improves the fit to data from the array considerably, except for underprediction on the N-S component. Our analysis also reveals that PGAs along the array can be modulated by up to 50% by topography, with the largest effects along the local topographic gradients. Our study shows that the anomalously large high-frequency amplification recorded at and near ARTY is caused by a combination of topographic effects and near-surface low-velocity material.

Findings from a Decade of Ground Motion Simulation Validation Research and a Path Forward

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Simulation of earthquake ground motions has advanced in recent years, with modelers utilizing various approaches (e.g., deterministic, kinematic, dynamic, stochastic, and hybrid methods) to represent real ground motions more accurately. Simulated ground motions have the potential to advance seismic hazard assessments and structural response analyses, particularly for conditions with limited recorded ground motions such as large magnitude earthquakes at short source-to-site distances. However, rigorous validation of simulated ground motions is needed for hazard analysts, practicing engineers, or regulatory bodies to be confident in their use. A decade ago, validation exercises were mainly limited to comparisons of simulated-to-observed waveforms and median values of spectral accelerations for selected earthquakes. The Southern California Earthquake Center (SCEC) Ground Motion Simulation Validation (GMSV) group was formed to increase coordination between simulation modelers and research engineers with the aim of devising and applying more effective methods for simulation validation. Here, we summarize what has been learned in over a decade of GMSV activities, principally reflecting the views of the SCEC research community but also extending our findings and suggestions for a path forward to broader U.S. and worldwide simulation validation efforts. We categorize different validation methods according to their approach and the metrics considered. These two general approaches are to compare validation metrics from simulations to those from historical records or to those from semi-empirical models. Validation metrics are categorized into ground motion characteristics and structural responses. We discuss example validation studies that have been impactful in the past decade and suggest future research directions. Key lessons learned are that validation is application-specific, our outreach and dissemination need improvement, and much validation-related research remains unexplored. The work to be presented is published as a journal paper (Rezaeian et al. 2023, Earthquake Spectra, doi:10.1177/87552930231212475).

Correlated Noise in Source Time Functions: A Method to Generate Realistic High Frequency Earthquake Sources

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We perform broadband ground motion simulations with a new methodology to create kinematic sources that account for small-scale rupture heterogeneity, whereby we focus especially on realistic source time functions (STF). Our broadband kinematic source generator begins with Von Karman patterns to create future slip distributions from amplitude and geometry source parameters. Using Mai and Beroza (2002) relationships, findings of Thingbaijam and Mai (2016) on slip distribution parameterization, and slip-constrained hypocentre locations (Mai et al., 2005), our rupture generator creates dynamically self-consistent kinematic source realizations. We then apply the methodology of Liu et al (2006) to perturb rupture onset times and the local rise times to define the main parameters of the rupture propagation.

Using a regularized Yoffe as STF, our method describes the local slip evolution at each subfault. As marked in previous studies, the regularized Yoffe function well replicates, in time and frequency, dynamic STF's. However, the regularized Yoffe function generates spectral notches in the high-frequency amplitude spectra. Those notches render the high-frequency source implementation unrealistic, affecting also the total moment rate function and far-field ground motions. To create more plausible rupture realization based on a Yoffe STF, we propose adding correlated noise. The correlated noise follows a 1D Von Karman random field. The parameters to define this random field are estimated by comparing STF from dynamic rupture simulations and regularized Yoffe function, using 21 dynamic simulations (from Mai et al., 2018). Using our rupture generator, we compute the ground motion at different locations, reproducing the mean and standard deviation from GMM in different intensity measures in simulations of M 6.0-7.0. Additionally, our rupture generator allows us to integrate low-frequency inversions and stochastically complement the high frequency of the original source. In summary, our improved pseudo-dynamic kinematic rupture generator produces realistic high frequency sources essential for seismic hazard analysis.

POSTER 87

A Parametric Analysis on the Behaviors of Seismic Waves Interacting With Geologic Metamaterials

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The idea of developing seismic invisibility cloaks that render geologic targets invisible to seismic waves has recently received increased attention for earthquake hazard reduction. Using the concept of invisibility cloaks, previous field experiments that considered sets of air-filled boreholes (seismic metamaterials) and forests of trees (above-surface resonators) as seismic cloaks successfully demonstrated the feasibility of both for seismic energy suppression at specific bandwidths for earthquake protection. While the experiments provide a strong motivation for the applicability of seismic cloaking to real world applications, designing optimal seismic metamaterials specific for a given field of interest requires a better understanding of how the design parameters and geologic factors affect the response of a passing seismic wavefield at geophysical scales.

Here, we investigate the behaviors of seismic waves through geologic metamaterials with different design parameters by conducting a thorough numerical modeling study. An in-house, finite difference modeling code is used to simulate elastic wave propagation in 3D geologic media. Our analysis particularly focuses on the interactions of a passing seismic wavefield with geologic media that are transformed into seismic metamaterials via borehole implantations. We systematically test the influence of geologic metamaterial design parameters (density and geometry of boreholes) and the complexity of the host geologic media on wave propagation.

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POSTER 88

Updated Regional Seismic Velocity Model for the US Atlantic and Gulf Coastal Plains Based on Measured Shear Wave Velocity, Sediment Thickness, Varying Geologic Structure With Depth, and Lateral Variations

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The Atlantic and Gulf Coastal Plains (CPs) consist of thick and soft sediments that overlie a stiff bedrock that increase the amplification and duration of earthquake ground motions. Understanding both the depth and the dynamic properties of these sediments is critical yet challenging at a regional scale. Sediment thickness and geology have been shown to be good indicators for regional characterization of shear wave velocity (V_S). Due to limited characterization of the velocity structure within site amplification models in the region, a new geology-based V_S model was previously developed to better characterize the CP sediments so that amplification and hazard levels can be estimated. This geology-based model was based on measured shear-wave velocity and sediment thickness, but geologic grouping was only based on surface geology. Median profiles were developed for five surface geologic groups with no lateral variation within each group. Thus, to further improve the characterization of the regional velocity structure, the previously developed velocity model has been updated to include correlations with stratigraphic sequences, constraints with depth, and lateral variations within geologic groups. Additional measured V_S data are also incorporated within the model to increase coverage in data-sparse areas. These updates will be helpful for the development of new GMMs aiming to characterize systematic site effects via the time-averaged V_S in the top 30 meters (V_{S30}) and sediment thickness in the region.

POSTER 89

Physics-based Numerical Modeling of Site-specific Amplification in Ground Motions: A Case Study of Wellington Basin

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The amplification effect of site-specific near-surface velocity structure plays a crucial role in modulating ground shaking level, and in turn, contributes to seismic risk. However, the general understanding of this effect is limited, owing to complex 3D geological structures and the influence of coseismic source dynamics on-site response (Olsen, 2000). In this study, we use physics-based simulations of ground motion to investigate fundamental characteristics of the regional seismic response that may not be easily analyzed using regional seismic recordings.

We develop numerical models for Wellington City, which is a seismically active area with multiple active crustal faults and the Hikurangi Subduction Zone beneath it. This unique geological setting requires investigating potential earthquake ruptures and their effects on ground shaking levels. Several geological and geotechnical surveys have provided valuable knowledge about high-resolution topography, shallow structures, and fault networks (Hill et al. 2022). We focus on simulating ground motions using either kinematic sources or spontaneous coseismic ruptures. Key aspects of our study include (1) incorporation of 3D fault geometry and complex ruptures of multiple faults, (2) utilization of regional 3D basin structure, (3) development of peak ground motion maps, and (4) evaluation of the impacts of regional topography, seismic attenuation, and 3D geological models on the ground motion levels.

By studying the dynamic earthquake source process, its interaction with regional geological structures, and its impact on site amplification, we combine advanced numerical simulations with regional geodetic, geological, and seismological records. Based on the simulated seismic scenarios of the regional earthquakes, we aim to advance our knowledge of future ground shaking levels in the city and to provide general theoretical references to improve empirical ground motion models, and consequently, seismic hazard analysis.

POSTER 90

Constraining Large Magnitude Event Source and Path Effects Using Ground Motion Simulations

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The most promising way to improve Probabilistic Seismic Hazard Analysis is through the separation of epistemic and aleatory uncertainties. For example, wave propagation path effects between a source location and a site should be considered as repeatable, with their possible ranges constituting epistemic uncertainty. However, path effects represented by Ground Motion Models (GMMs) often include unmodeled source effects, such as radiation pattern and directivity, which may lead to bias in seismic hazard assessment. Moreover, the path effects from one event to one site are assigned to a single path between one point and a site, regardless of the magnitude and extent of the rupture. For a large magnitude earthquake, seismic waves can travel from any point along the rupture plane that extends hundreds of kilometers. Hence the single travel path assumption for large magnitude earthquakes is potentially flawed.

The purpose of this study is to use ground motion simulations to investigate how source and path effects for large magnitude events can be represented in non-ergodic GMMs. We simulate earthquakes occurring on a fault plane with a large range of magnitudes, and sites covering a large range of rupture distances and azimuths. We first develop a non-ergodic GMM, in which radiation pattern and directivity effects are modeled using existing relationships. Then, we compare the mean path effects among groups of events with different magnitudes and examine any differences in dependence on distance and azimuth using two approaches. The first approach only considers smaller events that have the same shortest path to a site as a co-located larger event, while the second approach considers all smaller events on the larger event fault plane regardless of source to site path length. The results indicate that it is difficult to satisfactorily approximate the path effects of larger events with that of smaller events using either approach. This finding complicates our ultimate goal of developing guidelines for how large magnitude ruptures can be adequately represented within non-ergodic GMMs.

POSTER 91

The Case of the Missing Frequencies: Reduction of Artificial Spectral Deficiency in Semistochastic Broadband Simulation

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Semistochastic broadband simulation is a common method used to efficiently generate realistic full spectrum waveforms. For such methods, deterministic low frequency (e.g., < 1 Hz) waveforms are combined with stochastic high frequency (e.g., > 1 Hz) waveforms using a matched filter, which involves lowpass filtering the low frequency data, highpass filtering the high frequency data, and summing the filtered time-series. Oftentimes, a common filter corner frequency (f_{cc}) of 1 Hz is used for both the lowpass and highpass filters. However, this induces an artificial deficiency in the broadband spectra, which can have considerable effects on the resulting ground motion and seismic hazard assessments, especially in the field of earthquake engineering where the frequencies of ground motion hold significance. We investigate this phenomenon for Japan, Chile, and the Cascadia subduction zones, and explore various approaches to minimize the spectral deficiency, including varying the f_{cc}, varying the filter order, and using a two-corner frequency approach. We find that each approach, to some extent, reduces the deficiency and influences the ground motion (PGD, PGA, PGV, and SA). However, no single approach universally improves all ground motion intensity measures for events of varying magnitude. We suggest addressing this matter on a case-by-case basis.

POSTER 92

3D Ground Motion Simulations of the 1755 Lisbon Earthquake

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A recurrence of the 1755 Lisbon earthquake would be devastating for present-day Portugal. However, despite widespread research into the possible sources for the event, the associated fault(s) and magnitude of the earthquake are still uncertain. Previous simulation studies have used velocity models with relatively coarse resolution (Grandin et al., 2007) or stochastic modeling techniques that exclude potentially important wave propagation effects (Carvalho et al., 2004; Carvalho, Zonno, et al., 2008). Here, we use 3D physics-based simulation in the recent PRISM3D reference model for Iberia (Arroucau et al., 2021), that we validate against data from a 2018 M4.3 earthquake near Lisbon. We obtain an optimal fit to the 0-1 Hz strong motion recordings of the validation event using a geotechnical layer with a tapering depth of 350 m, a statistical distribution of small-scale heterogeneities with a standard deviation of 5 percent, and anelastic attenuation for S-waves using Qs = 0.1Vs (Vs in m/s). We then use the validated model to simulate 0-1 Hz wave propagation for 40+ plausible earthquake scenarios across proposed fault structures. Most of the single fault sources tested for the 1755 Lisbon earthquake inadequately replicate the observed Modified Mercalli Intensity (MMI) pattern from the event, while other scenarios violate reported tsunami arrivals or ground motion durations. However, we find that a Mw8.3 scenario event on the Guadalquivir Bank Fault generates MMI patterns most comparable to the reports. Moreover, the combined wavefield from a Mw8.4 event on the Marques de Pombal Fault with that of a (possibly triggered) Mw7.75 earthquake on the Tagus Abyssal Plain fault yields a satisfactory fit to the isoseismal data from the 1755 earthquake.

POSTER 93

Extended Finite-Fault Ground Motion Modeling Framework: Sensitivity Analysis of Number of Sub-Faults

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Ground motion stochastic simulations are essential for various engineering applications, specifically in seismic hazard assessment and calibration of ground motion models (GMMs). Such simulations are often employed for the purpose of augmenting regions with deficit earthquake datasets. Also, these simulations are often affected by various seismological parameters of source, path and site. Thus, the present study optimizes the seismological parameters stress drop (source) and kappa (site) and performs sensitivity analysis of the number of sub-faults. For the calibration of parameters and sensitivity analysis, a subset of the NGA West2 database (particularly for the California region) is employed. We utilized a total of 600 events and 4,615 records for Moment magnitude (Mw) > 3 and Joyner Boore distance (RJB) < 100 km. The optimal value of stress drop and kappa was determined using grid search procedure. Our observations indicate that as the number of sub-faults within simulations increases, the optimized stress drop value tends to decrease. Further, increasing the number of sub-faults was found to have a negligible effect on the residuals (i.e. log(PSAobs/PSAsim)), only adding to the computational burden and complexity. Thus, our study suggests use of one sub-fault for similar simulations. We also performed comparison with NGA-West2 GMMs (Abrahamson et al., 2014; Boore et al., 2014; Campbell and Bozorgnia, 2014; Chiou and Youngs, 2014; Idriss, 2014) and found consistent results with the GMSS2.0 simulations for different numbers of sub-faults. Thus our findings provide valuable insights to improve the GMMs by optimizing stress drop, kappa and reducing the computational resource and time.

Planetary Seismology

Oral Session • Wednesday 1 May • 4:30 PM Pacific

Conveners: Isabella Seppi, University of Alaska Fairbanks (irseppi@alaska.edu); Yuan Tian, University of Alaska Fairbanks (ytian4@alaska.edu).

Near Surface Excitation of the Martian Ground as Measured by Insight

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The InSight mission landed on Mars in November 2018 and deployed for the first time a seismometer, the SEIS instrument, on its surface. For more than two Martian years it recorded several thousands of marsquakes and other seismic events, allowing us to study diurnal and seasonal variations in seismicity to better understand the local atmospheric conditions and characterize the Martian interior. Among the many signals recorded by SEIS is a prominent mode around 2.4 Hz. Possible explanations for this signal include a specific lander mode due to the solar arrays, or a local ground substructure as described notably in Hobiger et al. 2020.

In this study, we test the hypothesis of Hobiger et al. 2020 that the 2.4 Hz dominant background noise and Horizontal to Vertical (H/V) ratio are caused by a seismic low velocity zone between 30m and 75m by simulating the amplitude of the 2.4Hz peak observed during marsquakes and during the quiet Martian night. We generate Green's functions of the ground substructure for high-incidence-angle teleseismic events and for regional surface sources. Subsequently we test the ground response to these excitations by convolving the simulated sources with the appropriate Green's functions.

We simulate a teleseismic marsquake at a given distance by superimposing a distance-dependent attenuated random signal that mimics the observed scatter of the Martian crust. Background noise is simulated by generating a signal with the frequency and amplitude characteristics of the InSight day and night pressure data.

We show that the simulated amplitudes of the 2.4Hz signal during teleseismic quakes are consistent with SEIS observations. Furthermore, also consistent with InSight observations, the background noise simulation is visible during the night, but is drowned by the elevated ambient environmental noise during daytime.

To test the link between the numerous 2.4 Hz events and excitation of the lander's solar array from wind bursts, a coupled model of the excitation of the InSight Lander and the subsurface structure will be needed.

Evaluation of Lunar Seismicity Parameters Based on Analysis of Newly Discovered Shallow Moonquakes in the Apollo Seismic Data

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From 1969 to 1977, the first lunar seismic observation was carried out during the Apollo missions, bringing us about 13,000 seismic events and opening the path to studying lunar seismicity and its internal structure. The lunar seismic events are roughly classified into four groups: deep moonquakes, meteoroid impact events, shallow moonquakes, and thermal moonquakes. Among them, shallow moonquakes are the rarest events on the Moon. While thousands of events have been identified for deep moonquakes, meteoroid impacts, and thermal moonquakes, only 28 shallow moonquakes were detected before (e.g., Nakamura et al., 1981). Despite their small population, shallow moonquakes show much larger energy release than any other lunar seismic events (e.g., Goins et al., 1981). Therefore, they are important for understanding the seismicity of the Moon. Recently, Onodera (2023) discovered 46 new shallow moonquakes, allowing us to renew the lunar seismicity parameters (such as the magnitude of completeness, seismicity rate, and b-value).

In the presentation, followed by the characterization of the newly discovered shallow moonquakes, I will show the estimated seismicity parameters for the Apollo 14, 15, and 16 landing sites and discuss the regionality of seismic activity on the Moon.

A Novel Statistical Technique to Distinguish Lunar Impacts From Shallow Moonquakes

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Between 1967 and 1977, The Apollo seismic network recorded thousands of signals, such as impacts and shallow moonquakes (Nakamura et al., 1981). Correctly classifying seismic signals is crucial for assessing lunar impact and seismicity rates. However, 60% of the original events remain unclassified due to low-quality data and the time required to analyse the data. We introduce a semi-automated and objective method for discriminating shallow moonquakes from impacts. First, we convert short- and long-period spectrograms to smoothed probability density functions. Then, we calculate the K-L divergence for pairs of events. The K-L divergence is a nonparametric measure of the differences between the two probability distributions; a K-L divergence of 0 indicates an identical pair of signals. We test this new statistical method on classified events in the catalogue. Preliminary results show a K-L divergence of > 1 between previously identified shallow moonquakes and impacts but a divergence of < 0.5 between pairs of shallow moonquakes; shallow moonquakes are more similar to each other than to impacts. Thus, the K-L divergence can discriminate between shallow moonquakes and impacts. Additionally, we analyse the short period time series of the seismic signals recorded at station S15 using the Python package tsfresh, which automatically calculates over 1200 time-series features. We again test this method on classified events in the catalogue. Spectral features, such as Fourier entropy and autocorrelation, vary systematically between shallow moonquakes and impacts. A recent study (Onodera et al., 2023) identified ~40 new shallow moonquakes, and we apply the same tsfresh algorithm to these newly identified events. The newly identified moonquakes have autocorrelation and Fourier entropy values similar to the previously catalogued moonquakes. Along with supporting reanalysis of the Apollo seismic signals, we suggest these methods to distinguish the lunar seismic signals could apply to future lunar seismic data.

A Reference Marsquake Catalogue

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NASA's InSight seismometer operated on Mars from 12.2018 - 12.2022. Since the mission is complete, the Marsquake Service (MQS) is preparing a final reference catalogue encompassing seismicity recorded across the entire mission. The analysis of marsquake is challenging, given the availability of only a single station, low magnitudes events with large epicentral distances, and strongly varying background noise. These factors collectively result in low event signal-to-noise ratios (SNR). Our reference catalogue heavily leverages a deep learning denoising approach to mitigate the noise contamination. We show that denoising performs comparably to fine-tuned bandpass filtering at high SNRs, and clearly outperforms it at low SNRs, with respect to accurate waveform and amplitude retrieval, as well as onset picking.

We produce a denoised waveform data set for all >1300 events in the MQS v14 catalogue. For the HF event family, we apply automated phase picking for the first time. For the LF family, consisting of around 100 events, we review each event, improving the event characterisation and location by new or updated phase picks and polarisation.

We find many new features that were missing in earlier catalogues. We find aftershocks and demonstrate that several complicated LF event waveforms can be explained by marsquake doublets—two similar strong quakes from similar locations that produce overlapping waveforms—that locate in Cerberus Fossae. In addition, we show that the unusual sequence on Sol 1157 consists of numerous marsquakes which are among the strongest events located at epicentral distances beyond Cerberus Fossae.

Regional-Scale Hazard, Risk and Loss Assessments

Oral Session • Thursday 2 May • 4:30 PM Pacific

Conveners: Ashly Cabas, North Carolina State University (amcabasm@ncsu.edu); John Cassidy, Geological Survey of Canada (john.cassidy@nrcan-rncan.gc.ca); Rodrigo Costa, University of Waterloo (rodrigo.costa@uwaterloo.ca); Cassie Gann-Phillips, North Carolina State University (cvgann@ncsu.edu); Mike Greenfield, Greenfield Geotechnical (mike@greenfieldgeotechnical.com); Tiegan E. Hobbs, Geological Survey of Canada (thobbs@eoas.ubc.ca); James Kaklamanos, Merrimack College (kaklamanosj@merrimack.edu); Albert Kottke, Pacific Gas and Electric Company, (albert.kottke@pge.com); Sabine Loos, University of Michigan (sloos@umich.edu); Cristina Lorenzo-Velazquez, North Carolina State University (clorenz@ncsu.edu); Andrew Makdisi, U.S. Geological Survey (amakdisi@usgs.gov); Hong-Kie Thio, AECOM (hong.kie.thio@aecom.com); Eric Thompson, U.S. Geological Survey (emthompson@usgs.gov); David Wald, U.S. Geological Survey (wald@usgs.gov); Erin Wirth, U.S. Geological Survey, (emoriarty@usgs.gov)

Probabilistic Approach for Site Response Analysis and Seismic Microzonation

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The purpose of site response analysis is to estimate probable earthquake characteristics on the ground surface to mitigate earthquake damage for the new buildings as well as for the existing building stock. The uncertainties in source characteristics, soil profile, soil properties, and characteristics of the building inventory would introduce critical uncertainties associated with these analyses. At this stage, the probability distribution of the related earthquake parameters on the ground surface may be determined considering all possible input acceleration time histories, site profiles, and dynamic soil properties. One option, the variability in earthquake source and path effects may be considered using a large number of acceleration records compatible with the site-dependent earthquake hazard. Likewise, a large number of soil profiles may be used to account for the site condition variability. A seismic microzonation methodology is proposed based on the probabilistic assessment of these factors involved in site response analysis. The second important issue in the seismic microzonation procedure is the selection of microzonation parameters. The purpose is mitigation of structural damage, it is possible to adopt earthquake parameters like cumulative average velocity (CAV) or Housner intensity (HI) that was observed to have a better correlation with building damage during past earthquakes. The main approach is to develop a microzonation procedure for ground shaking intensity considering probabilistic values of ground motion parameters.

Analysis of Shakemap Residuals for Spatially Variable Site Terms

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The U.S. Geological Survey (USGS) has produced and archived ShakeMaps for many decades as part of its earthquake monitoring efforts. The resulting ShakeMap Atlas contains thousands of recent and historical maps whose primary purpose is for calibrating the Prompt Assessment of Global Earthquakes for Response (PAGER) loss models. Here we develop spatially variable site terms (SVST), which could be considered a "partially non-ergodic" ground motion model (GMM) adjustment. Currently, ShakeMap assumes a constant spatial correlation structure across all events and regions. Given the global extent and data quantity available from ShakeMap, we investigate this assumption by looking for trends in the spatial correlation of model parameters with variables such as magnitude, tectonic environment, number of available records for a given station, and geographic region. Adding the SVST adjustment will incorporate repeatable variability into scenarios to capture physical phenomena traditionally unaccounted for by GMMs that underpin the ShakeMap interpolation method. Because real-time ShakeMaps are conditioned on recorded data for a given event, the impact of SVSTs will be less substantial, especially in areas with dense network coverage. However, these empirical factors will improve extrapolation between stations due to larger correlation lengths of the repeatable site effects. The "Did You Feel It?" (DYFI) system responses often have much greater spatial coverage than instrumental data for a large percentage of earthquakes yet take time to become available. In contrast, the SVSTs that we derive here will be available for the first version of ShakeMap. Further, DYFI responses can exhibit areas of missing data in which the most highly-damaged area is not covered because residents in these regions may be more concerned with safety than providing DYFI responses, and/or internet connectivity could be lost. These innovative SVST factors would be able to help fill in such regions.

Regionalized Earthquake Source Models of Subduction Interface Earthquakes

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In Skarlatoudis et al. (2016; Sea16) we developed a set of global scaling relations between seismic moment (M_0) and physical source properties such as earthquake rupture area (S), total asperity area (Sa), slip (D), and fault width (W), for large subduction interface events. That set of relations reduced the aleatory variability in the prediction of these source parameters. Since their publication, they have been used to predict ground motions and tsunamis from great subduction earthquakes for various applications (e.g. USGS NSHM).

Since the development of the database used in Sea16, 79 additional subduction interface events with published finite-fault solutions have been catalogued in the USGS Finite Fault database, the Online Database of Finite Fault Rupture Models (SRCMOD), and the Next-Generation Attenuation Subduction (NGA-Sub) database, nearly tripling the available data. In our search for subduction interface events, we use the Slab2.0 subduction-zone geometries. These additional models are used to update the Sea16 set of scaling relations, further improving the predictions of various source properties and more accurately quantifying uncertainties.

We augmented the Sea16 database with the additional models that became available in recent years, and developed an updated set of global scaling relations. Further, for the subduction zones with an adequate number of earthquakes in our database, we examined regionalized versions of the scaling relations and provide possible explanations for the observed regional differences in subduction interface ground motions by seeking correlations with the many parameters (e.g. trench-normal velocity, thrust dip angle, subduction partitioning) that were considered by other researchers.

The NGA-Sub project also quantified strong regional differences in the ground motions expected from various subduction zones. The observed regionalization of ground motions is likely the result of differences in the geological, geometrical, and mechanical properties of plate-boundary interfaces and the kinematic and dynamic processes of megathrust rupture generation in each region.

Region-Specific Geospatial Liquefaction Model for Alaska by Bayesian Model Updating of the Global Liquefaction Model

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Global geospatial liquefaction models are currently being used to predict the probability of liquefaction occurring after an earthquake. However, these models are limited in their ability to generalize to new regions because they are only trained on data from previous events using a global dataset. Additionally, the geology, saturation, and seismic activity of different regions can vary greatly, making it desirable to develop specific liquefaction models for each region. A recent example is the Mw 7.1 Anchorage, Alaska earthquake that occurred on November 30, 2018. This earthquake caused widespread liquefaction in natural fluvial-estuarine environments and damaged and tilted residential buildings in southern Anchorage. In this study, a regional geospatial liquefaction prediction model is developed for Alaska using liquefaction observations from the 2018 Anchorage earthquake. For this purpose, a Bayesian logistic regression model was trained to combine the knowledge from the existing global model and the region-specific relations between geospatial explanatory variables for the Anchorage region. This can be done by selecting the prior distribution of the model coefficients from the global model and then sequentially updating the model for each liquefaction observation from the region to find the posterior probability distribution of the model parameters. To create a balance between the information gained from the global model and regional data, prior and likelihood functions are weighted to create an optimal liquefaction prediction model. The resulting model shows a more accurate liquefaction detection in the Alaska region.

A Regional Earthquake-Triggered Landslide Susceptibility Map of the Cook Inlet Region, Southcentral Alaska

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Cook Inlet spans southcentral Alaska from the Gulf of Alaska to the Anchorage and Matanuska-Susitna boroughs, and the surrounding watershed holds the state's largest population. Cook Inlet is also a forearc basin of the Aleutian Trench, one of the most seismically active subduction zones globally. Surficial geologic units in the region include many loosely consolidated glacial sediments. The region has experienced devastating landslides, especially those triggered by the 1964 Great Alaska earthquake. These factors, in addition to the availability of detailed regional geologic maps, elevation models, and regional earthquake-triggered ground failure inventories, make the Cook Inlet region an important location for landslide susceptibility mapping. Motivated by the need to improve the global U.S. Geological Survey (USGS) near-real-time ground failure product with higher-quality regional information, we developed an earthquake-triggered landslide susceptibility map for the Cook Inlet region. We adapted methods originally proposed by Wilson and Keefer (1985) which combine slope and rock strength to assign classes of relative landslide susceptibility. The resulting relative landslide susceptibility classes range from 0 to 10, with a general trend of shallower slopes and stronger rocks showing less susceptibility, and steeper slopes and weaker rocks being more susceptible. We use this map as the input for two modeling approaches: 1) the HAZUS methodology and 2) a qualitatively updated version of the global model used by the USGS landslide near-real-time product. We compare these results to two newly available detailed inventories of earthquake-triggered ground failure from two large earthquakes in the region:

the 1964 Great Alaska Earthquake and the 2018 Anchorage Earthquake. We note that even though we use the susceptibility map with earthquake triggers, the map is also useful for landslide hazards in general and uses a susceptibility classification method common to other regional maps.

Development of a Physics-Guided Non-Ergodic Ground Motion Model for the Groningen, Netherlands Region

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We present the development of a non-ergodic ground motion model (GMM) for the Groningen natural gas field in the Netherlands. Non-ergodic GMMs are a promising development in probabilistic seismic hazard analysis as they offer the potential to reduce the aleatory variability that controls the seismic hazard, especially in larger return periods. This reduction in aleatory variability is accompanied by epistemic uncertainty in regions with sparse observation or a systematic shift in the median ground motion in regions with dense recordings. In order to further reduce the range of epistemic uncertainties, a series of 3D wave propagation simulations on a 3D velocity model for Groningen were performed, illuminating seismic wave propagation paths not represented in the empirical datasets. These simulations are currently limited to a maximum frequency of 5 Hz with plans to extend them to 10 Hz. The non-ergodic model is formulated as a Gaussian Process where the systematic source and site effects are expressed as spatially varying coefficients that depend on the event and site coordinates. A physics-informed kernel function is developed to describe the systematic path effects that takes into account the correlation between entire rays. Assimilating large sets of empirical and simulated data necessitated the development of efficient sparse approximations and the use of high-performance computing. Using the Sparse Cholesky Factorization following the procedure described by Schafer et al. (2021), we were able to reduce the memory and computational complexity from $O(N^2)$ and $O(N^3)$ to $O(N \log(N)^d)$ and $O(N \log(N)^{2d})$, respectively. While the use of the open-source coding language Julia, which is optimized for parallel computing scalability, allowed us to take advantage of the additional resources in HPC environments for the GP regression.

Developing a Data-centric Workflow for Seismic Source Model Construction and Testing

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Constructing and calibrating seismic source models for Probabilistic Seismic Hazard Assessment involves integrating disparate datasets into a cohesive whole, amidst substantial incompleteness and uncertainty in most observations. To build seismic source models repeatably, efficiently and with a maximal amount of data, the Global Earthquake Model Foundation has developed an evolving workflow based on open-source tools for modeling crustal fault networks, subduction zones, and distributed seismicity.

Initial fault network characterization is conducted using *Oiler*, a tectonic block modeling code. *Oiler* inverts geodetic velocity and geologic slip rate data to estimate fault slip rates and partial coupling at subduction zones. Subfault to multifault ruptures in the fault network are generated using *Fermi* through graph-theoretic methods, with occurrence rates calculated from fault slip rates and magnitude-frequency distribution (MFD) constraints through a choice of solvers. Shallow off-fault seismicity is modelled by zonal gridded point sources with occurrence rates smoothed according to past seismicity. Subduction zone interfaces and slab sources are modeled separately. The interface is represented by a nonplanar fault surface, accommodating floating ruptures conforming to the MFD derived from the seismic catalog and tectonic convergence rate. The subducted slab is modeled through gridded finite ruptures. Model components derived from instrumental seismicity rely on a homogenized seismic catalog classified to the main tectonic domains by event proximity to surfaces delineating the domains. The model's fidelity to seismicity data is evaluated using *Hamlet* (Hazard Model Evaluation and Testing), which conducts sanity checks and statistical analyses, comparing simulated seismic catalogs to observed data for the whole model domain, or spatial subdomains, individual logic tree branches, or source typologies. *Hamlet* can also address the goodness of fit of each epistemic uncertainty hypothesis expressed via the source model logic tree. We present use cases of these tools in models of different sizes and regions.

Developing Software to Assess the Seismic Risk of Natural Gas Infrastructure: OpenSRA

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Owners and regulators require performance-based earthquake engineering (PBEE) assessment procedures to proactively and cost-effectively make risk-informed decisions regarding the seismic performance of their infrastructure. An efficient PBEE tool is required to assess the potential performance of their system during an earthquake, to identify components that are most vulnerable, and to mitigate components that have the highest risk. This presentation will provide an overview of the 1) research performed on seismic demand and capacity models, laboratory testing, and finite element modeling, and 2) implemented findings from the research into a new open-source seismic risk analysis program called *OpenSRA*.

The overview of *OpenSRA* will include details on the easy-to-use graphical user interface, the state-of-the-art models addressing different seismic demands (e.g., ground shaking, fault rupture, liquefaction, and landslide), and the new fragility models for buried pipelines, wells, caprocks, and surficial elements. The graphical user interface provides a fully interactive map canvas for visualization of the inputs (e.g., infrastructure, ground motions, GIS data) and outputs (probability of failure) over different basemaps of California. The software allows end-users to select the analysis models according to the resolution of the available data (i.e., statewide, regional, or site-specific) and adjust uncertainties in the model parameters to study the risk. Finally, *OpenSRA* implements an efficient algorithm called polynomial chaos expansion for risk analysis that can be orders of magnitude faster than traditional analysis (i.e. Monte Carlo sampling). Overall, *OpenSRA* provides the industry an efficient program to understand the seismic risk of natural gas infrastructure and an environment easily adaptable to other types of infrastructure and natural hazards.

Addressing Challenges in Regional Seismic Risk Assessments in British Columbia: M9 Cascadia Subduction Zone Earthquakes, Deep Sedimentary Basin Amplification and Non-Ductile Reinforced Concrete Shear Wall Buildings

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This presentation aims to address some of the challenges associated with conducting regional seismic risk assessments in Southwest British Columbia: (1) the lack of ground motion recordings of M9 Cascadia Subduction Zone (CSZ) earthquakes; (2) the presence of the Georgia sedimentary basin, which can amplify ground motion shaking, particularly in the medium-to-long period range, and is not accounted for in current building codes; and (3) the large concentration of tall nonductile reinforced concrete shear wall (RCSW) buildings constructed prior to the 1980s, which are of special concern because they predate modern seismic codes and are clustered in densely populated areas, raising concerns about the risks to life, property, and recovery from large earthquakes.

Physics-based ground motion simulations of 30 plausible M9 CSZ earthquakes, which explicitly consider basin effects, are benchmarked against existing ground motion models to develop site-specific and period-dependent basin amplification factors. A framework to incorporate these factors into uniform hazard spectra (UHS) calculations, to enable the inclusion of these effects in the design and assessment of buildings, is proposed.

The collapse risk of older tall RCSW buildings is assessed via nonlinear response history analysis of 3D numerical models of 25 representative archetypes generated by means of a predictive model that leverages a detailed inventory of such buildings. Collapse risk is quantified using hazard estimates of Canada's national seismic hazard model, which neglects basin effects, and a "hybrid" hazard model that considers basin amplification. A scenario-based seismic performance assessment, under the M9 CSZ earthquakes previously introduced, to quantify economic losses and recovery times in these buildings, is also carried out.

The results aim to inform seismic policy development in British Columbia, in particular, ongoing efforts by the City of Vancouver to address seismic risks in its aging building infrastructure.

Using Comparative Subductology to Constrain Future Subduction Zone Earthquake Losses

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On its hundredth anniversary, we recount details of the M8 September 1923 Great Kanto earthquake, the most devastating natural disaster in Japanese historical times. This event destroyed most of Yokohama and Tokyo, attributable to the combined impacts of shaking, liquefaction, landslides, tsunami, and (primarily) fires, which resulted in over 105,000 fatalities. Although smaller in magnitude than other great Japanese earthquakes, including the M9 2011 Tohoku earthquake, the proximity of the subducting Philippines plate interface beneath the populated Tokyo region resulted in much more damage than other events in Japan's seismic history. In fact, despite being well-constrained by Slab 2.0 and regional models, interface proximity to the exposed population is often overlooked, and we emphasize this point via basic comparative subductology—that is, by comparing subduction zone characteristics worldwide. We do so first qualitatively by visual geometric comparisons and then quantitatively using ShakeMap and PAGER to compare shaking intensity and losses for significant cities above subduction zones worldwide. Though there are large uncertainties in several aspects of the hazard problem—such as seismogenic rupture extents, radiation complexity, and basin amplification—others are relatively well-constrained, including the potential source geometry. On the loss estimation side, there are also significant uncertainties, such as limited building inventories and fragilities, yet we can characterize the exposed population and overall vulnerabilities reasonably well. We show that once shaking is well-constrained via its source geometry, PAGER models perform well enough to infer and compare losses for future events. The central theme of this presentation is that source geometry and population, two well-characterized features of the loss estimation challenge, are well-known and critical diagnostics for future loss estimates via scenario realizations.

Regional-Scale Hazard, Risk and Loss Assessments [Poster Session]

Poster Session • Friday 3 May

Conveners: Ashly Cabas, North Carolina State University (amcabasm@ncsu.edu); John Cassidy, Geological Survey of Canada (john.cassidy@nrcan-rncan.gc.ca); Rodrigo Costa, University of Waterloo (rodrigo.costa@uwaterloo.ca); Cassie Gann-Phillips, North Carolina State University (cvgann@ncsu.edu); Mike Greenfield, Greenfield Geotechnical (mike@greenfieldgeotechnical.com); Tiegan E. Hobbs, Geological Survey of Canada (thobbs@eoas.ubc.ca); James Kaklamanos, Merrimack College (kaklamanosj@merrimack.edu); Albert Kottke, Pacific Gas and Electric Company, (albert.kottke@pge.com); Sabine Loos, University of Michigan (sloos@umich.edu); Cristina Lorenzo-Velazquez, North Carolina State University (clorenz@ncsu.edu); Andrew Makdisi, U.S. Geological Survey (amakdisi@usgs.gov); Hong-Kie Thio, AECOM (hong.kie.thio@aecom.com); Eric Thompson, U.S. Geological Survey (emthompson@usgs.gov); David Wald, U.S. Geological Survey (wald@usgs.gov); Erin Wirth, U.S. Geological Survey, (emoriarty@usgs.gov)

POSTER 156

Empirical Response of Subduction-Zone Ground Motions in the Cook Inlet Basin of Alaska

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Soft sediments and basins amplify ground shaking from earthquakes across a range of periods of engineering interest, and characterization of areas with potential strong shaking is critical for seismic design of buildings and infrastructure. Particularly important is the Cook Inlet region in Southern Alaska, an important commercial seaway that encompasses most of the state's population and is located near the Alaska subduction zone. The last major effort to update ground-motion models (GMMs) in Alaska, NGA-Subduction, compiled data through 2018 but did not consider basin amplification. Since then, multiple large (M7.2–8.2) subduction-zone interface earthquakes have occurred. Here, we seek to evaluate the efficacy of NGA-Sub basin-response models for three well-recorded events. Although stations encompass a region beyond the extent of basin depths (*Zx*, the depth to specific shear-wave velocity isosurfaces) obtained from the Cook Inlet basin model, we hypothesize that using *Zx* values from specific basin models can yield improvements in GMM performance of in-basin stations over using default V_{S30}-based *Zx* values built into the GMMs, as demonstrated in a related study for shallow-crustal earthquakes recorded in western U.S. basins.

Our goal is to determine whether using newly published estimates of (1) V_{S30} (the time-averaged shear-wave velocity in the upper 30 m) based on *P*-wave receiver functions, and (2) sedimentary basin depth (parameterized as *Zx*) improve GMM performance in southern Alaska. We compute two sets of ground-motion residuals, using either the default or new site and basin inputs, correct them for nonlinear site response from strong shaking intensities, and perform mixed-effects regressions to account for event- and station-specific effects. We then evaluate GMM performance by comparing the scaling of residuals with V_{S30} and *Zx* against the published scaling models and comparing the statistical moments of the two sets of residuals. This work can improve estimates of regional seismic hazard analyses, including future updates to the U.S. Geological Survey's National Seismic Hazard Model in Alaska.

POSTER 157

Physics-based Seismic Hazard Assessment Using Multi-cycle Earthquake Simulations: Influence of Segment Connectivity and Strength Distribution

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During the past decades, numerous seismic hazard assessment (SHA) studies have been conducted to help mitigate earthquake-related casualties and economic losses. However, the short instrumental period of recorded earthquakes poses a challenge to accurately estimate the recurrence rates of potentially hazardous earthquakes. Hence, a rigorous SHA should not rely solely on past seismic events or on deterministic extreme scenarios. Instead, novel approaches such as numerical multi-cycle rupture simulations producing synthetic seismic catalogs can be used to enhance the reliability of the SHA.

The mega-project of NEOM, located within the seismic active region of the gulf of Aqaba (GoA), the southern extension of the Dead Sea fault zone, has attracted increased scientific attention due to the region's susceptibility to large-magnitude earthquakes (e.g., 1995 M7.3 Nuweiba earthquake). Therefore, we conduct physics-based simulations using a multi-cycle engine (MCQsim) to create long-term synthetic seismic catalogs. We model different

seismic-source realizations varying the spatial gaps among the strike-slip segments as well as the strength distribution throughout the complex fault system of the GoA. The resulting synthetic catalogs provide a possible pathway to quantify epistemic uncertainties that arise from poorly constrained parameter space (e.g., fault geometry and frictional strength). By analyzing MCQsim catalogs spanning tens-of-thousands of years, we infer the recurrence rates and complex patterns of multi-segment ruptures. Furthermore, we establish a workflow to incorporate these rupture scenarios into the probabilistic seismic hazard assessment framework of OpenQuake to compute exceedance probabilities of different ground-motion intensity measures. Our findings indicate that both spatial fault continuity and strength distribution affect the resulting long-term multi-cycle catalogs and hence have a measurable impact on peak ground accelerations and uniform hazard spectra.

POSTER 158

Seismic Hazard Assessments for the Jackson Purchase Region (Upper Mississippi Embayment) Using Reelfoot Fault Scenarios and Site-Specific Vs Profiles

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The New Madrid Seismic Zone (NMSZ) produced at least three magnitude 7.0 or greater earthquakes in the winter of 1811-1812. This Zone, which can affect several population centers in the central U.S., underlies the Upper Mississippi Embayment, a southward-plunging, broad basin containing up to a kilometer of unlithified sediments. Seismic hazards in the region are therefore affected by both the large, active faults and strong site effects. Because large NMSZ earthquakes have not occurred in the instrumental period, and their recurrence probabilities are difficult to estimate, scenario-based hazard assessment provides an appropriate tool to estimate ground-motion hazards for the region. In addition, numerous studies have indicated the inadequacy of the ubiquitous *Vs30* parameter to account for site effects in the Embayment and that site-specific *Vs* profiles are needed to reliably estimate seismic hazard in this region.

Here, we simulated time-histories across the Jackson Purchase Region (JPR; the Kentucky part of the Embayment) for moment magnitude (M) 6.8, M 7.2, and M 7.6 scenario earthquakes on the Reelfoot Fault, the thrust fault in the NMSZ understood to be responsible for the largest event of the 1811-1812 sequence. The modeling accounts for finite-fault effects using the stochastic-source model. Simulated time-histories were then input into 1D equivalent-linear site-response analyses conducted at each site. For the 1D analyses, we used site-specific *Vs* profiles developed from surface reflection and refraction studies and a recently developed 3D JPR sediment *Vs* model. There is considerable uncertainty in the bedrock *Vs* in the Embayment and we used the average of the estimates determined at the two deep vertical seismic arrays in the JPR. The resultant scenario-based hazard maps not only reflect regional variability in ground-motions due in part to nonergodic site-effects, but also are straightforward for stakeholders and communities to understand and use. Future scenario-based seismic hazard assessments in the JPR may be improved by incorporating 3D wave propagation effects.

POSTER 159

A Remarkable Absence of Liquefaction: Data-Driven Lessons From the 2014 South Napa Earthquake

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The M6.0 2014 South Napa earthquake is often recognized for having a remarkable absence of liquefaction. But why? We investigate the subsurface soil and groundwater conditions in the vicinity of the fault rupture to determine the potential reasons that liquefaction observations were nearly absent, despite rigorous reconnaissance efforts. Through an analysis of several thousand borehole-based samples and monitoring well observations, we determined that the near absence of liquefaction was not remarkable but was rather predictable. First, the borehole data in the vicinity of Napa indicate that the Holocene alluvial soils tend to be more clay-like than elsewhere in the San Francisco Bay region. Second, the groundwater at the time of the earthquake was significantly lower than the typical elevation due to a prolonged drought. The combination of these factors resulted in a low probability of liquefaction.

While the low groundwater levels at the time of the earthquake were fortuitous from a liquefaction perspective, groundwater levels can be highly variable. We also investigate the potential for liquefaction under different groundwater conditions with a novel spatial and temporal groundwater model. The groundwater model is based on a relatively simple 2D flow analysis coupled with a Gaussian Process regression scheme to interpolate the groundwater elevation between well observations. The analyses indicate that if the earthquake had occurred during typical, non-drought conditions, the liquefaction ground damage would have been more severe. Likewise, the influence of sea level rise associated with climate change impacts groundwater conditions, which would further increase the probability of liquefaction.

POSTER 160

Offshore Seismic Hazards in Southern Cascadia

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Large (6.5-7.5) earthquakes within the Gorda plate offshore of northern California have been damaging communities in the region for more than one hundred years. Many models have been proposed to explain the occurrence of these intraplate events, a response of the Gorda plate being squeezed in a tectonic die. The most recent of these intraplate earthquakes took place on December 20th, 2022, causing extensive damage in the towns of Rio Dell, Fortuna, Loleta, and Ferndale. We demonstrate that this event occurred on the same patch of the same fault as an earthquake 47 years ago, on June 7th, 1975. Additionally, we find that "stationary" intraplate faults capable of hosting recurring events are not unique to the 2022-1975 pair. There are at least five offshore faults in southern Cascadia with a history of multiple damaging earthquakes.

POSTER 161

Modelled Impacts of Rupture on the Newly Discovered XEOLXELEK-Elk Lake Fault, BC, Canada

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Canada has not experienced a fatality from earthquake shaking since 1870. This relative seismic quiescence, and the lowered public perception of risk that is causes, are at odds with a national risk assessment that estimates a mean value of nine fatalities per year from earthquake shaking. Additionally, it is estimated that a major earthquake near an urban center could cause hundreds or even thousands of fatalities for the country, in addition to tens of thousands of ruined buildings and infrastructure assets and up to tens of billions of dollars in direct financial losses, without accounting for secondary perils. The newly discovered XEOLXELEK-Elk Lake Fault on the Saanich Peninsula, British Columbia, poses a threat to the major population center of Victoria as well as several important pieces of infrastructure on Vancouver Island. Its shallow extent and proximity to housing will pose additional challenges by thwarting earthquake early warning and potentially creating localized fault displacement damage that residential homes are not designed to withstand.

In this study, the Canadian Seismic Risk Model framework is used to assess the impact of earthquakes on the XEOLXELEK-Elk Lake Fault, in terms of building damage, life safety, and disruption. Attention will also be paid to the major highways in the area, which connect Victoria to mainland British Columbia via the BC Ferries terminal in Swartz Bay. These results can be used by emergency managers, planners, and other decision makers to justify needed preparedness and mitigation work to respond to this newly discovered fault line.

POSTER 162

A Future Scenario Earthquake and Ground Motion Hazards for Kathmandu, Nepal

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We constructed a new distribution of the rupture zones of great historical earthquakes along the Main Himalayan Thrust (MHT) by integrating the distribution in a previous study and the results of recent trench surveys.

Additionally, recent Global Navigation Satellite System (GNSS) observations revealed that the boundary between the Indian and Eurasian plates is strongly coupled from the southern boundary of the MHT to a depth of approximately 10 km and there is almost no lateral change in the coupling. This implies that all regions along the MHT have similar rates of strain increase. Therefore, it is most probable that the rupture zone of the oldest previous event will rupture as a future scenario earthquake. In the new distribution, the 1255 earthquake is the oldest. However, large earthquakes have already occurred in 1934 and 2015 within its rupture zone. Thus, we adopted the area obtained by removing the 1934 and 2015 rupture zones from the western part of the 1255 rupture zone. As this area is close to Kathmandu, we assumed that it would be the rupture zone of a possible scenario earthquake for seismic hazards in Kathmandu. The relationship between the rupture zone size and seismic moment of the 2015 earthquake falls between the scaling formulas for crustal earthquakes and plate boundary earthquakes, but closer to the former formula. Therefore, we constructed a characterized source model based on the former formula. We simulated broadband ground motions in Kathmandu using this source model, our 3-D velocity structure model, and a hybrid method combining the finite difference method and the stochastic Green's function method. We obtained the peak ground accelerations (PGAs) of simulated ground motions, and calculated the seismic intensities in the modified Mercalli scale from the PGAs as indexes of hazards for Kathmandu. Intensities IX were identified in the center of the Kathmandu Valley, and we mostly found intensities VIII and VII in the area surrounded by the sedimentary boundary and the southernmost part of the valley.

POSTER 163

Unraveling Seismic Complexity: Repeating Rupture Patterns and Varied Seismogenic Environments in the Mexico Subduction Zone

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Accurately determining the locations of repeating or quasi-repeating large earthquakes allows for a more reliable estimation of recurrence periods and the identification of seismic gaps. In this study, we systematically investigate the complexity of earthquakes within the Mexico Subduction Zone. Using waveform comparisons, we identify six sets of repeating rupture patterns, and subsequently refine the slip models of historical events through joint finite fault inversion method. Our findings indicate significant differences in tectonic activities between the northern (Jalisco-Michoacan) and southern (Guerrero-Oaxaca) segments of the Mexico Subduction Zone. By clarifying these differences, we provide valuable insights for future seismic risk assessments along the Mexico Subduction Zone, enabling a more accurate and region-specific understanding of the potential impact of earthquakes. This research serves as a foundation for enhancing preparedness measures and resilient infrastructure development, particularly in regions where the seismogenic environment poses unique challenges.

POSTER 164

Influence of Site Effects' Spatial Variability on Spatially Variable Ground Motion Intensity Measures

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Spatially variable ground motions (GMs) challenge the assessment and design of largely distributed infrastructure in earthquake-prone areas. The spatial variability of GMs is a complex function of source heterogeneities, varying ray propagation paths, and varying local soil conditions. Because soil properties can be spatially correlated at nearby locations, the expected site response affecting civil infrastructure systems will also be spatially correlated. Therefore, the spatial correlation structure of soil properties can inform the spatial correlation of GM intensity measures (IMs). Current spatial correlation models treat site effects either as a fixed amplification factor or as randomized amplifications, but site effects are neither. In this work, we evaluate the significance of the spatial correlation for different site parameters corresponding to Kiban-Kyoshin Network (KiK-net) stations with respect to the observed spatial correlation of GM IMs residuals from collocated events including the 2011 Tohoku earthquake sequence. This earthquake sequence caused significant damage, such as pipeline ruptures due to the strong shaking in the Tohoku and Kanto regions. These co-located events provide an opportunity to capture site-specific correlations while isolating the influence of both source and path effects on correlation structures. Particularly, the residual analysis of GM IMs (e.g., spectral acceleration; SA) was performed using a ground motion model (GMM) to remove the effects of attenuation with distance and further examine the correlation of the IMs at different periods of interest. Preliminary findings show that the spatial distribution of GM IMs is affected by the variation of geology and topographic conditions captured by site parameters.

POSTER 165

Towards Probabilistic Tsunami Risk Estimates Using Stochastic Earthquake Sources

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Tsunami hazard acalculation methodologies have undergone significant evolution in recent years with significant attention being placed on the probabilistic tsunami hazard assessment formalism. The next logical step is to extend the focus from purely hazard-centric perspectives to inclusive evaluations of risk and loss. The most substantial challenges of this shift are twofold: accurate estimation of likely seismic sources and defining the exposure of any given region, both demanding appropriate modeling of rupture dynamics and high-resolution hydrodynamics, as well as determining useful fragilities. Here we propose an approach that integrates stochastic rupture simulations, advanced inundation modeling, and exposure assessment. Through amalgamating these disparate elements into a cohesive framework, we aim to provide a comprehensive tool that not only quantifies the potential for seismic activity and consequent tsunami hazard, but also robustly predicts the associated risk and loss. We will present results from a prototype workflow utilizing this methodology, and discuss its potential applicability in probabilistic calculations for any subduction system globally. Furthermore, we will illustrate the scalability of this innovative model, asserting its feasibility for global implementation. This step forward offers a promising avenue for significant improvements in our understanding of tsunami hazards, risks, and their potential impacts on both local and global scales.

POSTER 166

Seismic Geohazards in Italy: Seismic Geohazards in Italy: An Integrated Geotechnical Earthquake Hazard Assessment Map

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The study presents an integrated approach to assess three co-seismic geohazards: site amplification, liquefaction, and landslides for Italy. The novelty of the approach lies in the construction of 30m x 30m geotechnical spatial grids by adopting a systematic framework, considering the local site response characteristics. The results are discussed in terms of three individual maps: time-averaged shear wave velocity to 30m depth (Vs30), liquefaction, and landslide susceptibilities. Due diligence is given to assess the pertinent hazards for major areas viz. Central Apennines, Southern Italy, Sicily, and the Adriatic Coast. The study also focuses on Northern Italy where the supplementary risks viz. liquefaction and lateral spreading were widely observed post the 2012 Emilia Romagna sequence. We present a novel Vs30 map based on constraining Vs30 observations within multiple secondary parameters such as surficial geology and Multi-Resolution Valley Bottom Flatness (MrVBF) for unconsolidated geology units. The improvements result in a reduction of around 15–30% in residual standard deviation in Holocene depositions. A matrix of multidisciplinary datasets that includes geological, hydrological, geotechnical, and terrain data is used to assess the liquefaction susceptibility of Italy. The results provide both lateral and vertical displacements which are further validated using historical observations in Italy. Earthquake-induced landslide hazard assessment is carried out using a bi-variate statistical model of Landslide Susceptibility Zonation (LSZ), augmented with a multi-criteria structured decision technique. Four landslide controlling parameters: geological units, slope angle, slope roughness, and Peak Ground Acceleration are considered to produce an LSZ map for 5 historical earthquake events. The resultant geotechnical site hazard maps provide an exhaustive representation of local site effects and coseismic instabilities in cognizance of seismic risk.

The study offers valuable insights for establishing a framework for disaster risk reduction.

POSTER 167

An Empirical Bayesian Kriging Approach for Site Period Mapping of Santiago Basin, Chile

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Seismic site classification plays an important role in the estimation of site amplification, which directly influences earthquake-induced damages. Site effects are strongly dependent on site-specific conditions as well as the spatial distribution of the geotechnical parameters in the region. Since the fundamental site period depends on the subsurface condition, surficial maps such as terrain or geology have a high probability of being well constrained only to shallow depths. At the same time, it is hard to find a consistent source of bedrock depth parameters around the globe. The use of geostatistical methods such as ordinary kriging or simple kriging can resolve this issue by relying on a spatial variogram for predictions at unsampled locations. However, uneven, or sparse data distribution usually creates unrealistic patterns. This study proposes the use of the Empirical Bayesian kriging interpolation method for site period mapping in Santiago basin, Chile. A low-precision model using depth to basement is used as prior information and ~200 fundamental site period measurements are considered as precision data within the basin. This study shows that the spatial prediction accuracy can be further improved over the ordinary kriging approach using the Empirical Bayesian kriging technique.

POSTER 168

Understanding Regional Site-Amplification Effects in the San Francisco Bay Region, California Through Ground-Motion Analysis and Modeling of Regional Seismic Velocity Structure

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We explore the relationship between regional site amplification and seismic velocity profiles in the San Francisco Bay region of California through ground-motion analysis and modeling of one-dimensional profiles from three-dimensional seismic velocity models. We compute Fourier amplitude ground motions using a dataset of 34,000 records from 200 M>3.3 earthquakes. The site terms are computed from mixed-effects regressions of the ground-motion residuals, relative to the Bayless and Abrahamson (2019; BA19) ground-motion model (GMM), and partitioned into bias, event, and station-specific components. We first evaluate the effect on data misfit from the use of site parameters—time-averaged shear-wave speed to 30 m (V_{S30}) and depth to the 1-km/s shear-wave horizon (Z_1). The impact of the and parameters on fits from the BA19 GMM is assessed by comparing sets of site terms that result from the use of uniform reference V_{S30}, V_{S30}-only, and from V_{S30}-Z 1 -pairs at each site when evaluating the GMM. We identify regions of persistent long-period (T>1 s) misfit, which indicate site response that differs from that of the GMM. For all sites, we extract profiles from the U.S. Geological Survey San Francisco Bay region seismic velocity model (Aagaard and Hirakawa, 2021) and the National Crustal Model (Boyd, 2020). Using Thompson-Haskell propagator matrix methods, we compute amplifications from the profiles and compare the period-dependent trends in amplification with the trends in the ground-motion residuals. With a primary focus on the sedimentary basins of the region, we explore the effect of seismic velocity structure on the ground-motion misfits. Understanding the causes of varying site amplifications will be an important step towards integrating nonergodic GMMs in regional seismic hazards assessments and may lead to improved models to predict site response that extend beyond the San Francisco Bay region.

POSTER 169

Development of a Seismically Induced Landslide Susceptibility Scale for Greece for Addressing Data Imbalance

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The persistent conundrum of data imbalances in landslide susceptibility zonation (LSZ) practices leads us to develop a data driven heuristic scale of LSZ which is used to integrate landslide and seismic hazards for Greece. Three landslide controlling parameters *viz.* slope angle, slope roughness and friction angle are integrated with one seismic parameter: Peak Ground Acceleration (PGA) to generate the seismically induced LSZ map of Greece. The landslide database is prepared using the USGS ScienceBase-Catalog for Lefkada Earthquake, 2003. As only 274 landslide events are available for this earthquake, there is an accentuating problem of data/inventory imbalance which results in overfitting/underfitting of weights. Application of traditional LSZ models with such limited dataset generally shows exacerbated effects of one landslide controlling parameter and often neglects the impact of others. This might produce an LSZ map which is heavily skewed towards the overfitted controlling parameter. To address this issue, we develop a LSZ scale using Frequency Ratio, Information Value and Fuzzy Cosine Amplitude methods where concurrency of weights for each thematic layer of landslide controlling parameters are established. In the next phase, a scale of 1 to 9 is derived based on the established concurrency, and the consistency of the decision is further checked using a multi-criteria structured technique: Analytical Hierarchy Process (AHP). If the consistency ratio (CR) for each decision is less than 10%, it is accepted, else the process is revised. Once all the weights (now in the range of 1 to 9) are calculated, they are overlaid arithmetically in a GIS environment to produce the final seismically induced LSZ map of Greece. The resultant LSZ map demarcates the study area into five distinct zones of landslide susceptibility with 77% predictive accuracy. The study demonstrates the applicability of the proposed LSZ scale for areas with problems of data/inventory imbalances.

POSTER 170

National Seismic Hazard Assessment for Azerbaijan Using New Seismic Data and Ground Motion Simulations

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A new probabilistic seismic hazard assessment (PSHA) was carried out in Azerbaijan under the Seismic Cooperation Program at the Lawrence Livermore National Laboratory. The study started with a Caucasus-wide compilation of an earthquake database. Next, Mw was calculated for about 400 earthquakes using Coda Calibration Technique. Azerbaijan had many stations where modern digital seismometers were co-located with Soviet-era equipment, which was instrumental in developing magnitude conversion relations between Mw and Soviet era magnitude scales. Following magnitude harmonization, catalogue completeness intervals were computed. In addition, earthquake relocation was carried out providing more accurate locations and depths for earthquakes, better delineating a subduction structure that have been the subject of past investigations. Two versions of the PSHA-ready catalogue were generated, one with declustering applied and one without. Known active faults with geologic slip rates in this region are sparse, but a few were identified in neighbouring countries that might impact Azerbaijan. A source model was put together using both the seismic activity rates based on the earthquake catalogue and the identified active faults. Azerbaijan has a strong motion network that has about 40 accelerometers. Contemporary ground motion models (GMMs) from US, Japan, Europe and Middle East were tested against recorded data, which showed that the ground motion attenuation in much of Azerbaijan is generally slower than active tectonic regions like California, but faster than stable continental regions like Eastern North America. The difference also varies by frequency/period of vibration. The reason for the difference appears to be not tectonic in origin but rather due to thick sedimentary layers in the Kura basin. In order to quantify these effects, we perform 3-D hybrid ground motion simulations to inform the selection of the GMMs and the weights to use in the PSHA. We present preliminary results that have been well-received by the engineering community in Azerbaijan and are currently being considered for use in the building code update.

POSTER 171

Data-Driven Performance Evaluation of Ground Motion Models Applicable for Active Crustal Region in Italy

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The influence of regional crustal wave propagation effects and complex geologic structures has been observed in strong motion records in Italy. These phenomena are critical and are captured by ground motion models (GMM) for developing regional seismic hazard maps. The aim of present work is to select and rank GMMs applicable in active crustal regions of Italy for seismic hazard analysis. In this study, we evaluated the relative performance of 15 active crustal GMMs, including regional, pan-European, globally derived default and regionally adjusted ones. We compiled a comprehensive strong motion flatfile containing over 43,000 recordings from ESM and ITACA between 1969-2022. First, we processed the strong motion records to remove duplicates and selected only records having magnitudes greater than 4.5. Then, residual analysis was performed using strong motion records from rock site stations (having V_{S30} of 600-1000 m/s) and all stations with varying V_{S30}. We analyzed the influence of minimum magnitude, rupture distance, and fault mechanism on overall bias and between event as well as within-event residuals. Finally, data-driven scoring methods were employed, using univariate (LLH) and multi-variate (mLLH) logarithmic scores, to assess relative performance of GMMs. Regional level seismic hazard analysis was also performed using selected candidate GMMs, by assigning weight of 1.00. Results of residual analyses showed that almost all GMMs are over-predicting at the short period due to regional factors, where the degree of over-prediction is significant among earlier version of pan-European and global GMMs. On the other hand, almost all GMMs were under-predicting at the long periods (approximately after 1-2 seconds). In general, regional and pan-European GMMs showed relatively better performance (in terms of better LLH and mLLH scores), by capturing regional characteristics than global and global model with regional adjustments. Finally, rock-level hazard maps, corresponding to V_{S30} of 760 m/s and 475-year return period, revealed that regional models exhibit lower hazard than pan-European model.

POSTER 172

Dependence of Seismic Hazard Assessment on the Observation Time Interval: Insights From Physics-Based Simulated Seismicity in Southeastern Spain

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The magnitude-frequency distribution (MFD), which defines the seismicity of a region, is obtained using the earthquake record. In slow-moving fault systems, where seismicity is low to moderate, earthquake catalogues may not cover the full seismic cycle of active faults. This implies that seismogenic sources may be incompletely characterized on Probabilistic Seismic Hazard Assessment (PSHA), since the quantification of seismic hazard is associated with the specific time period during which earthquake catalogue have been recorded. To evaluate the dependence that exists between seismic hazard and the observation interval, this study develops some PSHAs based on synthetic seismicity. The selected site is the Eastern Betics Shear Zone in SE Spain, where some damaging earthquakes have occurred. The synthetic seismicity of this fault system consists of a million-year earthquake catalogue generated using the RSQSim earthquake simulator. The digital model considers the geometry, slip rates and friction properties of major faults. From the global synthetic catalogue, ten thousand sub-catalogues have been obtained. Their duration has been selected to be equivalent to that of the actual earthquake record (i.e. 1,000 years). Each sub-catalogue shows different features in their MFDs, which can be quantified by the distribution of values of the slope of the Gutenberg-Richter relationship, the annual earthquake rate and the maximum magnitude. A hundred sub-catalogues have been randomly selected to conduct individual PSHA. Seismic hazard curves have been obtained for the cities of Murcia, Lorca, Alicante, Vera, Torrevieja and Almería using R-CRISIS. These curves reveal that each sub-catalogue leads to different return periods for specific values of Peak Ground Acceleration (PGA). The variability coefficient was used to quantify hazard variability, with a maximum value of 58% found in Torrevieja for a PGA=1g and a minimum of 10% in Almeria for a PGA=0.02g. These results show that seismic hazard depends on the time interval during which an earthquake catalogue is recorded. This dependence increases for large PGA values.

POSTER 174

Improving Geospatial Liquefaction Prediction Models by Optimizing Non-Liquefaction Points Sampling: A Case Study of the 2023 Kahramanmaras, Turkey Earthquake Sequence

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To create geospatial liquefaction prediction models, we need to observe both liquefaction and non-liquefaction points to use this information to extract the value of explanatory geospatial proxies like VS30, distance to water, etc. Reconnaissance teams usually report only the location of liquefaction; therefore, to sample non-liquefaction points, we need to make different assumptions. In the literature, a donut-shaped area with an inner radius of 1 km and an outer radius of 15 km is used to create a fishnet with desired grid size and sample non-liquefaction points. This study looks at the critical aspect of non-liquefaction point sampling strategies and how the geometric properties of the donut-shaped non-liquefaction sampling region around the liquefaction observation affect the accuracy and generalizability of the resulting model. This study uses the extensive reconnaissance reports from the 2023 Kahramanmaras, Turkey Earthquake Sequence to compare different sampling strategies based on their impact on the accuracy of the logistic regression model. We use the inner and outer radii of the donut-shaped non-liquefaction sampling buffer as optimization variables to do a grid search over the different combinations of them. The resulting models are then compared in terms of balanced accuracy, area Under the ROC Curve (AUC), precision, and recall. The insights gained from this study will help refine the methodology for creating geospatial liquefaction prediction models and provide valuable guidance for optimizing earthquake risk assessment strategies.

POSTER 175

Correlating Resonance Frequency From Hvsr With Vs30 Along the Wasatch Fault, Northern Utah, USA

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The Wasatch Fault Corridor of northern Utah has an increasingly high seismic risk due to rising population density. Vs30 (time-averaged subsurface shear-wave velocity for the upper 30 meters) is the key parameter to determine how a site will respond to earthquake shaking; however, finding Vs30 usually requires an intensive array-based measurement with an active seismic source. The horizontal to vertical spectral ratio (HVSR) single-sensor technique is passive, unintrusive, and more convenient, potentially allowing for rapid assessment if a transformation can be obtained between Vs30 and the fundamental resonance frequency (f_0) provided by the HVSR for the shallowest stratigraphic layers. The purpose of our study is to evaluate the effectiveness of correlating the Vs30 with HVSR f_0 to either supplement or replace Vs30 measurements. Reoccupying previously surveyed Vs30 sites in Utah County, Utah, we measured the f_0 using HVSR with a three component TROMINO seismometer. The sites are located on the hanging wall (west) of the Wasatch fault zone amongst alluvial and lacustrine Quaternary sediments. For each site, we recorded ambient noise for 20 minutes and computed the amplitude frequency spectra for the three components (N-S, E-W ("H"), up-down ("V")), then converted these to H/V response as a function of frequency, from which we observed the f_0 of the site by choosing the highest H/V spectral peak. The f_0 ranged between 0.28 and 1.09 Hz for all sites. To produce the best transformation of Vs30 to f_0, we selected those measurements for which the lowest-frequency prominent H/V peak was observed within the spectrum. Sixteen out of the 23 measurements were selected due to their well-expressed H/V spectral peaks and lower uncertainties. The linear regression between Vs30 as a function of f_0 resulted in a moderate positive correlation. Further work will include collection of more HVSR measurements to increase the accuracy of our study.

POSTER 176

Epistemic Uncertainty and Aleatoric Variability within Probabilistic Liquefaction Analysis

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In probabilistic seismic hazard analyses (PSHA), well established approaches have been developed for handling aleatory variability and epistemic uncertainty related to ground motion models and the associated predictive variables. However, extending these concepts to probabilistic liquefaction analyses (PLA) raises questions about how uncertainties are accounted for in the development of liquefaction triggering models. Specifically, in some of the more recently developed probabilistic triggering models, uncertainties in the estimated seismic demand and the measured in-situ test metrics associated with liquefaction and no-liquefaction case histories have and have not been considered, resulting in triggering models reflective of "total" and "model" uncertainties, respectively. How these triggering models are used within a PLA and the division between the aleatory variability and epistemic uncertainty related to the triggering model and associated predictive variables are explored herein.

Research Advances in "High-Impact", "Under-Studied" Earthquakes and Their Impacts on Communities [Poster Session]

Poster Session • Friday 3 May

Conveners: Susan Bilek, New Mexico Institute of Mining and Technology (susan.bilek@nmt.edu) Marianne Karplus, University of Texas at El Paso (mkarplus@utep.edu); Zhigang Peng, Georgia Institute of Technology (zpeng@gatech.edu); Elizabeth Vanacore, University of Puerto Rico (elizabeth.vanacore@upr.edu); Aaron A. Velasco, University of Texas at El Paso (aavelasco@utep.edu)

POSTER 144

Impact of November 2023 Earthquake in Western Nepal.

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On 3 November 2023 5.6 M earthquake struck Nepal, with epicenter in Jajarkot of Karnali province. Several aftershocks have occurred since. Tremors were felt across North India.

According to the National Disaster Risk Reduction and Management Authority (NDRRMA) 153 people have been killed and 140 injured. Thousands of families were left under the open sky as rescuers searched for survivors in the mountainous villages where the earthquake struck.

With the completion of the government's search and rescue operation, the number of deaths stands at 153 (Male: 70, Female: 83) and 338 (Male: 138, Female: 200) injured. The initial findings of the Government's Initial Rapid Assessment (IRA) launched on 05 November say over 4,000 homes were damaged in the hardest hit districts. Following the initial assessment of the remote damage assessment of available secondary data satellite images USGS data and earthquake risk model, around 1.3 million people might have been exposed and about 0.25 million people may need humanitarian assistance.

According to the National Emergency Operation Centre (NEOC), by 15 November, approximately 62,000 homes were affected (35,455 partially damaged, 26,557 completely damaged) by the earthquake. Some 250,000 people were affected by the earthquake and require humanitarian assistance. The situation is further compounded as rainwater is posing a significant risk to partially damaged homes that are fragile and face the risk of collapsing. Survivors of the earthquake are also beginning to report health issues related to increasingly cold weather. Public health authorities have warned of outbreaks of communicable and vaccine-preventable diseases in the affected areas as thousands of people are displaced, compromising health and hygiene standards.

So, in this paper I will explore the current situation in the Earthquake affected area and what needs to be done to the people of Western Nepal which is affected by this Earthquake.

POSTER 145

Examining the 1953 Kefalonian Earthquakes, From a Social Perspective.

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The Ionian islands, situated at the most western part of Greece, experienced the domination of Venice from 14th until the 19th century, and Great Britain from 1815 to 1864, when they were annexed to Greece. Isolated from the mainland of Greece, the culture of the inhabitants was influenced by their rulers, mostly the Venetians, with a severe impact on their social and economic life. Earthquakes, from historical to modern times, were the most influential disaster in their culture, leaving traces on the mentality, architecture and literature of the population in Zakynthos, Kefalonia, Ithaki and Lefkada islands. The 1953 earthquake series (9 August M6.4, 11 August M6.8 and 12 August M7.2) is a characteristic example of how a natural disaster seriously affected the everyday life of the population, mainly in Kefalonia, Ithaki and Zakynthos. Their effects were many casualties, whole towns and villages covered by debris and fires, leading to homelessness, and pleas for aid. The earthquakes also had significant psycho-social repercussions on the locals, especially to women and children. Most of the population was poor, similar to the rest of Greeks, trying to recover from WWII and the civil war. According to the authorities reports and the local and international press, the first to arrive for aid on 13 August were battleships of the British Royal Navy, United States and Israel, which were conducting a military drill offshore Kefalonia, followed by ships from Italy, carrying water supplies, two days later. The King of Greece arrived on 14 August and ordered the military to dispose the debris. Of great importance was the financial assistance from France, Sweden and Switzerland who "adopted" villages of Kefalonia, reconstructing them from scratch (e.g. Agia Efthymia and Lakithra). Additionally, international humanitarian organizations, such as Red Cross and CARE, rushed to provide aid (food, tents, etc.). The 1953 earthquakes were a milestone in the history of Greece, leading to internal migration, and influencing the perception of time scales to pre- and post-earthquake.

POSTER 146

Seismic Hazard and Risk in Lae City, Papua New Guinea (PNG)

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Lae is Papua New Guinea's second largest city, most significant port, and a major economic hub critical to PNG's development. It also straddles the Ramu-Markham Fault Zone (RMFZ), which accommodates convergence rates of approximately 50 mm/yr associated with the arc-continent collision between the Australian and South Bismarck plates. Recently published updates to PNG's national seismic hazard assessment have identified that Lae is exposed to high seismic hazard. In order to better understand and mitigate this threat, a comprehensive seismic hazard and risk assessment has been undertaken for the city. This work has included: detailed mapping of active fault traces from lidar elevation models; an earthquake geology study to constrain the timing of past large earthquakes by dating flights of uplifted fluvial terraces; a GNSS survey to constrain fault slip rates; a microzonation survey to understand site amplification and liquefaction potential; and a building inventory survey that has captured relevant engineering data for more than 3300 structures in the city. Fault mapping has shown that the RMFZ bifurcates west of the city, with one strand continuing to the east 10 km north of the city (as previously mapped), and a second strand (previously unmapped) trending southeast through Lae itself. GNSS results suggest that about a quarter of the plate convergence rate is accommodated along this second strand, likely contributing to higher seismic hazard estimates for the city. Integration of the hazard information with the building survey data and an assessment of the vulnerability of key building types is creating a picture of concentrated earthquake risk in the Lae urban area, port and airport. Ongoing work is focused on updating PNG's building standards, with a particular focus on critical infrastructure including bridges.

POSTER 147

The "Earthquake Suitcase"—A Research-Inspired Educational Tool for Earthquake Vulnerable Communities

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The "Earthquake Suitcase" is a travelling laboratory, designed and developed to inform, educate and familiarize the public in earthquake prone areas with earthquakes and their impacts, aiming in reaching people at remote locations, unable to visit a natural history museum. It includes presentation and videos on the earthquake basics (why, how and where large earthquakes occur, their effects on people, objects and buildings/infrastructure), reading material, hands-on exercises and instructions to build a family emergency plan, the contents of an earthquake emergency bag, interactive educational toys, leaflets and a model small-scale shake table. This is a stable platform, upon which a moving platform is fixed. The upper platform converts the initial manually controlled rotary motion to axial motion, thus simulating ground shaking. It is equipped with two model buildings of different vulnerability and an accelerometer recording the simulated motion. It may produce various levels of shaking, thus simulating higher and lower ground accelerations of various frequencies. The supplied software/mobile app provides various signal analysis options of the simulated "event". Persons with knowledge of Physics may perform spectral analysis of the simulated event and compare the response of model buildings to the different levels of shaking. The suitcase is presented in the Europe-wide public event "Researchers' Night" and in Greek classrooms, evaluated by schoolchildren and their educators, as an example for disaster preparedness. It was also used in the partnership project "Supporting Social and Emotional Learning" between Greek and US Fulbright alumni to develop resources that bring a strong awareness of mental health needs to practices in educational settings and refugee camps, where the earthquake phenomenon was used as an analogy of mass trauma-producing disaster, aiming at simulating the circumstances, due to which adolescents are likely to be traumatized. The suitcase and the earthquake lesson were presented in US classrooms, thus embedding social and emotional learning into science content.

POSTER 148

High-Impact Earthquakes on Hidden, Secondary Faults Within the Sparsely Instrumented Golden Triangle Region of Laos, Thailand, and Myanmar

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The Golden Triangle region of Laos, Thailand, and Myanmar (SE India-Eurasia collision zone) is crossed by >100 km-long, NE-striking sinistral faults, host to events of up to M_w 6.8 (2011 Tarlay). In the past decade, six M_w ≥5.5 events struck the area, providing new insights into its active tectonics. The largest of these, the 2019 M_w 6.2 Sainyabuli, Laos earthquake, struck 40 km from a major reservoir and 90 km from a UNESCO World Heritage Site, illustrating the need to reassess the earthquake potential of this area despite its modest background seismicity. In this study, we solved for source parameters of three M_w ≥5.5 events using Sentinel-1 InSAR. The Sainyabuli mainshock ruptured a previously unknown, 24 km-long, NNW-trending, dextral strike-slip fault with little topographic expression, with slip focused above 12 km but leaving a pronounced shallow slip deficit. InSAR modelling of the other two M_w ≥5.5 events also revealed rupture on NW-trending, ~10 km-long, unmapped faults. Collectively, this shows that the region contains conjugate faults long enough to generate damaging earthquakes but which are little evident in the topography. To understand the seismicity depth distribution and its implication for seismogenic thickness, we also relocated 198 well-recorded events between 1978–2022 using mloc software. We overcame the challenge of limited local-regional station coverage by incorporating seismic sequences from across a broad area into the relocation cluster. Since these events also share teleseismic station recordings, the collective local-regional coverage is improved. The calibrated catalog contains focal depths of 6–24 km, each with ±4 km uncertainties. The seismicity cut off thus extends far deeper than the Sainyabuli mainshock slip, potentially leaving an unruptured deeper fault as an ongoing hazard. Our combined geodetic and seismological approach shows that shorter, NW-oriented faults should be considered alongside the longer NE-trending faults in hazard models and earthquake scenarios. Our study also provides a blueprint for relocating earthquakes in other sparsely instrumented regions.

POSTER 149

The Center for Collective Impact in Earthquake Science (C-CIES)

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The Center for Collective Impact in Earthquake Science (C-CIES), funded as a Track 1 planning grant by NSF's Centers for Innovation and Community Engagement in Solid Earth Geohazards program, aims to address fundamental science questions related to earthquakes by implementing a collective impact (CI) model for science and community engagement. CI solves complex problems though the creation a network of community members, organizations, and institutions by adopting a common agenda, centralized support, continuous communication, mutually reinforcing activities, and shared measurement. The science and engineering driver of C-CIES is to study high consequence, low frequency of incidence (HC-LoFI) events. The mission is to increase societal resilience to earthquakes through collective impact hazard research with a vision to become an interdisciplinary research center rooted in equity, diversity, and engagement. The core values of the center are scientific integrity, equity, excellence, diversity, access, justice, inclusion, and collective impact. The goals of the center are to: 1) Advance convergent and transdisciplinary earthquake science and engineering research, 2) Recruit, retain, and train the next generation of diverse, interdisciplinary Earth scientists and leaders, 3) Establish a foundation of CI in Earthquake Science for shared, value-driven research that is responsive to the needs of communities, and is transferable and scalable to other geohazards, and valuable to other disciplines, and 4) Develop strong CI management structure for the center that translates results of scientific discovery into actions that can improve resilience and reduce risk from geohazars. C-CIES is currently undertaking pilot projects that will address faulting, earthquakes, and their impacts, and which, upon evaluation, may be promoted to full projects as the center launches in one year. Using collective impact, we aim to change the way geoscience is conducted by answering fundamental community-driven science questions that will have a broad, positive impact.

Seismic Cycle-Driven Sea-Level Change Over Decades to Centuries: Observations and Projections [Poster Session]

Poster Session • Friday 3 May

Conveners: Kate J. Clark, GNS Science (k.clark@gns.cri.nz); Andrew Howell, University of Canterbury (andrew.howell@canterbury.ac.nz); Jeonghyeop Kim, University of Washington (jey.kim@uw.edu)

POSTER 150

Validation of Probabilistic Coseismic Coastal Deformation Models using Geologic and Geomorphic Evidence

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Incorporating the likelihood of sudden earthquake-driven coastal uplift or subsidence into sea level change forecasts is important in tectonically active countries such as Aotearoa New Zealand (A-NZ). Several historical earthquakes in A-NZ have demonstrated the impacts that sudden coastal displacement can have on society, the environment and infrastructure. A proof-of-concept probabilistic model that forecasts coseismic vertical displacement over 100 years in the Wellington Region of A-NZ has been developed, and there is an intention to expand this model nationwide. Alongside this is a need to develop methods of validating the probabilistic coseismic coastal deformation results. Validation of the coastal deformation model can be done through a comparison with historical and some prehistoric coastal deformation data. The A-NZ historical record is short (~185 years) but there have been 6 earthquakes that have caused coastal deformation within this period. The prehistoric coastal deformation record is much longer but precisely how we compare geologic and geomorphic evidence of past coastal uplift and subsidence with modeling results is challenging. For example, the modeled coseismic displacements represent a mix of permanent and elastic tectonic deformation but the geomorphic record preserves net permanent displacement over multiple seismic cycles, so the geomorphic record may under-represent displacements from primarily elastic subduction zone earthquakes. We are exploring whether net uplift/subsidence rates from Pleistocene marine terraces are a useful source of data, or whether recurrence intervals and single-event displacement data from Holocene sedimentary and geomorphic records are preferable. However, using single-event displacement necessitates some understanding of the preservation and detection limits of various coastal paleoseismic proxies. Regardless of the approach, model validation is important for establishing confidence in the results and for targeting which model input parameters may benefit from further research.

POSTER 151

How Will Earthquakes Change Sea Level? a Probabilistic Coast-Seismic Hazard Model

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Coseismic uplift and subsidence can cause near-instantaneous meter-scale relative sea level changes that may exacerbate or reverse the effects of ongoing sea level rise. Characterizing hazards in tectonically active coastal regions, therefore, requires careful consideration of coseismic vertical deformation. We developed a proof-of-concept probabilistic model that forecasts coseismic vertical displacement over 100 years in the Wellington Region of Aotearoa New Zealand. This model repurposes fault source, earthquake rupture, and epistemic uncertainty data from the New Zealand National Seismic Hazard Model (NZ NSHM) to quantify the magnitude, direction, location, and likelihood of vertical displacement from both crustal fault and subduction interface earthquakes. The model results suggest that both crustal fault and subduction sources contribute to significant (>0.2 m) vertical displacement hazard at most coastal Wellington sites. In general, the subduction interface contributes more to subsidence hazard while crustal faults contribute more to uplift hazard, though proximity to specific faults and fault geometry influence the hazard at specific sites. Coseismic subsidence, in particular, can be generated by both crustal and subduction earthquakes and should be considered in sea-level rise forecasts and resilience planning. Future versions of this model may benefit from refinements to crustal fault geometries at depth and subduction interface rupture extents. Overall, this study highlights how assumptions and choices in regional scale hazard models underpin coseismic multi-hazard analysis. With the appropriate considerations, however, ground-shaking hazard models may also be useful for estimating coseismic vertical deformation and associated sea level changes in other regions worldwide, particularly where several different seismic sources contribute to hazard.

POSTER 152

Toward Resilient Coastal Communities: A Probabilistic Assessment of Co- and Inter-Seismic Vertical Land Motion

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The Cascadia subduction zone stands out for its capacity to generate great megathrust earthquakes in the future, which can cause abrupt coastal subsidence of a few meters. Thus, it is critical to understand the probabilistic nature of vertical land motion (VLM) along the Pacific Northwest shoreline to minimize the effects on coastal communities and to inform community planners of possible outcomes. Here, we present a probabilistic framework to assess future tectonic VLM to aid in planning. Considering both inter- and co-seismic scenarios, we derive probability density functions (PDFs) of future tectonic VLM for various locations along the coastline. For coseismic PDFs, we first calculate elastic vertical responses at coastal areas to 37,500 "fakequakes" (Melgar, 2021), using a boundary-element modeling tool. We then construct PDFs guided by the logic tree for the National Seismic Hazard Map (NSHM) and geological constraints. Interseismic PDFs are obtained using a geodetic locking model. We scale these PDFs by multiplying estimated likelihoods of co- and inter-seismic scenarios for a return period of interest. We estimate these likelihoods using a Brownian recurrence model that incorporates the mean recurrence interval and aperiodicity of past earthquakes as inputs. Using the turbidite catalog from Goldfinger et al. (2017), for example, we calculated the likelihood of a full-margin megathrust earthquake within the next 50 years to be ~ 15 %, which is consistent with the value used by the NSHM. Applying the total probability theorem, we merge the scaled PDFs to generate total PDFs of tectonic VLM and the associated hazard curves for the coastal areas. This final product, when coupled with sea-level rise and tsunami models, enables community planners to better assess the hazards for coastal communities in the Pacific Northwest. Our comprehensive probabilistic framework may be applied to other subduction zones to foster a better understanding of potential seismic hazards and offer insights to strengthen resilient planning and disaster preparedness efforts worldwide.

POSTER 153

Decade-to-Century Scale Vertical Earthquake-Cycle Deformation at Subduction Zones: Implications for Cascadia and Nankai

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Despite significant progresses in studying subduction earthquake cycles, their vertical deformation is still not well understood. Here, we use a generic viscoelastic earthquake-cycle model that has recently been validated by horizontal observations to explore the dynamics of vertical earthquake-cycle deformation. Subjective to two dimensionless parameters (i.e., the ratio of earthquake recurrence interval T to mantle Maxwell relaxation time t_M (T/t_M) and the ratio of downdip seismogenic extent D to elastic upper plate thickness H_c (D/H_c)), our modeled viscoelastic deformation shows significant spatiotemporal deviations from the simple time-independent elastic solution. Caution thus should be exercised in interpreting fault kinematics with vertical observations if ignoring Earth's viscoelasticity. By systematically exploring the two parameter spaces, we further investigate three vertical characteristics, i.e., the pivot line near the coast (CPL), the uplift zone (UZ) landward above the downdip seismogenic extent, and the secondary subsidence zone (SSZ) in the back-arc region. We find that they all can be time-dependent, influenced by D/H_c and T/t_M. CPL location and UZ width are mainly controlled by D/H_c and T/t_M, respectively. The presence of SSZ is found prevalent during the interseismic phase due to viscous mantle flow driven by ongoing megathrust locking, consistent with observations in Cascadia and Nankai. The maximum uplifting rate of UZ and maximum subsiding rate of SSZ are likely controlled by the plate convergence rate inferred from the observations in Cascadia and Nankai. These findings suggest that vertical crustal deformation bears fruitful information about subduction-zone dynamics and are potentially used for inversions after careful forward validations, deserving properly-designed monitoring.

POSTER 154

Assimilation of Vertical Land Movement Observations and Models to Support Sea Level Rise Planning Along the Shorelines of the Cascadia Subduction Zone

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Deformation associated with the Cascadia Subduction Zone (CSZ) drives complex and highly variable patterns of vertical land movement (VLM), that can locally modify expected sea level trends, and therefore complicate the development of, and confidence in, sea level rise projections. Relative sea level projections for Washington State utilized vertical land movement estimates derived from multiple sources, including continuous GPS databases, a single-differencing approach using tide-gauge data, and repeat leveling of survey control monuments near highways.The observations were assimilated with a tectonic deformation model of the Cascadia Subduction Zone to develop a best-fit surface for the study area, along with its associated uncertainty. The best fit VLM surface and its uncertainty was principally guided by the observations; but in locations with sparse data, the tectonic deformation model dominates the fit of the surface. The results suggest considerable variability in coastal vertical land movement in coastal Washington State, ranging from 0-3 mm/yr over spatial scales of 10s-of-kms. Using a Monte Carlo approach, vertical land movement estimates and their uncertainties are integrated into sea level projections at high resolution, and the variability in vertical land movement translates into spatial differences in projected relative sea level change of ~0.3 m by 2100. The analysis was limited in a variety of ways, though: Perhaps most importantly the VLM estimates derived with this approach relied on interseismic VLM observations, and therefore did not model possible future VLM that might influence relative sea level along the shoreline of the CSZ. A new assessment, supported by NSF through the Cascadia CoPes Hub, uses more robust approaches, updated observational data sets, and will provide new insights about relative sea level patterns and projections across the entire shoreline of the CSZ, including a probabilistic approach to the impact of a megathrust earthquake. The work can provide a template for sea level rise planning in other regions of the world with active tectonic margins.

POSTER 155

Complex Earthquake Deformation Drives Relative Sea-Level Change Where Oblique Contraction Focuses Rock Uplift West of the Fairweather Fault, Southeast Alaska

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Along the Yakutat-(Pacific)-North America plate boundary in southeast Alaska, episodic earthquake deformation controls relative sea-level (RSL) change by driving rapid rock uplift along Earth's fastest slipping (≥49 mm/yr) ocean-continent transform fault, the Fairweather fault. Between Icy Point and Lituya Bay, the near-vertical Fairweather fault focuses rock uplift and rapid right-lateral slip by accommodating both vertical and fault-parallel strain during ruptures with a substantial vertical-slip component and separate, predominantly strike-slip events. We use 1-m resolution digital elevation models and offshore seismic reflection profiles to map active faults and uplifted marine and fluvial terraces, and document past reverse fault earthquakes with a maximum of 3–5 m coseismic uplift per event. We differentiate the tectonic from the glacial isostatic contribution to RSL over the past 7 ka by comparing RSL curves at Icy Point and tectonically stable Icy Strait. Radiocarbon and luminescence dating provide timing to estimate 4.6–9.0 mm/yr Holocene rock uplift rates. These rates result from plate-boundary strain that is partitioned onto west-verging reverse faults that form, together with the steeply dipping Fairweather fault, a 10-km-wide, asymmetric, positive flower structure along a 20°, 30-km-long restraining double bend in the Fairweather fault. The principal reverse fault in the flower structure is the offshore, blind Icy Point-Lituya Bay fault, above which 9–12 uplifted marine shorelines imply Holocene ruptures every 460–1040 years. Evaluated over a range of dips, the uplift on this reverse fault implies a maximum of 3.1–10 m dip-slip per event and estimated earthquake magnitudes of M_w 7.0–7.5. Our findings suggest that, first, oblique slip on the Fairweather fault at seismogenic depths occurs with and without co-rupture on the reverse fault. Second, sudden vertical land movements during earthquakes can dominate RSL changes along restraining bends in strike-slip plate boundaries. Therefore, projections of global sea level rise also must include regional tectonic vertical deformation along plate boundaries.

Seismic Monitoring, Modelling and Management Needed for Geothermal Energy and Geologic Carbon Storage

Oral Session • Thursday 2 May • 8:00 AM Pacific

Conveners: Erkan Ay, Shell (Erkan.Ay@shell.com); Kai Gao, Los Alamos National Laboratory (kaigao@lanl.gov); Chet Hopp, Lawrence Berkeley National Laboratory (chopp@lbl.gov); Lianjie Huang, Los Alamos National Laboratory (ljh@lanl.gov); Federica Lanza, ETH Zürich (federica.lanza@sed.ethz.ch); Nori Nakata, Lawrence Berkeley National Laboratory (nnakata@lbl.gov); Annemarie Muntendam-Bos, Delft University of Technology (A.G.Muntendam-Bos@tudelft.nl); Kristine L. Pankow, University of Utah (pankowseis2@gmail.com); Ryan Schultz, ETH Zürich (ryan.schultz@sed.ethz.ch); Nana Yoshimitsu, Kyoto University (yoshimitsu.nana.6i@kyoto-u.ac.jp); Yingcai Zheng, University of Houston (yzheng24@central.uh.edu)

DOE's Best Practices for Addressing Induced Seismicity Associated With Enhanced Geothermal Systems

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In 2004 the U.S. Department of Energy (DOE) initiated and participated in an international activity to develop a "Protocol" to address both technical and public acceptance issues surrounding Enhanced Geothermal Systems (EGS)-induced seismicity. This resulted in an International Energy Agency (IEA) Protocol in 2009 followed by a DOE Protocol in 2012 which served as general guidelines to geothermal operators for the siting, design and operation of EGS systems. The guidance was also used by regulators and to inform the public. Although the DOE Protocol was used and followed by several geothermal operators, the DOE felt a complementary "Best Practices" document was needed and which was developed in 2014. Much has happened in the world of induced seismicity in the past decade resulting in an update of the "Best Practices" document. The increased attention to induced seismicity worldwide, in general, has led to a dramatic increase in research in the causes, impact, and control of induced seismicity. Increased attention has not only been placed on EGS induced seismicity but also on other technologies requiring fluid injection. Notable examples of significant induced seismicity have been from wastewater disposal from oil and gas operations, carbon capture and sequestration, and various waste fluid disposal projects. Like the Protocol, the updated Best Practices is intended to be a living document and to supplement the existing DOE Protocol. It reflects the state-of-the-art knowledge and practices, both technical and non-technical. It is not, however, intended to be a state-of-the-science document. The focus is on current proven technologies. As methods, experience, knowledge, and regulations change, so will the Best Practices.

Geophysical Monitoring of Anthropic Underground Operations in Italy: An Operative Center for Risk Mitigation.

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Following the deadly M≈6 earthquakes that struck the Emilia-Romagna region (northern Italy) in May 2012, public concern raised whether those shocks could have been triggered by the nearby activities of oil and gas production and storage. In response to that concern, in 2014 and 2016 the Italian Oil & Gas Safety Authority (DGS-UNMIG) issued guidelines (ILG) regulating procedures, responsibilities and roles in the monitoring of georesources exploitation, specifically hydrocarbon exploitation, waste-water injection, natural gas storage and geothermal energy production. The ILG define standards for the monitoring of pore pressure, microseismicity and ground deformation and guide the application of a four-stage traffic light protocol (actually applied exclusively for reinjection of waste water), depending on location, magnitude, and peak ground motion of the recorded seismicity. Within this framework, the Italian National Institute of Geophysics and Volcanology (INGV) instituted in 2017 the Center for the Monitoring of Subsoil Activities (CMS), as the structure dedicated to the collection, analysis, interpretation and modeling of data associated with the anthropic exploitation of georesources. We present the structure and operating principles of the CMS, its IT architecture, and the organization of the monitoring procedures. Such principles were designed for delivering reliable products supporting the decision tools adopted by authorities for risk management. We also discuss the main criticalities thus far emerged, which concern: [1] the unbiased assessment of background seismicity when pre-existing, nearby active plants are already in operation; [2] the discernment between tectonic and triggered seismicity, in case the monitored activity is located in a tectonically active region (as mostly happens in Italy); [3] the robust evaluation of uncertainties in all the monitored parameters; [4] the possible overlapping between the attention areas of adjacent reservoirs, possibly operated by different subjects; [5] The procedures to be adopted for activities (namely: CO2 storage) not yet foreseen by the ILG.

An Open-Source Tool for Operational Forecasting of Induced Seismicity (Orion)

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Forecasting induced seismicity activity is one of the challenges facing the growing fields of geothermal energy production and carbon sequestration. Historically, the forecasting process has required significant effort from experts in seismology, geomechanics, and reservoir engineering in order to manage data, evaluate models of subsurface processes, and to calibrate and interpret the results from a range of forecasting models. The Operational Forecasting of Induced Seismicity (ORION) toolkit is an open-source, observation-based forecasting toolkit that is being co-developed by the National Risk Assessment Partnership (NRAP) and the Science-informed Machine Learning for Accelerating Real Time Decisions in Subsurface Applications (SMART) Initiative to address these issues. One of the major design goals for ORION was to build a tool that is responsive to the needs of users ranging from site operators to expert seismologists. The code is written in python and is composed of a desktop graphical user interface (GUI) and an underlying forecasting engine. The forecasting engine takes available reservoir property, well and fluid injection, and observed seismic catalog data as inputs and produces a set of temporal and spatio-temporal seismic forecasts.

The in-situ fluid pressurization rate (dpdt) is one of the key factors that drives the forecast model predictions. Rather than evaluating a full-physics model of the reservoir, ORION has options that allow the user to estimate dpdt using efficient closed-form solutions (e.g. the Theis model), machine learning models, other reduced order models, or to interpolate pre-computed results from external tools. The forecasting engine implements multiple, redundant forecasting methods that are based on statistical principles and/or physical models. ORION uses a decision-tree model to mediate between these different forecasts and produce an ensemble model.

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Forecasting the Next Largest Earthquake During EGS Stimulations

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Most traffic-light systems (TLS) related hydraulic fracturing stimulations still adopt the maximum observed magnitude as the decisive metric to aid decision making by stakeholders. However, waiting for the red-light magnitude to be observed is not a proactive stance, especially given that jumps of up to two magnitude units are evidently common enough between events. Clearly there is a need to actively forecast rather than to passively record the size of the next largest earthquake (NLE). In this study, we demonstrate that we can do just that using an ensemble of 6 existing models from the literature designed with similar purposes in mind (Shapiro et al. 2013; McGarr 2014; Mendecki 2016; van der Elst et al. 2016; Galis et al. 2017; Cao et al. 2020). Following a logic-tree approach, these 6 models are calibrated and dynamically weighted in near real-time using as sole inputs the initial parts of the earthquake catalogs and the reported injection rates. The proposed forecasting tool is tested against 19 past stimulations from 9 different Enhanced Geothermal Systems around the world (Helsinki, Basel, Soultz, Cooper Basin, Pohang, FORGE, Paralana, Newberry). Overall, the results indicate a consistent (across sites and time) and accurate estimation of the next largest magnitude with a tight uncertainty range (1σ) of less than 0.5 magnitude units. Our proposed framework underestimated the next largest magnitude only in two occasions (out of the 19 stimulations), while reliably maintaining a tight safety margin of less than 1 magnitude unit. We recommend that the forecasted NLE replaces the largest observed magnitude as the default metric adopted by future TLS governing any type of fluid-injection operation.

Stress-Based Forecasting of Seismicity Induced by Geothermal Operations and CO2 Storage.

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The need for more and cleaner energy and for sequestration of large quantities of CO_2 in geological formations to mitigate climate change is driving various activities involving extracting or injecting fluids from the subsurface. These activities induce deformation and can eventually activate faults. Fault slip can be either seismic or aseismic. Fault activation can be a benefit, for example in the context on geothermal energy as it is a way to enhance fluid circulation. It is also a source of hazard as significant, potentially damaging earthquakes might be induced as has been observed a number of geothermal operations. In the context of carbon dioxide or gas storage, faulting of the caprock could, in addition to exposing surface infrastructure to seismic hazard, jeopardize the mechanical integrity of a reservoir. We will review recent progress made in understanding these processes based on the study of case examples where we combine remote sensing, GPS geodesy, and seismic monitoring on the observational side and us a versatile modelling framework to relate reservoir operations to deformation and seismicity. The model accounts for the possibility of triggering faulting and earthquakes due to pore-pressure diffusion and poroelastic stress changes. It accounts for the time-dependent nature or earthquake nucleation and for the possibility that the faults might be in a relaxed state of stress of stress. We will show that this modelling applies to a wide range of operations and can provide the foundation for effective methods to forecast earthquakes and faulting due to anthropogenic activities. These methods

could in principle be used to mitigate and eventually control fault activation and seismicity during reservoir operations.

Factors Controlling Rate and Magnitudes of Induced Seismicity

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Advancements central to the world's transition to a greener economy such as geothermal energy are hampered by a lack of understanding and control of the maximum magnitude event. We develop a physical model for induced seismicity rate and identify the dominant factors on induced event magnitudes in the context of a control and optimization framework that may be utilized for sophisticated design of injection schedules.

Induced seismicity observed during Enhanced Geothermal Stimulation (EGS) at Otaniemi, Finland is reproduced by a physical model based on pore pressure diffusion and rate-and-state friction. The physical model produces simulations closest to the observations when assuming rate-and-state friction for shear failure with a diffusivity matching the pressure build-up at the wellhead at onset of injections. At the same time, pressure drawdown immediately following shut-in's is best modelled with a lower diffusivity, indicating a significant change in diffusivity through fracture opening and closure. The physical model shows that the time-dependent nucleation process significantly affects the spatial evolution of seismicity. This implies that neglecting rate-and-state effects can bias estimates of fluid diffusivity from the seismicity triggering front. The potential of the model to serve as a forecasting tool is demonstrated by a pseudo-forecast that closely matches the entire seismicity rate history, using only the first injection stage as the training period.

Next, we focus on the magnitude-frequency distribution of seismicity and how they may correlate to the injections. We observe a dominant, negative correlation of the *b*-value and *Mmax* to depth, and additional negative correlations to cumulative injected volume. We observe a non-linear relationship between magnitudes and distance from the injection source, similarly to the geothermal stimulation operation in Basel. We aim to identify the dominant factor from injections and possibly the initial conditions of the nucleation sources that is consistent with the non-linear relationship of the magnitudes to distance.

How to Tame an Earthquake (Analogue)

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Subsurface fluids are important to earthquake physics since they influence every phase of the earthquake cycle: from inducing earthquakes, generating slow slip, dynamically weakening a fault, to producing afterslip. Despite this prominent role, comparatively little thought has been directed toward intentionally controlling fault slip. I take the spring-slider as the simplest analogue for an earthquake and train a deep reinforcement learning agent to design fluid injection that reins-in slip motion. These reining algorithms can mitigate stick-slip instability via a three-step process. First, by injecting to induce slip nucleation; second, by harnessed withdrawal that governs slip speed; third, by injection-driven steady-state sliding. I discuss the relevance to prior studies, implications for induced seismicity mitigation, and future potential for earthquake control. These results suggest that earthquake (analogues) could be tamed with carefully designed injection policies.

Picoseismic Response of Hectometer-Scale Fracture Systems to Stimulation With Cm-Scale Resolution Under the Swiss Alps, in the Bedretto Underground Laboratory

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We performed a series of hydraulic stimulations at 1.1 km depth in the Bedretto underground laboratory in the Swiss Alps. The goal was to achieve an unprecedented detailed and profound understanding of hydromechanical and seismic processes during hydraulic reservoir development with a dense multi-sensor monitoring network. With our seismic network that includes various sensor types with different sensitivities, we succeeded in characterizing induced seismicity down to the pico-seismicity level (Mw<-4), thus illuminating details of a complex fracture network more than 100 m from the injection locations. Here, we present the experiments and seismic catalogs as well as a comparative analysis of event number per injection, magnitudes, b-values, seismogenic index and reactivation pressures. During a first-order data analysis, we could make the following observations:

-We find that the ultra-high frequency seismic network with custom-made AE sensors, allows us to observe seismicity over 3 orders of magnitude scale. Thanks to collocated accelerometers and acoustic emission sensors, AE sensors could be calibrated in-situ and adjusted moment magnitudes could be implemented into the seismic catalog.

-The volume impacted by the stimulations in different intervals differs significantly with a lateral extent from a few meters to more than 150 m. Most intervals activated multiple fractures. Only during the stimulation of an interval located next to a dominant shear zone, an extended single fracture was activated, which is likely attributed to the dominant shear zone in this area. The seismic clouds typically propagate upwards towards more permeable, shallow depth on parallel dipping planes that are consistent with the stress field and seem to a large extent associated with preexisting open fractures.

-The reactivation pressures hint at hydraulic shearing as the dominant process, since the elastic fracture opening appears to be mostly aseismic.

-The seismicity shows no distinct deviation from "normal" behavior with regard to Gutenberg Richter or McGarr.

Characterization of Fracture Activation During EGS Stimulation Using Waveform Cross-Correlation: An Example Application at Utah Forge

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One of the many technical challenges in the safe stimulation of Enhanced Geothermal Systems (EGS) is the control of induced seismicity. Fluid injections during simulation may cause induced earthquakes. Microseismicity analysis provides real-time risk management, and detailed knowledge of activated fracture size, orientation, stress state and seismogenic potential. Due to subsurface heterogeneity within the reservoir, analysis of microseismicity is strongly influenced by the surrounding medium. Waveform cross-correlation utilizing the full wavefield of microseismic events, and can significantly improve the fracture characterization. Here, we apply waveform cross-correlation analysis to microseismic events during stage 3 of 2022 stimulation at the FORGE site to detect similar event clusters, and asperities with nearly identical waveforms, and obtain improved in-situ seismic parameters. The Frontier Observatory for Research in Geothermal Energy (FORGE) is a geothermal project located at Milford, Utah, providing pioneer research and insights in EGS with a comprehensive microseismic monitoring network including nodal arrays, borehole arrays and DAS fibers. The 2022 stimulation features over 20,000 microseismic events over three stages. We identify ten similar clusters from cross-correlated waveforms with a minimum CC coefficient of 0.65 from at least 8 stations. Analysis of cluster propagation and orientation reveals fracture planes with low b values being activated first, suggesting the activation of a planar structure with similar orientation to natural fractures at this site. We identify successive activation of different clusters, in particular, some clusters with larger events were activated post shut-in. To characterize the seismogenic potentials of different fractures, and their relationship with injection history, we obtain improved magnitudes based on precise relative magnitude measured from principal component analysis of aligned waveforms, and characterize magnitude-frequency for different fractures

Circulation Experiments at Utah Forge: Post-Shut-in Fracture Growth Revealed by Limited Near-Surface Monitoring

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The Utah Frontier Observatory for Research in Geothermal Energy (FORGE) is a large-scale experimental facility de-risking Enhanced Geothermal Systems (EGS). Full-scale testing allows the study and development of new tools, methodologies, and strategies to improve the economic viability of EGS and mitigate induced seismic activity. After the completion of an injection-production well doublet at a depth of 2.5 km within basement rock, four circulation experiments were conducted in July 2023. These experiments showed that the two wells were successfully connected via the fracture network created during the 2022 stimulation treatments, which were pumped to evaluate different injection methods required to form a heat exchange system.

We analyze the microseismic activity induced during the circulation experiments using only five (near-)surface stations of the regional permanent seismic network and state-of-the-art full-waveform-based methods for detection and location. The microseismicity rates and magnitudes (<M0.45) induced during the circulation experiments are similar to those observed during the 2022 stimulations. This was unexpected when considering fluid flow through pre-stimulated rock volumes. During the circulation experiments, flow data indicated that highly productive reservoir volumes were both aseismic and seismically active. The seismic activity occurred predominantly after shut-in of the last two circulation stages. It is attributed to the complex dynamics of opening, further propagating, and closing of hydraulic fractures during circulation in the absence of major conductive features that allow for substantial flow into the production well. The complexity of the fracture network created within a granitoid rock, such as that at FORGE, can result in poorly stimulated volumes within the zones that are mapped by large-scale microseismic clouds. Hence, the presence of microseismic activity may not guarantee the presence of stimulated fractures that can enable efficient fluid flow, and the lack of microseismic activity does not imply the lack of stimulated fractures.

Geophysical Monitoring for Feeding Decision Support Tools: The Crucial Role of Uncertainty for a Sound Management of Induced Seismicity

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Geophysical monitoring is a frequently used tool to manage the potential effects of underground anthropogenic activities. Different parameters such as earthquake hypocentral location and magnitude, peak ground motions, and ground deformation, among others, are growingly used as input for decision support tools (e.g., traffic-light systems) that are implemented for managing induced seismicity. Such decisional systems define the operative reactions to be enacted once a seismic event occurs near a certain anthropogenic underground activity. The outcome of the geophysical monitoring in such cases is critical, since any decision taken, on the basis of the information provided by the monitoring data, involves a great deal of responsibility. In this context, any effort for a reliable evaluation of the parameters feeding the decision support tool is as important as the determination of its "near-to-reality" uncertainty. Here, by 'near-to-reality' uncertainty, we refer not only to formal errors resulting from fitting a given model but also to the effects of all the 'known unknowns' in the modeling process. A careful assessment of uncertainties becomes crucial for rational decision making. In this work we analyze different sources of uncertainty that can be relevant for the determination of different geophysical parameters generally used for managing induced seismicity. We use a logic-tree-based ensemble modeling approach for framing the problem in a decision-making context. We find that often-neglected epistemic uncertainties (i.e., arising when considering alternative plausible modeling approaches or data) can be considerably larger and more representative of the state of knowledge than the standard errors that are usually reported. Due to the potential impact of decision making under uncertainty, we stress that an objective evaluation of epistemic uncertainties associated with any parameter used to support decisional processes must be a priority for the scientific community. The implementation of this approach is framed within the activities of the INGV's Center of Monitoring Underground Activities in Italy.

B-Positive for Induced Seismicity Catalogs With Time-Varying Incompleteness? Proceed With Caution.

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The relative frequency of large versus small earthquakes is characterized by the b-value of the earthquake magnitude-frequency distribution. The b-positive method, recently introduced by Van der Elst (2021) to estimate the b-value in transient incomplete catalogs, is based on the Laplacian distribution of magnitude differences. The method was developed to handle time-varying incompleteness in aftershock sequences and was found to be much more robust to unknown or variable incompleteness due to network limitations. However, the method still requires some minimum cutoff value M'_c above which the b-value can be accurately derived.

More recently, the method has also been applied to induced seismicity sequences with time-varying incompleteness in the catalogs. These assessments generally adopt small minimum cutoff values, similar to the values presented for aftershock sequences. The results show significantly different time-variations in b compared to the traditional Gutenberg-Richter exponential maximum likelihood estimates. However, turns out these low cutoff values lead to significant underestimations of the actual b-values. Closer analysis on synthetic catalogs shows that a significant trade-off exists between the minimum value M'_c and the magnitude range over which incompleteness occurs, the scale parameter σ describing how quickly 100% detection is achieved. As time-varying incompleteness may also imply time-varying σ, the implication for the interpretation of time-varying b-values is very significant. Analysis of the Groningen induced seismicity catalog demonstrates this further. As the b-value is one of the critical parameters controlling seismic hazard and risk, the b-positive estimate should thus be handled with due care.

Heimdall: A Graph-Based Seismic Detector and Locator for Microseismicity

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The application of Machine Learning (ML) has significantly transformed traditional tasks in observational seismology such as phase picking and association, earthquake detection and location, and magnitude estimation. Despite progress, the use of ML-based classical workflows in microseismic data analysis still poses challenges. We present HEIMDALL, a grapH-based sEIsMic Detector And Locator for microseismicity, powered by the latest advancements in Deep Learning (DL) methodologies. HEIMDALL utilizes an attention-based, spatiotemporal graph-neural network for detecting seismic events. It also implements a waveform-stacking approach for event location, leveraging output probability functions over a dense regular grid. We tested HEIMDALL using a month-long waveform dataset from December 2018, obtained during the COSEIMIQ project (active from December 2018 to August 2021) at the Hengill Geothermal Field in Iceland. This dataset is optimal for testing seismic event detection and location algorithms due to its high seismicity rate (over 12,000 events in about two years) and the presence of burst sequences with very short interevent times (e.g., less than 5 seconds).

We evaluated HEIMDALL's performance by comparing the catalog we generated with those produced by two different DL methods, as well as one manually created by ISOR for the same timeframe. The DL algorithms tested included (i) MALMI, a waveform-based location algorithm, and the recent (ii) GENIE graph-neural-network algorithm. To optimize GENIE for our specific study area, we repicked continuous waveforms using the PhaseNet algorithm and trained a new model. We discuss the advantages and limitations of each method and explore potential enhancements for detecting and locating microseismic events, with a focus on monitoring induced seismicity at Enhanced Geothermal System (EGS) sites.

Characterizing Subsurface Structures for Geologic Carbon Storage at Iron Mountain in Utah

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Subsurface structure imaging and fault detection are crucial for site characterization and risk assessment of geologic carbon storage. We use 2D surface seismic data acquired at Iron Mountain, Utah, USA to characterize subsurface structures. These seismic data were acquired using vibroseis sources along three 2D walkaway lines at the surface of the survey area. The source spacing of each survey line is about 91 m and the receiver spacing is about 45 m. The lengths of the seismic lines are around 9 km. We build 2D velocity models along three seismic survey lines using first-arrival traveltime tomography and prestack depth migration velocity analysis. We then use prestack depth migration to produce high-resolution images of subsurface structures. Finally, we employ a machine learning algorithm to delineate faults on the migration images. Our results provide valuable information for studying the feasibility of geologic carbon storage at Iron Mountain in Utah.

3D Fault Detection on a Seismic Migration Image at the Lightning Dock Geothermal Area

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Lightning Dock Geothermal (LDG), is an operating power plant in Hidalgo County, southwest New Mexico, USA. LDG LLC conducted a 3D active-source surface seismic survey in 2011 using accelerated weight drop sources for subsurface characterization. The 3D seismic survey covered a region of approximately 4 km in the east-west direction and approximately 3.5 km in the north-south direction. This 3D seismic survey used a simple square pattern to distribute source and receivers. The survey used a total of 17 receiver lines with a quasi-equal spacing of 660 ft and with an orientation of the north-south direction, and a total of 21 source lines with a quasi-equal spacing of 600 ft and with an orientation of the east-west direction. Within the source lines or the receiver lines, the source interval is 110 ft and the receiver interval is 220 ft. We perform migration velocity analysis and prestack depth migration to produce a high-resolution subsurface image, and then delineate faults on the migration image using a machine learning method. Our results provide valuable information for siting new wells to improve the geothermal energy production at the Lightning Dock geothermal area.

Seismic Monitoring, Modelling and Management Needed for Geothermal Energy and Geologic Carbon Storage [Poster Session]

Poster Session • Thursday 2 May

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POSTER 88

Applying Dynamic Fracture Propagation and Activation Models to Microseismicity Generation in a Geothermal Development Project at Blue Mountain, Nevada

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EQdyna is a Finite Element Method (FEM) code for simulating dynamic fracture propagation and seismic wave propagation in elastic or elastoplastic medium. In this project EQdyna is applied towards the microseismic activity that is caused by hydraulic fracturing (HF), specifically focusing on the propagation of the opening fractures and its effect on nearby shear fractures. Using EQdyna, pre- selected propagation distances are varied to investigate the effects on the characteristics of the induced events and observed seismic signals. The induced events occurring here are believed to be a result of the shearing that occurs on pre-existing natural fractures (NF) in response to the dynamic stresses that are induced as HF propagation occurs. A three-case scenario is explored to determine the most likely cause for micro-seismicity that is observed in a geothermal development project at Blue Mountain, Nevada due to the stimulation of a geothermal well system. In these scenarios HF propagation will be explored using propagation termination points that are located just before, directly on (fracture network amalgamation), or just after a NF is encountered, it is believed that these scenarios will produce different microseismic distributions due to different driving forces. Distributed Acoustic Sensing (DAS) technology will be integrated into the model through utilization of a strategically placed seismic station network that will act as a sensing cable placed parallel to a specified NF. The goal of this investigation is to determine the scenario that can most be associated with the microseismicity occurring at the site, by creating a model containing a geometry and properties similar to what exists at the real-world field site.

POSTER 89

End-to-End High-Quality Geophysics Workflow to Analyze Das-Acquired Induced Seismicity

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Cost-effective, easy to deploy make distributed acoustic sensors a tool of choice for long-term induce seismic monitoring either independently or in conjunction to 3C sensors. We propose a DAS-based end-to-end workflow for induced seismic monitoring operation.

First, to maximize the rock volume monitored while minimizing assets deployed, we perform a survey modeling leveraging an accurate velocity model while including attenuation and background noise previously gathered. Second, we model the waveforms associated to the various types of failure mechanisms likely to occur considering known geological and geomechanical data so to compare with waveforms issued from the failure locii as seen by the sensors. Third, we use a simulator of DAS-acquired passive seismic data observed in previous similar jobs to output data at real-time speed to verify the viability and effectiveness of the acquisition geometry and the processing system consider to monitor the long-term passive seismic activity. Fourth, knowing that an accurate velocity model is required to properly estimate source location, source parameters, and source mechanism of a detected microseismic event, we use a new method to simultaneously invert for the hypocenter and the velocity model to provide a robust long-term monitoring workflow. Thus, bypassing the repeated use of man-made, man-controlled sources to calibrate the velocity model while including scenarios when the velocity field evolves with time due to induced changes associated with operations. Fifth, we leverage a new real-time processing flow that involves image processing techniques applied to induced seismic datasets. This approach mimics an expert geophysicist's view to identify passive seismic events acquired using DAS data taking advantage of an algorithm integrating both image processing and traditional geophysical processing.

POSTER 90

Application of State of Stress Analysis Tool (SoSAT) to Estimate Risk of Induced Seismicity From CO2 Injections

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The sequestration, storage, and utilization of anthropogenic carbon emissions is projected to play a major role in mitigating the accumulation of greenhouse gases worldwide. CO_2 can be injected under supercritical fluid conditions into subsurface geologic units like saline aquifers, basalt formations, depleted/matured oil and natural gas reservoirs. The focus of this study is to demonstrate the application of State of Stress Analysis Tool (SoSAT), developed under the National Risk Assessment Partnership (NRAP), in estimating the probability of failure due to hydraulic fracture or seismic fault activation, both of which are major risks anticipated under incremental CO_2 injection pressure. SoSAT uses a Bayesian approach for geomechanical uncertainty quantification and risk assessment. Various constraints, including those based on stress measurement, regional stress environment, and borehole breakouts, can be applied to constrain the posterior probability distribution of in-situ stresses. This allows for the computation of the risk associated with induced seismicity. The ultimate goal is to create a seismic risk index map for the western USA for the Carbon Utilization and Storage Partnership (CUSP) which will provide guidance on CO_2 injection operations for commercial-scale carbon storage.

POSTER 91

Toward Improving the Assessment of Induced Earthquakes in the Rome Trough of West Virginia

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As part of the Midwest Regional Carbon Initiative, a project funded by DOE and managed by Battelle, the potential for inducing earthquakes from future geologic CO_2 storage (GCS) is being assessed across a 20-state region of the northeastern quadrant of the U.S. Recent studies of induced seismicity (IS) in the project area, specifically in Illinois, Indiana, Ohio, Pennsylvania, and West Virginia, suggest that an injection zone's proximity to crystalline basement is a major factor related to IS susceptibility. To assist with identifying candidate reservoirs for GCS with low IS susceptibility, we investigated correlations between earthquake activity and geologic structure using a new earthquake catalog and a new topographic map of the top of the Precambrian crystalline basement. The earthquake compilation includes events induced or likely induced by wastewater disposal and fracking and contains all known earthquakes of magnitude 2.2 and greater and all known events of any magnitude since 2009.

Consistent with previous studies, we find that earthquakes were typically induced by fluid injections within ~1 km of the top of Precambrian. An exceptional case occurred in West Virginia from 2010 to 2013 near the southeastern boundary of the Rome Trough. In this case, probable IS correlated with fluid injections at heights in the sedimentary strata from ~3.5 km to ~4.5 km above the Precambrian. These events were reported at anomalously shallow depths, also well above Precambrian. However, their focal depths are poorly constrained and seismicity appears diffuse. Here, we attempt to enhance the earthquake catalog and to improve the hypocenter determinations by detecting additional events using continuous broadband datasets from regional stations and by jointly relocating the events in the region surrounding the injection activities. Preliminary detections using standard techniques have revealed only a single earthquake in the nearly two years after the sequence appeared to end. The next steps will involve enhancing the detections using machine-learning-based techniques.

POSTER 92

OhioNET: Reducing Risk from Induced Seismicity Using Real-Time Seismic Monitoring for Regulation and Mitigation in Ohio

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Over the past decade, induced earthquakes have increased dramatically across the US from expanding anthropogenic operations including brine disposal, oil/gas production, hydraulic fracturing, and carbon sequestration. In Ohio, the rapid increase in oil and gas operations from the Utica shale indicated the necessity for a seismic monitoring program as cases of induced seismicity started to emerge in areas with no previous history of seismic activity. In 2012, the Ohio Department of Natural Resources (ODNR), Division of Oil & Gas Resources Management (DOGRM) created the OhioNET seismic network, a real-time seismic monitoring network designed for accurately evaluating seismic events and generating automatic alerts. By gaining this ability, ODNR-DOGRM began developing best practices through collaboration with researchers and academia that focused directly on how seismic monitoring can be used to help mitigate, regulate, and reduce the seismic risk associated with induced seismicity. These situations highlighted the need for mitigation protocols and coordinated communications among staff and industry. ODNR continues to prioritize science-based results and rulemaking that protects citizens, the environment, and advances responsible development of natural resources.

POSTER 93

Automated Earthquake Detection and Location Applied to Local-Scale Seismic Monitoring

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Comprehensive catalogs of microseismicity are crucial to effective monitoring of induced seismicity. Due to the large quantity and low signal-to-noise of microseismic events, maintenance of such catalogs is labor-intensive. Recent advances in machine-learning workflows for detection and location have shown promise as a potential solution to this issue. Here, we use the BPMF package (backprojection and matched filtering, *Beaucé et al.*, 2023) in concert with a pre-trained convolutional neural network model (*Leifer et al.*, AGU 2022) to automatically detect and locate microseismic events induced by hydraulic fracturing within a local-scale seismic monitoring array. The array consists of 9 wideband seismometers installed in shallow postholes with approximately 1 km spacing. Conventional operations consisting of automatic, real-time processing in Earthworm, manual review, and template matching provide the basis for this deployment, producing a catalog of 1375 events in the upper 5 km spanning magnitudes from M-0.94 to M2.8 over the course of 32 days. The machine learning model used in this study was trained on a proprietary dataset containing data from seven local-scale arrays with similar characteristics. In comparing the automatically generated catalog to our conventional operations, we find that the machine learning workflow recovers more than 90% of the manually reviewed events. However, locations for the recovered events show higher residuals when compared to the manual locations due to small inaccuracies in the arrival times produced by the BPMF workflow. Additional fine-tuning of the parameters used in backprojection and matched-filtering in conjunction with improvements to the pre-trained picking model should enhance both the percentage of recovered events and location quality. These results demonstrate the potential of automated machine learning workflows to efficiently generate valuable microseismic catalogs in near real-time. Future applications of this workflow will aim to improve seismic monitoring capabilities of enhanced geothermal systems and carbon sequestration projects.

POSTER 94

Using Deep Learning for High-Resolution Fault Analysis and Stress Characterization at the Forge Site, Utah

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The precise determination of fault location and geometry assumes major importance in the context of induced seismicity management during reservoir stimulation. By increasing the size of new datasets, we need new techniques to get the most information from these datasets. In this study, we used Machine Learning and Neural Networks to prepare data for focal mechanism determination and stress field evaluation of the FORGE site in Utah. The dataset used for this purpose is derived from dual-borehole seismic arrays located at the FORGE site. Accurately determining focal mechanisms for microseismic events is a challenging task, primarily due to the inherent limitations in geometric coverage. To eliminate this challenge, we used various seismic attributes such as P-wave polarities and P/S amplitude ratio, with the aim of supplying a robust estimation of the focal-plane mechanisms.

Our study focuses on the analysis of 1500 microseismic events recorded during phase 3 stimulation in 2022 at the FORGE site. We used PhaseNet to pick P and S arrival then we developed A Convolutional Neural Network (CNN) by using Southern California Earthquake Data Center (SCEDC) dataset to predict the first motion polarity. By using this approach, we prepared a dataset consisting of 738 events for focal mechanisms inversion. We obtained 681 A and B quality focal mechanisms solutions by using HASH method. The high-resolution focal mechanisms map shows different patterns at different parts of the site area with more strike-slip fault at shallower depth, while mixture of reverse and normal faulting at deeper depth. By utilizing MSATSI package, we estimated the stress field principal axes orientation and relative magnitude at each section. The stress result shows different stress regimes at different sections, also the stress map showed a clear transition in principal axes orientation with depth at the FORGE site area.

POSTER 95

A Comparison of Machine Learning and Array-Beamforming Methods in Detecting Microearthquakes Near Cushing, Oklahoma, Using a Dense Nodal Array

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Midcontinent seismic activity in the United States has sharply increased from background levels in the last 15 years. Oklahoma has been at the center stage for this increase due to the production of oil and gas and the associated injection of fracking fluids and wastewater disposal. While there were notable large earthquakes, such as the M5 Cushing and Pawnee events, there are a vast number of smaller events; detecting and cataloging these events can provide valuable insight into the evolution of the subsurface, leading to better industry practices and a more robust understanding of the impact that fluid injection has on fault activations. Here, two methods are employed to detect small earthquakes using continuous waveform with a dense nodal array near Cushing, Oklahoma. Array-beamforming detection requires no prior knowledge of the region's waveform or local velocity model, which detects events by comparing inter-station waveform similarity. LOC-FLOW is a machine learning-based workflow combining several algorithms to detect and locate earthquakes. Both methods have been shown to detect more events than are contained in previous catalogs and, if automated, can be a hands-off approach to creating catalogs of high resolution. The merits and drawbacks of each method must be understood to apply them most appropriately. The array-beamforming method detected thousands of events compared to the machine learning method's 112 events for the same period. However, array-beamforming is susceptible to detecting non-tectonic events such as passing traffic, perhaps owing to its roadside deployment. Event location remains variable between earthquakes detected by both methods, with an average offset of 3.18 km between the 43 co-detected events. Fine-tuning processing parameters will improve the beamforming event detection to remove false detections, such as increasing the maximum inter-station distance for which waveform similarities are compared, increasing the duration of the time window over which waveforms are compared, or considering different sub-arrays. Further characterization of detected events will be performed.

POSTER 96

Innovative Use of Broadband Sensors for Carbon Capture Utilization and Storage ("CCUS") Monitoring Applications

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Safe and effective solutions for CO_2 injection and storage are becoming increasingly more important on the global stage as we transition to net-zero. Carbon Capture Utilization and Storage ("CCUS") has been identified as a crucial tool for achieving these goals. Broadband seismometers are being utilized in all stages of the injection activity lifecycle. For example, the risks of injection-induced seismicity must be effectively managed to ensure safe operation, with passive seismic monitoring being a key component of the monitoring strategy.

Operators are making use of a mix of both sub-surface and surface stations to effectively monitor injection operations, with broadband stations being sparser in their distribution providing a cost-effective alternative and supplement to dense geophone arrays. Broadband sensors can detect lower frequencies, providing more accurate moment magnitude (M_w) estimates than geophones at larger magnitudes (M_w >2). This is important to gauge the physical size of any induced rupture and maintain the integrity of any traffic light monitoring regulations that may be in place.

Güralp Systems Ltd. ("GSL") has developed a range of medium-motion broadband systems that focus on ease of use to allow operators to carry out real-time monitoring. The Güralp smart sensor module can operate at any angle, a novel feature of broadband seismometers, allowing it to be easily buried at depth to increase Signal-to-Noise Ratio. This mitigates the need for more costly vault installations. GSL's Minimus digitizer platform allows for efficient real-time monitoring networks to be set up to alert for anomalous seismic events with low latency.

Such sensors have recently been utilized to establish a dense, onshore array of broadband instruments to monitor the first offshore UK CO_2 storage project at the Endurance structure. Onshore monitoring of offshore storage offers a cost-effective, real-time strategy when compared to dedicated offshore monitoring systems. However, array geometry and local geology are important considerations in establishing an array, and constraining event depths is a current challenge.

POSTER 97

The Utah Frontier Observatory for Research in Geothermal Energy: A Field Laboratory for Enhanced Geothermal System (EGS) Development

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In 2014, the US DOE authorized funding for a field-scale laboratory dedicated to testing tools and technologies for Enhanced Geothermal System (EGS) development. The ultimate goal of the project is to create a roadmap for commercialization of EGS. The Frontier Observatory for Research in Geothermal Energy (FORGE), operated by the University of Utah, was constructed in southwestern Utah. Since 2016, eight wells have been drilled at the site. The wells range in vertical depth from 304 - 2896 m. Hot, low permeability granitic and metamorphic basement rocks that will form the reservoir were found at depths ranging from 716 - 968 m. Laboratory measurements on core and the results of injection tests yielded permeabilities of 20-80 microDarcies. Six of the wells are vertical and are used for tool testing, seismic monitoring and water production. The deepest well reached an estimated temperature of 241oC. Two deviated wells were drilled for the injection-production pair that will be used to circulate fluids. The injection well was deviated 65° from vertical and drilled to a measured depth (MD) of 3349 m The production well was drilled parallel and approximately 100 m above the injection well to a MD of 3337 m. Both wells were cased throughout most of their length. Circulation tests and pressure monitoring demonstrate the two wells are connected.

A permanent monitoring system has been established. It includes fiber optic cables cemented in the annulus of production casing strings, surface accelerometers, and concentric rings of near-surface borehole seismometers. The fiber optic cables allow monitoring of temperature, strain and seismicity. During stimulations, the permanent monitoring network is augmented with geophone strings in the vertical wells and with surface nodal arrays. Stimulation of the injection well in 2022 yielded more than 50,000 seismic events with moment magnitudes (Mw) ranging from -2.3 to +0.5 Mw. These events occurred as much as 150 m from the injection well. The next stimulation is planned for early 2024.

POSTER 98

Microseismicity Observation and Structure Characterization at Cape Modern, Utah

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To prepare the new stimulation and exploration of geothermal resources at Cape Modern, Utah, we deploy seismometers, test noise level, and refine velocity models. Shallow boreholes (a few tens of meters) help to improve the signal-to-noise ratio with combined with different types of sensors such as surface nodal sensors. We numerically simulate seismic wavefields generated by microseismicity using a realistic velocity model and noise level to understand our monitoring capabilities, which helps us to understand the capability of our array for seismicity characterization and magnitude completeness. Background seismicity ratio before stimulation with the new seismometers will be discussed. The velocity model are refined using available active seismic surveys at the Utah FORGE area, which is a neighbor geothermal field to the Cape Modern site, using full-waveform inversion. The updated velocity model has a better shallow subsurface model, especially in the sedimentary layers, to constrain the location of microseismic events.

POSTER 99

Weak Soils, Active Faults, and the Inheritance of Groningen Induced Seismicity: How to Proceed With Safe Use of the Subsurface for the Energy Transition in the Netherlands?

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The Netherlands is known for its induced seismicity by gas exploration in the Groningen field. The earthquakes are unique for their high ground motions at relatively low magnitudes ($M_L \leq 3,6$). This is partly due to local site amplification by unconsolidated surface geology, which is common throughout the country. Consequently, buildings in the region sustained structural and non-structural damage. Along with slow progress of building reinforcements, implemented to mitigate the increased seismic risk, this led to cessation of Groningen gas production in 2023. Currently, the Netherlands is moving to a renewable energy market. This requires considerate, safe use of the subsurface e.g. for geothermal heat production and storage of hydrogen and carbon dioxide in salt caverns or former gas reservoirs. Such a transition also impacts areas that may not have experienced subsurface activities yet. This is challenging for two reasons: citizens worry they will be faced with a 'second Groningen'—reflecting a potential loss of the social license to operate—and there is less knowledge of the subsurface.

To add to the complexity is the natural seismic hazard: the southeastern Netherlands contains the Ruhr Valley Graben, an active, slowly deforming rift system. The largest instrumental earthquake here was the 1992 M_L=5,8 Roermond event. However, recurrence intervals are long and not all faults—and their reactivation potentials—are known. Nevertheless, local events have also been linked to geothermal heat production and to post-coal mining groundwater ingress. State Supervision of Mines, the Dutch authority for mining safety, aims to understand risks of induced seismicity, within the local tectonic context and also beyond the area impacted by Groningen gas exploration. To do so, research must be done simultaneously with the development of renewable energy sources and storage sites. How does one ensure the safety of people and protection of the environment during this transition while accounting for the many subsurface uncertainties? What research should be prioritized, what (pragmatic) choices can and/or need to be made?

POSTER 100

Application of Static Stress Drops and Similarity of Seismic Events Induced by Underground Fluid Injection in Characterization of Seismogenic Zones on the Example of The Geysers Geothermal Field

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Characterization of seismogenic zones in the areas of underground fluid injection is an important issue for seismic hazard assessment in such destinations. It is well known that subsurface discontinuities can be successfully imaged using multiplets, i.e. seismic events with very similar waveforms. On the other hand, recently static stress drop of earthquakes has been suspected to reflect the strength of rocks. In this study we propose to utilize combined information from spatiotemporal multiplet analysis and statistical assessment of static stress drop variability to characterize the origin zones of injection induced seismicity. As an example, we present results obtained using dataset from Prati-9 and Prati-29 injection wells at The Geysers geothermal field. With the use of multiplet analysis followed by double-difference relocation we imaged three fractures and one fault within the reservoir and described their different seismic response to injection. Moreover, we statistically proved the occurrence of independent spatial and temporal variations of static stress drop of events and interpreted them as an image of differences in strength of discontinuities. Obtained results prove the fact that the information obtained from multiplet and stress drop analyses is complementary and can be interpreted together. In order to check the utility of proposed method for the purposes of hazard assessment, we related the locations of the strongest events in the cluster to identified discontinuities. Moreover, we assessed the maximum expected magnitude basing on the dimensions of identified fault. Finally, we calculated the effect of analyzed events on the surface (PGV, PHV, PVV) and related obtained values to observed stress drop differences. *This research was supported by research project no. 2022/45/N/ST10/02172, funded by the National Science Centre, Poland, under agreement no. UMO-2022/45/N/ST10/02172. This work was also partially supported by a subsidy from the Polish Ministry of Education and Science for the Institute of Geophysics, Polish Academy of Sciences. This research was supported in part by PLGrid Infrastructure.*

POSTER 101

Mapping of the Seismic B-Value Before and After Mine Collapse Main Shocks, Rudna Mine, SW Poland

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Rudna Deep Copper Mine, located in SW Poland, is known for producing a large number of seismic events on a daily basis in a magnitude range starting below M0 and often ending in large mine collapses with magnitudes over M4. In previous work (Sobiesiak et al., 2022), we were able to enhance existing data sets with induced seismicity from the mine by using the software BackTrackBB (BTBB) (Poiata et al., 2016). This automated detection and location procedure resulted in three large daily data sets from ~6000 and up to ~ 10000 events per day enhancing the catalogs mainly in the range of small scale events. This work permitted a first attempt to apply short term hazard assessment on a daily basis using SHAPE software (Leptokaropoulos and Lasocki, 2020) which would be a crucial aspect for early warning procedures.

Aiming at additional information on processes around the major mine collapses, we decided to perform a mapping of the seismic b-value of the Gutenberg-Richter relation using the software ZMAP (Wiemer et al., 2000). As the b-value possesses the dual capability of displaying ambient stresses as well as changes in material properties and thus mirrors the interaction between internal structures and outer forces, we choose this parameter to decipher more about processes on going in time and space around major mine shocks. The sheer number of events on relatively small volumes further support the method and makes the statiscical approach more stable. Here, we present the results of this mapping procedure for three daily data sets of induced seismicity from Rudna Mine and compare it to the results gained from the application of a short term hazard assessment.

POSTER 102

Focal Mechanisms of Microseismicity at the Decatur, Illinois, CCS Site Inverted From Multiple Borehole Seismic Arrays

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Underground fluid injection can trigger earthquakes by activating hidden fault systems favorable to diffusive pore pressures with local stress fields. Tracking down microearthquakes during passive seismic monitoring in fluid injection sites enables imaging fault systems and estimating their seismic productivity. Along with the hypocentral distribution of microseismicity in the fluid injection field, focal mechanisms of earthquakes directly provide the geometries of fault systems and instabilities with respect to the regional stress field. While borehole sensors near injection wells effectively detect microseismicity by suppressing ambient noise near the surface, the co-location of

sensors at different levels limits the analysis of the radiation patterns from different faulting types. In this study, we examine fault mechanisms of microseismicity at the Decatur CO_2 injection site by using recordings at two borehole seismic arrays. The first P-motions of two borehole arrays still do not suffice to determine the focal mechanisms. The coherence measurement of the S/P amplitude ratios at sensors within individual arrays further constrains the uncertainty of focal mechanisms. This contradicts the unstable S/P amplitude measurements associated with site-specific calibrations at surface sensors. We validate the solutions obtained from first motion polarity and S/P amplitude ratios by comparing solutions of a few events for which surface and borehole sensors observe the first P-wave motions. The obtained focal mechanism solutions generally match the distribution of earthquakes and the local maximum stress direction. The subtle variation of focal mechanisms in each earthquake cluster represents either the heterogeneity of the fault system or the local-scale perturbation of the stress field. Our observation highlights the importance of installing multiple borehole arrays to investigate focal mechanisms of small earthquakes to estimate small-scale fault systems.

POSTER 103

Microseismicity Moment Tensor Estimation Using Surface and Downhole Geophone Arrays at Utah FORGE

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Microseismicity associated with the 2022 spring stimulation at Utah FORGE exhibits magnitudes from -2 to 0. The concurrent passive seismic monitoring system was consisted of a dozen of downhole geophones along two wells and a ~200-geophone surface array. Geophones emplaced downhole within granite were < 1 km from the stimulation locations and the recorded seismicity waveforms have high signal-to-noise ratio (SNR). On the other hand, the surface array was generally ~2.5 km away deployed on the sediment layer, which causes high attenuation of signals and only events close to M0 are recorded with reasonable SNR. Despite the limitation, the surface array has strength of azimuthal coverage that is crucial for moment tensor solution. Therefore, in this study, we leverage complementary information from both geophone arrays based on their *P* polarities and amplitudes.

Beginning with the set of ~M0 events, for the surface array, we perform beamforming and a noise-suppression filter to align and enhance the incoming *P* energy, which outperforms linear stacking methods. Meanwhile, for the downhole array, we employ an SNR detection and visual inspection to identify the first arrivals. The resultant moment tensors reveal strike-slip mechanisms with fault strikes consistent with the known geologic formation. Next, we aim to retrieve the moment tensor for smaller events (< M0) that exhibit high similarity with the ~M0 events. To achieve this, we apply cluster analysis and waveform correlation. For the highly similar event (correlation coefficient larger than 0.9), we refine the SNR detection picks using correlation lag time for downhole data and we adapt the first arrival information from the corresponding surface data. We will further discuss the sensitivity from the aspects of first-arrival detection, moment-tensor inversion, and the applicability of the similarity-based method within this specific geothermal setting.

POSTER 104

Shear-wave Splitting Observed in the Geysers Geothermal Field to Monitor the Spatiotemporal Crustal Conditions

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S waves propagate in an anisotropic medium separate orthogonally to each other, called shear wave splitting. Mineral properties or crust cracks are considered as the heterogeneous structure to split shear waves. The characteristics of the heterogeneous structure are estimated from the leading shear wave polarization direction (LSPD) and the travel time difference (DT). Some studies pointed out local heterogeneity, for example, faults and dense cracks, affect the direction of the LSPD. In a geothermal field, crack status is affected by the increase and decrease of water as a result of the power plant operation. If we could utilize shear wave splitting observed from microearthquakes in the geothermal fields, it would be useful for spatiotemporal reservoir monitoring.

The Geysers geothermal field locates in northern San Francisco. In that region, rich seismic network is provided by The Northern California Earthquake Data Center (NCEDC). I select five three component stations, LCK, FFA, ESM, ACR, and DRH. These stations have a small incident angle from the source and less impact from reflection and surface waves. LCK, FFA, ESM, ACR locate the eastern side of the swarm activity, and DRH locates the western side. The sampling frequency is 500 Hz. There are 30 earthquakes observed from 2020 to 2023, with magnitudes between 3.0 and 4.0, latitudes between 38.5 and 39.0, and longitudes between -123 and -122. DSPD and DT are estimated from the Cross-correlation method (e.g., Shin and Meyer, 1990), with a 1-second time window.

The stations LCK, FFA, and ESM show the predominant polarization direction for the northeast, while ACR does not show a strong polarization direction. The characteristics of the polarization direction are consistent with the shear wave splitting research in this region (Elkibbi and Rial, 2005). Though the LSPD estimates showed relatively large variation, there are no clear temporal changes for three years. DRH shows a similar predominant polarization direction while it is located in a distant area from the current active swarm area.

POSTER 105

A Cost-Effective GCS Monitoring Approach Using Localized Seismic Waves

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As geological carbon storage (GCS) is being adopted worldwide, monitoring possible CO2 migration in the subsurface is needed to ensure conformance and containment. A scalable turnkey solution is favored over repeated dense data acquisition (4D seismic) for GCS monitoring. Expensive time-lapse 3D seismic monitoring has been used in CO2-enhanced oil recovery (EOR) fields, but its use in GCS is not economically feasible. We propose a cost-effective GCS monitoring approach using localized seismic waves and permanent source arrays. Given the spatially finite nature of the localized wave, we only need a few geophones on the surface to record scattered localized seismic wavefields. To quantify the amount of CO2 using time-lapse changes of localized seismic waves, we conduct lab measurements of the P-wave velocity and density for supercritical CO2-saturated brine under various pressure-temperature conditions and a fluid substitution equation. Our monitoring approach using localized seismic waves could be a turnkey solution to cost-effective, long-term GCS monitoring.

POSTER 106

A Risk-Based Adaptive Monitoring Planning Tool Based on Elastic-Wave Sensitivities for Cost-Effective Seismic Monitoring for Geologic Carbon Storage

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Geologic carbon storage (GCS) is a viable approach to reducing CO2 emissions into the atmosphere. The risk of CO2 leakage from GCS operations is of concern to regulators, operators, and the public. Monitoring is indispensable for a GCS project to detect CO2 leakage and account for CO2 mass in storage formations. The US DOE sponsors the National Risk Assessment Partnership (NRAP) project to develop a risk-based adaptive monitoring planning (RAMP) tool for the selection, evaluation, and optimization of monitoring technologies. RAMP will be useful to support the deployment of large-scale GCS projects. This presentation focuses on optimal 2D surface seismic monitoring design through elastic-wave sensitivity analysis for detecting and imaging CO2 plumes. We simulate a hypothetical GCS scenario at the Kimberlina site in Southern San Joaquin Valley, California, and generate 2D elastic-wave sensitivity data with respect to seismic velocity models at six timesteps (80, 85, 90, 95, 100, and 125 years) after the start of CO2 injection with a focus on the post injection phase. We develop a 2D seismic survey design tool using simulated elastic-wave sensitivity data. An optimal monitoring design provides seismic source and receiver locations with high sensitivities to the target monitoring region(s). This source-receiver configuration varies with time for either detection or imaging and is adaptive with time according to CO2 migration and/or leakage. For cost-effective monitoring, the RAMP tool provides the minimum number of sources and receivers required to meet the monitoring objectives.

Acknowledgments

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Seismoacoustic, Geodetic and Other Geophysical Investigations of Active Volcanoes

Oral Session • Friday 3 May • 8:00 AM Pacific

Conveners: Josh Crozier, U.S. Geological Survey (jcrozier@usgs.gov); Ricardo Garza-Giron, Colorado State University (rgarzagi@ucsc.edu); Margaret Glasgow, U.S. Geological Survey (mglasgow@usgs.gov); Alicia Hotovec-Ellis, U.S. Geological Survey (ahotovec-ellis@usgs.gov); John J. J. Lyons, U.S. Geological Survey (jlyons@usgs.gov); Diana Roman, Carnegie Science (droman@carnegiescience.edu)

Using Deep Long-Period Earthquakes to Constrain Magmatic Volatile Transport at Mauna Kea

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Seismic signals generated at volcanoes, such as deep long-period earthquakes (DLPs), can result from diverse physical processes, posing challenges for the interpretation of such signals. However, Mauna Kea provides a unique setting to explore the processes behind DLPs due to a large and well-characterized catalog of these events. Between 2000 and 2019, beneath Mauna Kea, over 1 million DLPs occurred near periodically with interevent times between 7 to 12 minutes. Wech et al. (2020) cataloged and characterized these events, locating them at ~22 km b.s.l. beneath Mauna Kea and constraining their primarily non-double-couple source mechanisms. The authors proposed a conceptual model for these repeating events where stalled, crystallizing mush at the base of the crust results in second-boiling driven degassing. The degassing supplies magmatic volatiles to an overlying network of pre-existing fractures generating the DLPs. From this conceptual model, we have developed a physics-based numerical crack model for these repeating DLPs from which we compute synthetic seismograms. By tuning the model parameters and comparing the resulting synthetic seismograms to observed seismograms, we successfully reproduce observations such as the p-wave first motions and the amplitudes of these events. Furthermore, the range of suitable parameters from the tuned crack model provides valuable insight into the elastic properties of the rock surrounding the fractures, fracture system size and geometry, and magmatic volatile supply rates to the fractures—quantities otherwise poorly constrained at lower crustal depths in magmatic plumbing systems. More broadly, this approach improves our understanding of one potential source of seismicity at volcanoes and provides novel insight into passive degassing of magmatic volatiles.

Probing Magma Storage and Transport Beneath Pāhala, Hawaiʻi

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Deep (> 20 km below sea level) earthquakes occur along mantle fault zones beneath the southern coast of the Island of Hawaiʻi, near the active volcanic centers of Kīlauea, Mauna Loa, and Kamaʻehuakanaloa (formerly Lōʻihi). Previously, long-period tremor and a recent ten-fold increase in seismicity at these depths since 2019 centered beneath the town of Pāhala have been observed. We hypothesize that magma transport processes trigger some of the deep seismicity along these mantle faults. These may potentially provide pathways for magma to the summit storage systems of these volcanoes via sub-horizontal mantle fault zones. Detailed seismicity studies in this region have relied on 1-D velocity models; construction of local 3-D velocity models to better understand relationships between magma storage and earthquake processes has been precluded by the scarcity of seismic instruments deployed in this region. In summer 2022, we conducted a three-month deployment of 80 continuously recording three-component seismic nodes extending from the epicentral region of the Pāhala swarm towards Kīlauea's summit. This included a dense line of nodes to enhance imaging of geologic structures embedded within a sparser grid designed for precise earthquake detection and location. We use a machine-learning based workflow to detect and locate earthquakes with this novel dataset. The earthquake dataset complements imaging from receiver functions and is used for body wave tomography, which together provide improved constraints on crustal and upper mantle structures in the region. The combined interpretation of these datasets will shed light on the magmatic structure and processes that have contributed to the dramatic increase in seismicity since 2019.

Seismic Velocity Changes at Mauna Loa Derived From Seismicity Prior to and During Its 2022 Eruption

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Mauna Loa's short-lived eruption from late November to early December 2022 marked the culmination of nearly a decade of elevated seismic activity and geodetic inflation. The volcano has been monitored by a network of permanent, primarily single-component short-period seismometers with open data since 2012. I used the continuous waveform data from that network to generate a catalog of seismicity using the open source "REDPy" Python package. This catalog enhances the Hawaiian Volcano Observatory's public seismic catalog with additional detections and groups earthquakes by waveform similarity. Analysis of subtle differences in the recordings of the earthquakes in this catalog yields a history of changes in the shallow seismic velocity structure of the volcano. Seismic velocity changes are thought to be sensitive to changes in strain, and therefore might be expected during volcanic unrest and eruption. Indeed, initial results show a decrease in seismic velocity centered on the summit beginning in September 2022, corresponding to the onset of a vigorous precursory swarm of seismic activity and shallow inflation. During the eruption itself, I observe a complex spatiotemporal pattern, perhaps due in part to dike opening along the Northeast Rift Zone. Seismic velocity changes associated with non-volcanic sources such as large regional earthquakes and seasonal climate changes are also observed, investigated, and compared with supporting data. An open question in this work is whether the changes observed in September 2022 were unique to the pre-eruptive increase in unrest, which has direct implications for the use of this technique as a monitoring tool.

A Catalog of Automated Focal Mechanisms for Microearthquakes at Axial Seamount Based on Waveform Cross-Correlation

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Axial Seamount is a submarine volcano at the intersection of the Cobb hotspot and the Juan de Fuca Ridge. The last eruption in 2015 was recorded by 7 ocean bottom seismometers on the Ocean Observatories Initiative Regional Cabled Array. A small number of manual composite focal mechanisms (FMs) obtained by Levy et al. (2018) confirmed that the motion on an outward dipping ring fault beneath the summit caldera reversed during the 2015 eruption. Our earthquake catalog for Axial Seamount comprises ~150,000 hypocenters from 2015-2024. A large data set of FMs would provide constraints on the geometry and deformation of the caldera ring faults, the impacts of magma movement and hydrothermal process on faulting, and the evolution of crustal stresses through the eruptive cycle. To generate FMs automatically, we incorporate the methodology of Shelly et al. (2016) which determines polarities by maximizing congruence with signed waveform correlation coefficients. We first tested the approach on subsets of 5000 earthquakes from the east and west walls of the caldera. We obtained 53,000 polarities which show a 95% consistency with the sign of the cross-correlation coefficients and a 99% accuracy rate when benchmarked against 3,000 manual picks. Considering just earthquakes with at least five polarities and 5 S/P amplitude ratios, we created 680 groups of ~15 earthquakes with fully consistent polarities and similar locations and S/P ratios. Finally, we used the HASH program to generate composite FMs. The hypocenters beneath the west wall mostly fall on an outward dipping ring fault and most FMs are normal faults consistent with this fault plane. The hypocenters in the test data set beneath the east wall have a more complex distribution and the focal mechanism similarly show more variation, consistent with the influence of ring faulting and deformation in the regions where dikes are injected during spreading events. We are presently extending the approach to the entire catalog and based on the number of earthquakes with sufficient polarities and S/P ratios, expect to obtain ~7,000 composite FMs.

The Influence of Multiple Scattered Waves on the Spectral Stability of Volcanic Tremors

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The conventional understanding of the stability observed in the spectral content of volcanic tremors attributes it primarily to the consistency of the source mechanism generating these signals. In our study, we perform a more detailed examination of the origin of seismo-volcanic signals through numerical simulations utilizing spectral elements methods. Our findings reveal that the stable features observed in the signal spectrum can be produced by interference of multiply scattered waves on strong structural heterogeneity within the volcano plumbing system, arising from a complex distribution of magmatic sills and dikes. To simulate the plumbing system's heterogeneity, we used a model of its growth by multiple injections of magma into surrounding crustal rocks (Melnik 2022). By computing the propagation of waves in this medium over extended durations, we show that the highly heterogeneous structure results in a strong multiple scattering of seismic waves whose interference creates a distinctive signature in the signal spectra. This phenomenon holds true even when considering a source spectrum that exhibits randomness. Our results provide valuable insights into the heterogeneous structure of volcano plumbing systems that is expressed in the observed complexity and stability of the spectra of the seismo-volcanic signals. This study broadens our comprehension of volcanic processes and emphasizes the significance of multiple scattering of seismic waves within volcanic media.

Local Infrasound Monitoring of Lava Eruptions at Nyiragongo Volcano (d.r. Congo) Using Urban and Near-Source Stations

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During eruptions, volcanoes produce air-pressure waves inaudible for the human ear called infrasound, which are very helpful for detecting early signs of magma at the surface. Compared to violent ash-rich explosions, recording more discrete atmospheric disturbances from effusive eruptions remains a practical challenge depending on the distance to the source. In contrast with powerful volcanic explosions, close-range deployment of instruments around the active vent (for instance < 15 km) is generally needed for continuously monitoring long-living lava effusion or degassing as observed at open-vent volcanoes, such as Kīlauea (Hawaii) or Nyiragongo (D.R. Congo). Nyiragongo, towering above a 1-million urban area, hosted the world's largest lava lake up to 2021, which was drained during the third known flank eruption of this volcano on 22 May 2021. We analyzed local infrasonic records between January 2018 and April 2022. A persistent acoustic signature from the crater before and after the flank eruption was detected up to the volcano observatory facilities in Goma city center about 17 km from its crater. We also explore these records for characterizing the temporal and spatial evolution of the flank eruption on May 22, 2021. These ~4-year results show remarkable local recordings of eruptive infrasound from near-source and city-based stations and have significant implication for optimizing future monitoring efforts in a harsh field environment. Remote observations from space (ground deformation, gas emissions, thermal anomalies) can also provide essential information about the eruptive state of a volcano and were jointly analysed with infrasound records. The multidisciplinary approach with infrasound and space-based observations of the intra-crater activity leads to a comprehensive picture of Nyiragongo's eruptive activity during this period.

Here Comes the Boom! Tracking Audible Acoustics Across Aotearoa New Zealand From the 2022 Eruption of Hunga Volcano

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On 15 January 2022, Hunga volcano in the Kingdom of Tonga erupted in what is thought to be one of the largest volcanic eruptions in recent history. Atmospheric disturbances caused by the eruption generated long-range audible sounds that were reported around the world, including the length of Aotearoa New Zealand. This unusual phenomenon presented a rare opportunity to document and analyse the long-range propagation of audible volcanic acoustics from both geophysical and social perspectives. In response to the event, public feedback was obtained via a crowdsourced survey to understand the spatial and temporal distribution of eruption sound observed across NZ. The results of the survey complemented a dense geophysical record, including data from microphones, barometers, seismometers, and strong-motion accelerometers.

In all, over 1700 members of the public from across the country reported hearing "booming" noises on 15 January 2022. On average, 5 "booms" were heard over a 2-hr period with half the respondents reporting a "light" or "moderate" perceived loudness, commensurate to 60–79 dB. Manual analysis of shockwave-like waveforms recorded by a seismo-acoustic station in the North Island found >140 events across two distinct wavepackets within the same time period, of which 7 had amplitudes >60 dB. Detailed analysis of seismo-acoustic data from across Aotearoa New Zealand clearly highlights the two acoustic wavepackets propagating north-to-south on 15 January. The first wavepacket coincided with the Lamb wave generated by the main explosive phase of eruption. However, the second wavepacket propagated at a slower apparent velocity (~270 m/s) and was likely associated with an atmospheric gravity wave generated during a later phase of the Hunga eruption sequence. This presentation highlights how crowdsourced data can engage the wider public in volcanology, how joint analysis with geophysical data is shedding new light on a historic eruption, and how such multi-disciplinary studies may be used to understand future volcanic activity.

Internal Gravity Waves During the 2023 Eruption of Shishaldin Volcano, Alaska

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The 2023 eruption of Shishaldin volcano, Alaska, produced several significant explosive events between mid-July and early November. Similar eruptive styles at the volcano had been instrumentally observed during previous eruptions in 1999 and 2020. Here we report on high-quality acoustic recordings of the eleventh explosive event (Event 11, September 25 13:35 UTC) on two local infrasound sensors within 7 km of the volcano. We also analyze air-to-ground coupling on three broadband seismometers, two of which are co-located with the infrasound sensors. Event 11 had the distinction of being among the most powerful of the explosive events and it occurred during a time period of low wind noise, resulting in excellent signal-to-noise ratio. Restitution over a wide frequency band reveals acoustic signals with low frequencies down to at least 0.75 mHz (22 minutes period) following the start of the paroxysmal phase. In this period range, acoustic-gravity wave phenomena are expected. The low-frequency signals had maximum peak-to-peak pressure amplitudes of approximately 100 Pa, similar to previously reported observations of internal gravity waves at Montserrat (Ripepe et al., 2016; Sci. Rep.). Such internal gravity waves offer a novel way to quantify the time history of mass eruption rate and estimate overall erupted volume. From the local seismo-acoustic data, we show that the low frequency atmospheric waves propagated with a group velocity on the order of 10 m/s, much lower than the usual speed of sound and consistent with internal gravity wave properties. Furthermore, polarization analysis of the associated air-to-ground coupled wave at a three-component seismometer indicates transverse particle motion, again in line with the characteristics of internal gravity waves. Using a 3D time-domain finite-difference code, we model the acoustic-gravity wavefield and infer details of the eruption source, including mass eruption rate and source altitude. We additionally analyze internal gravity waves from other explosive events during the 2023 eruption.

Seismic and Infrasound Signals from the 2023 Shishaldin Volcano, Alaska Eruption

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On July 12, 2023, Shishaldin Volcano, Alaska commenced a months-long eruption consisting of at least 13 discrete explosive events. In addition to hazardous ash plumes and tephra fall, these eruptive episodes exhibited similar inter-eruptive durations and increases in seismic and infrasound tremor amplitudes prior to each explosive eruption. Here we focus on analyzing the three local seismic and infrasound stations at Shishaldin and describe their notable features. We utilize a recently introduced Machine Learning tool (VOISS-Net) to detect and classify the seismic spectral characteristics (Tan et al., 2024) to determine the type, onset, and duration of seismicity. We also compute reduced displacement and infrasound pressure to analyze amplitude variability over time. We find that the eruptive episodes were preceded by hours to days of broadband seismic tremor. The seismic amplitudes increased prior to the paroxysmal phase and often had a double-peaked shape. Infrasound signals, when not masked by wind noise, generally follow similar trends to the seismic data and often display a transition from discrete explosions to sustained signals. The paroxysmal phases had notable ground-coupled acoustic waves in the seismic spectra above ~3 Hz, complicating interpretation. The seismic and infrasound data from these eruptions were critical for eruption monitoring by the Alaska Volcano Observatory, and were the foundation of numerous eruption forecasts. We demonstrate that the signal classifications and trends we observe here have utility for eruption monitoring and forecasting at other volcanoes worldwide.

Reference:

Tan, D., Fee, D., Girona, Haney, M. M., Witsil, A., Wech, A. (2024) “Investigation of tremor and explosion sequences from the 2021-2022 eruption of Pavlof Volcano, Alaska using deep learning”. SSA Annual Meeting Abstracts.

A Seismic Sequence Capturing Magmatic Fluid Ascent and Phreatomagmatic Eruptions at Semisopochnoi Volcano, Alaska

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The 2018-2023 phreatomagmatic eruption of Semisopochnoi volcano, Alaska was well-recorded with local seismic and infrasound data following a network upgrade in 2021. The dataset provides an excellent opportunity to investigate precursory and syn-eruptive geophysical signals from a phreatomagmatic eruption. We generated explosion and long-period (LP) event catalogs through novel implementations of the REDPy repeating event detector. The explosions show a high degree of infrasound waveform similarity in hundreds of events over more than a year, indicating a repeating source mechanism. The seismic LP catalog shows that events began over a month prior to renewed explosive activity at the beginning of August 2021, and that the frequency index (FI) of LPs changed ~10 days prior to the onset of explosions. We applied a recently developed machine learning tool (VOISS-Net) to identify abundant broadband and harmonic tremor recorded before and during the renewed explosive activity, along with LPs and explosions. The tremor catalogs complement the LP and explosion catalogs by filling out the seismic sequence with all the dominant signal types. Harmonic tremor was observed during just two short time periods — most notably ~10 days prior to the onset of explosive activity, concurrent with the change in FI of LP events. Broadband tremor was widely observed following the onset of explosive activity.

Together, these catalogs reveal a seismic sequence of renewed unrest that started with several weeks of LP events, followed by LPs with lower FI values and harmonic tremor in the days prior to explosive activity, and finally the onset of discrete explosions and broadband eruption tremor. We interpret this sequence as the ascent of a new pulse of magmatic fluids that first interacted with the hydrothermal system to produce LPs, followed by harmonic tremor, and that ultimately drove explosive eruptions and periods of continuous ash emissions. The VOISS-Net tool represents a major advancement in our ability to classify multiple signal types from continuous waveforms over months to years, with potential for near real-time applications.

Investigation of Tremor and Explosion Sequences from the 2021-2022 Eruption of Pavlof Volcano, Alaska using Deep Learning

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Volcanoes can show variable behavior and unrest mechanisms over the course of long eruptions. However, systematically documenting discrete episodes of elevated seismicity and infrasound can be challenging and laborious, especially if monitoring parameters remain heightened or if the eruption lasts for months or years. The 2021-2022 eruption of Pavlof Volcano, Alaska is an example of a 1.5 year long eruption characterized by intermittent explosions, lava effusion, and low-level ash emissions. Although reliably monitored by the local seismo-acoustic network, satellites, and webcams, the volcano exhibited transitions in unrest regimes which are non-trivial to distill and analyze. In this work, we leverage the diverse tremor and explosion dataset from this eruption to construct an extensive set of labeled seismic and infrasound spectrograms. The labeled spectrograms, representing classes of different tremor types, explosions, earthquakes, and noise, are then used to train VOISS-Net—a convolutional neural network for each data type. Then, the trained models are applied to classify two years of seismic and infrasound data bounding the 2021-2022 eruption, and we implement a local network-wide weighting scheme to collapse station-specific classifications into a single result to reduce uncertainty. We find that our machine learning derived timeline highlights explosion-rich phases in the eruption embedded within months of broadband tremor, as well as explosion-poor phases that coincide with increased thermal output and, at times, observed lava effusion. Beyond general comparisons with multidisciplinary observations and eruption chronology, our approach also reveals interesting explosion-tremor sequences that demonstrate pre-explosive quiescence, microseismicity, and/or transitions in tremor spectra. We additionally demonstrate the transferability of our methods to earlier Pavlof Volcano eruptions (2007, 2013, 2014 and 2016), and elucidate the inter-eruption variability of the volcano’s characteristic seismicity.

Unique Seismic and Eruption Precursors to the 1996 Magmatic Eruptions of Popocatépetl: Coupled and Fluidized Bed Events.

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Volcanic seismicity is generated by stress changes caused by many processes occurring at different temporal and spatial scales, including those involved in transporting magma and fluids from the mantle to the surface. Precursory seismicity at Popocatépetl followed three of the four stages in White and McCausland’s (2019; doi.org/10.1016/j.jvolgeores.2019.03.004) seismic and geologic model of precursory volcanic seismicity. Seismicity began in 1990 with Stage 2, distal volcano tectonic (VT) seismicity, and peaked in magnitude and rate in late 1993 and early 1994. Then Stage 3 proximal vent-clearing seismicity dominated while CO_2 and SO_2 emissions peaked. Stage 3 continued after initial vent-clearing eruptions in December 1994 through the eruption of the first domes in 1996. Stage 3 included three unique types of seismicity, fluidized bed events (tremor with coincident gas emissions that fluidize vent deposits) and two types of coupled events: 1) spasmodic burst coupled events, a burst of VTs coupled with a large eruptive explosion, and 2) explosion couplet coupled events, a pair of events with a deeper first event and shal-

low second event that correlates with a gas emission or explosion. Spasmodic burst coupled events accompanied the initial 21 December 1994 and second 5 March 1996 eruptions. Starting mid-January 1995, fluidized bed events occurred with continuing emissions after initial eruptions while SO_2 emissions were elevated. Fluidized bed events and SO_2 emissions waned in late March. After the 5 March 1996 eruption, Stage 4 final magma ascent seismicity began as explosion couplets, and their properties were useful for forecasting magmatic eruptions at Popocatépetl volcano. Explosion couplet properties systematically changed as the magma approached the surface the first three times between March and June 1996: interevent times (time between the first and second event) decreased by a factor of 4, while the amplitude ratio between the second and first event increased by a factor of 5. Consistent gas, visual and seismic observations enabled this direct correlation of gas, magma and seismic phenomena.

Constraining Links Between Seismicity and Eruptive Processes for the December 2018 Flank Eruption at Mt Etna

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Volcanic systems produce a range of eruptive styles and durations; determining whether future eruptions will be explosive or effusive is key for reducing the hazards faced by local communities. Volcanic seismicity is a powerful indicator of activity at volcanoes worldwide, providing information on volcanic structures and subsurface processes such as magmatic fluid transport. Mt. Etna is the largest volcano in Europe and is continuously monitored by a substantial seismic network; this provides an ideal location to quantitatively constrain links between eruptive styles and seismicity. During periods of intense volcanic activity, many seismic events will go undetected. Repeating earthquakes are events that have identical waveforms, implying that they are from the same source origin and mechanism. A matched filter search identifies repeats of template events, including those which are hidden behind the noise, and can increase a seismic catalogue by a factor of 10. The detected seismicity is categorised into families of repeating and non-repeating sources, and is analysed alongside subsurface observations to decipher information on how the source process varies through time. Here we focus on a flank eruption in December 2018 which saw a large increase in seismicity during the first few days of the eruption. We use 483 events detected by the INGV seismic catalogue in December 2018 as templates for a matched filter search, detecting over 35,000 events during the month. We use a combination of relative and absolute location methods to further constrain hypocenter locations for the detected events. This is used to establish a framework that links subsurface processes and structures, providing a quantitative comparison with the vast and complex eruptive history of Mt. Etna.

Tracking Seismicity in an Underfunded Institution: The Case of La Soufrière St Vincent Volcanic Eruption 2020–2021

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An unusual volcanic transition was recorded at La Soufrière Volcano in the Lesser Antilles during the 2020-2021 eruptive episode. Initial activity was an effusive phase that lasted three months and turned explosive on 9 April 2021. Although the transition was recognized when it occurred and people were timely evacuated thanks to the detection of subtle geophysical patterns, this work attempts to extract more detailed information from the seismic dataset to improve the monitoring of future events. Due to network limitations and the low amplitudes of the recorded signals, the elaboration of a conceptual model from earthquake locations turned out to be challenging. Accordingly, new analysis methods were developed, including: seismic interferometry using cross-correlation functions to locate the sources of tremor and explosions and a fluid-filled crack model to quantify the bulk modulus of magma stored in the system and translate it to gas content. Both are now applied in quasi-real time for the interpretation of future unrest. The VT locations feature a NNW-SSE alignment across the eruption site with focal depths shallower than 4 km. The banded tremor located at shallow levels (~1 km depth) and the explosions featured two distinct behaviors, deepening of sources as the eruption progressed, as well as the activation of near-surface sources associated with the eruptive jet. A fluid-filled crack model points to an injection of gas into the system on 9 April, which amounts to approximately 76% gas-volume fraction. We propose a volatile injection equivalent to a 7% gas-volume fraction entering the system on 12 March; however, it was not energetic enough to produce changes in the extrusion rate. Seismological analyses support the conceptual model proposed by Joseph et al. (2022), where a dome sealed the system with a minimal amount of gas exsolved (0.7% gas-volume fraction). For the onset of the explosive phase, the system accumulated enough gases to produce the dome collapse and cleared the vent, decreased the internal pressure and triggered fragmentation.

Understanding Volcanic Tremors Based on Seismic Network Analysis

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Seismic tremors are largely used for monitoring the volcanic unrest. Single station approaches empirically relate them to the volcanic activity without providing information about their source locations and generation mechanisms. To advance the understanding of tremors, we developed a method based on the o network covariance matrix and is adapted to detect spatially coherent signals without clear impulsive offsets, to measure their time-frequency properties, and to locate their sources.

We present applications of the network-based analysis to seismic tremors in two volcanic systems: Piton de la Fournaise volcano at la Réunion Island and Klyuchevskoy Volcanic Group at Kamchatka. In the first case, the distribution of tremor source depths is well correlated with magma gas content, indicating that the tremor generating mechanism is controlled by the shallow magma degassing. In the second case, the tremors sources are distributed over a wide range of depths and the tremor activity is characterized by rapid migrations. Overall, the tremor properties at the Klyuchevskoy volcanic group indicate the existence of a highly dynamic trans-crustal magmatic system.

The tremors contain multiple narrow spectral lines that remain stable over long periods of time and could be reminiscent of the particular source properties. Alternatively, we argue that they can be due to the interference of multiple seismic waves resulting from a strong scattering. We perform numerical experiments with propagating seismic waves in a medium containing multiple melt-rich pockets as can be expected in an active magmatic system. We demonstrate that such type of media heterogeneity leads to a strong scattering and results in source spectra containing multiple spectral peaks, similar to observations of tremors. The shape of these peaks is controlled by the propagation effects and remains stable for fixed source position and media properties. Therefore, variations of tremor spectral patterns can be used to detect changes in the volcano-plumbing systems such as moving positions of the seismic activity sources or variations of the media properties.

Seismoacoustic, Geodetic and Other Geophysical Investigations of Active Volcanoes [Poster Session]

Poster Session • Friday 3 May

Conveners: Josh Crozier, U.S. Geological Survey (jcrozier@usgs.gov); Ricardo Garza-Giron, Colorado State University (rgarzagi@ucsc.edu); Margaret Glasgow, U.S. Geological Survey (mglasgow@usgs.gov); Alicia Hotovec-Ellis, U.S. Geological Survey (ahotovec-ellis@usgs.gov); John J. J. Lyons, U.S. Geological Survey (jlyons@usgs.gov); Diana Roman, Carnegie Science (droman@carnegiescience.edu)

POSTER 68

Surface Deformation at the Socorro Magma Body: A Natural Laboratory for Probing Mush and Magma in the Mid-Crust

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Surface deformation measurements play a key role in illuminating magma transport at active volcanoes. However, it is often challenging to untangle shallow volcanic deformation signals from deeper magma dynamics. The Socorro Magma Body (SMB) is a seismically-inferred mid-crustal magma body which lacks an upper crustal magma transport system, providing a rare opportunity to directly link geodetic measurements with mid-crustal magma dynamics. New InSAR observations confirm a pattern of central surface uplift surrounded by a region of subsidence (previously coined "sombrero" deformation) has persisted for over 100 years at the SMB with minimal change to its wavelength or magnitude. Seismic observations suggest the presence of a large (>100 km width), seismically slow region surrounding the inferred SMB. This low velocity zone may be caused by thermal weakening and/or partial melt related to the magma body. Inspired by these observations, we develop numerical models that explore the interactions between a weaker-than-ambient, compliant region (CR) surrounding a pressurizing sill-like source. Episodic pressurization (potentially due to melt injection and/or volatile exsolution) within a viscoelastic CR drive a sombrero deformation pattern, producing good agreement in width, magnitude, and duration with InSAR and previous GPS and leveling studies. Long lasting sombrero deformation in our models is dependent both on a sufficiently weakened (low viscosity) CR and an asymmetric (re-/de-)pressurization cycle. Building on these results, we investigate how time and temperature dependent rheology of the CR, together with poroelastic effects, may manifest in surface deformations. Additionally, to explore more complex volcanic systems, we include a second, shallower pressurizing source within the CR. Our goal is to understand how multiple magma bodies within a weaker-than-ambient CR may interact and drive complex surface deformation at volcanoes.

POSTER 69

Automated Detection of Volcanic Seismicity Using Network Covariance and Image Processing

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Seismicity at restless volcanoes commonly features a variety of signal types reflecting both tectonic and fluid-driven source processes. However, traditional catalogs of seismicity are often incomplete, especially with respect to events with emergent onsets such as those driven by the dynamics of magmatic and hydrothermal fluids. The detection of all discrete events and seismic tremor regardless of the underlying source processes would therefore improve the ability of monitoring agencies to forecast eruptions and mitigate their associated hazards. We present a workflow for generalized detection of seismic events based on the eigenvalue decomposition of the network covariance matrix. We invoke new approaches for data-preprocessing and apply image processing techniques (i.e., noise reduction, smoothing, and thresholding of the spectral width image) to enable event detection and classification. Our unsupervised workflow requires no model building, data labelling, or *a priori* knowledge regarding event types. This approach can simultaneously detect continuous and short duration events and provide information about the frequency content of the signals. We test the workflow on a 15-month record of seismicity from Mammoth Mountain, California (7/2012–10/2013) and detect 62% of long-period events and 94% of volcano-tectonic events in the existing Northern California Earthquake Data Center catalog. In addition, thousands of new events and tremor signals are detected. The method is suitable for near-real time analysis of continuous waveforms and can provide a valuable supplement to existing algorithms to improve the completeness of catalogs used for monitoring volcanoes.

POSTER 70

Long-Period Earthquakes in the Yellowstone Volcanic System: When, Where, Why?

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Long-Period earthquakes (LPs) have been observed at many volcanic systems throughout the world including Kilauea, Long Valley, and the Cascades just to name a few. However, LPs have never been documented in the over 50 years of seismic recording in the Yellowstone Volcanic region. Seismologists have often wondered why LP events have not been observed in Yellowstone and whether they just are not occurring or if they just haven't been identified in the data. Recently, the University of Utah Seismograph stations located two events that may be LP events. Both these events occurred in 2021 and are enriched in energy below 5 Hz. We present data on these two potential Yellowstone LP earthquakes as well as results using them as templates and searching through continuous waveform data in Yellowstone for more potential LP events.

POSTER 71

Mining for Hidden Seismicity at Mount St. Helens

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Mount St. Helens is the most active and well-instrumented volcano in the Cascade Range. Seismicity catalogs provide fundamental observations of active volcanic and tectonic structures within Mount St. Helens and can reveal its deep-seated volcanic plumbing system. We develop a more comprehensive seismicity catalog at Mount St. Helens by making use of novel machine learning algorithms and traditional matched-filter procedures to detect previously unidentified earthquakes from continuous seismic data recorded from permanent seismometers (networks UW, CC, and PB) from 2009 to 2023. With our new seismicity catalog, we hope to further address several outstanding problems surrounding the nature of seismicity at Mount St. Helens and Cascade volcanism. Such inquiries may inform the relationship between seismicity amongst deep and shallow depth structures, stress transfer between the volcanic conduit and chamber due to magma transport, and potential for seasonal dependence of shallow volcanic earthquake swarms.

Our workflow uses a convolutional neural network trained with analyst-made phase picks from Mount St. Helens to identify P- and S-wave phase arrivals, which are then associated with GaMMA–a Gaussian Mixed Model clustering algorithm and located by grid search of three-dimensional P- and S-wave velocity travel time grids from the shallow crust velocity models of Kiser et al. (2019). To maximize our detection capabilities and measure differential travel times, we then apply a continuous matched-filter with templates consisting of previously cataloged earthquakes and newly detected earthquakes from our machine learning algorithm. Lastly, we locate or relocate all detected earthquakes with the GrowClust3D double-difference location algorithm.

POSTER 72

Ground-Tilt Caused by Atmospheric Lamb Waves From the 2022 Tonga Eruption Recorded at Fiji and Pinon Flat Observatory

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Ground tilt is commonly attributed to atmospheric pressure changes such as hurricanes and strong storms. In these cases, ground tilt has been measured as horizontal-to-vertical component pseudo spectral amplitude ratios and correlated to barometric pressure (e.g., Anthony et al., 2014; Tanimoto and Wang, 2018). Directly comparing time histories, with amplitude and phase, between air-pressure and rotational motions or strain tilt-meters is not performed as storms are not distinct events. We used the atmospheric Lamb waves induced by the 2022 Hunga-Tonga volcanic eruption to directly compare the barometric pressure change to ground tilt estimated from array-derived strain at the Pinon Flat Observatory (PFO). PFO is 8658 km from the eruption and operates a broadband seismic array, a rotational seismometer, and strain meter. The PFO maximum rotation rate is $4x10^{-9}$ radians/sec which is similar to tilt recorded by magnitude 3 earthquake at a distance of 800 km. We also find good agreement between Monasavu Fiji (MSVF) low-frequency transverse component displacements to barometric pressure time histories suggesting MSVF was also affected by ground tilt at 750 km distance. The response of MSVF air-to-ground coupling to a low-pressure pulse may have mysteriously caused the absence of high-frequencies signals > 1 Hz. These observation underscores the potential of including more strain and barometric pressure sensors into seismic network monitoring for the detection and modeling of atmospheric pressure waves. Prepared by LLNL under Contract DE-AC52-07NA27344. LLNL-ABS-858923.

POSTER 73

Soundquakes: Seismo-Infrasonic and Seismo-Infra-Seismic Phases During a Swarm of Earthquakes at Kilauea Volcano on September 30th, 2021

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Seismic waves produced by earthquakes can shake the ground and produce infrasound either local to an infrasound station (i.e., primary infrasound) or from locations away from the recording site, which then propagate sound sub-horizontally toward the station (secondary infrasound). This study focuses on infrasonic waves generated by ~20 earthquakes occurring during a one-hour period prior to a summit eruption of Kilauea starting at 01:21 UTC on September 30th, 2021. These small earthquakes (M<=2.7) were shallow (<2 km) and all but two were located near the Halema'uma'u crater. A network of three infrasound arrays located about 3 km E, ENE, and ESE of Halema'uma'u crater was operational during this swarm and recorded prominent (infrasonic) air phases from these earthquakes.

The infrasound arrays were capable of detecting infrasound and also determining apparent velocities, which ranged from those expected for horizontal sound to faster velocities associated with primary infrasound. Backazimuth projection of the infrasound showed that secondary sources from a single 'soundquake' typically lasting tens of seconds originated from a range of directions apparently from different topography around the Kilauea Caldera excited by ground motion. Several locations, including the western caldera walls of Kilauea, appear to be particularly pronounced 'hotspots' for infrasound generation. The networked array of sensors is useful for triangulating many of these sources using reverse time migration and beam information.

The unique topology of the Kilauea infrasound network of arrays permits particularly high resolution mapping of earthquake infrasound radiators. A significant finding is the prevalence of earthquake infrasound and its (perhaps) poorly appreciated impact upon the seismic wavefield. Similarly-shaped signal envelopes for the coda wave decay for both infrasound and seismic energy suggests that some of the infrasound is re-transmitted to the ground. This energy, contributing to the seismic coda, represents the prevalence of an underappreciated seismo-infrasonic-seismic phase in the seismic records.

POSTER 74

Laboratory Experiments on Gas-Driven Volcanic Tremor and Long Period Seismicity

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Volcanic tremor and long-period (LP) events are seismic signals linked to magmatic/hydrothermal fluid processes. Previous theoretical research suggests that the accumulation of gas beneath permeable caps within the shallow volcanic conduit leads to spontaneous pressure oscillations that can produce volcanic tremor and LP events (Girona et al., 2019; https://doi.org/10.1029/2019JB017482). Here we explore experimentally this hypothesis as a function of gas flux and geometry and permeability of the permeable cap. We devised an experimental setup comprising a vertically-arranged cylindrical pipe (4 cm internal diameter) which, from base to top, includes: 1) a water infill; 2) an air pocket; 3) a permeable cap; and 4) an upper pipe open to air. We injected air into the water at the base of the pipe using a set of gas flow meters and monitored pressure oscillations in the air pocket beneath the permeable cap, tracked vibrations (acceleration) of the pipe, and recorded pressure signals in the upper pipe above the cap using a microphone. Different permeability, pore arrangements, and thickness of the cap were explored. Preliminary results show that gas flow through the water without permeable cap generates low-frequency pressure oscillation (< 1~5 Hz) in the free air above, potentially related to bubble bursts. In the presence of the permeable cap, pressure oscillations in the 2-150 Hz frequency band appear in the air pocket beneath the cap, implying resonance due to gas accumulation. Different characteristics of the porous media, such as straight capillary pores and spongy materials with varying permeability, generate distinct waveform features, including different vibrations and microphone signals. For example, gas flow through straight capillary pores exhibits periodic peaks in microphone records, suggesting that permeable gas flow may control periodic volcanic outgassing. Our study offers a laboratory approach to unveil the seismoacoustic signals linked to gas circulation within porous media and serves as a reference for explaining volcano monitoring signals in natural settings.

POSTER 75

Monitoring Unrest at a Supervolcano: Insights From the 2022-23 Unrest Episode at Taupō Volcano, Aotearoa New Zealand

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Taupō is a large caldera volcano located beneath a lake in the North Island of Aotearoa New Zealand and most recently erupted ~1800 years ago. The volcano has experienced at least 16 unrest episodes since 1872, many of which were characterised by increased seismic activity. In May 2022 the volcano entered a new unrest period with increased earthquake activity and ground deformation within the caldera. The unrest was notable for two reasons: (1) the Volcanic Alert Level for Taupō was raised from VAL 0 to VAL 1 for the first time, and (2) a M 5.7 in November 2022 was one of the largest magnitude earthquakes detected beneath the lake for at least 50 years, triggering a small yet complex tsunami within the lake. The unrest ended in May 2023 when seismic activity returned to background levels. This presentation aims to give an overview of seismic, geodetic, and tsunami observations during the unrest and what indications these give on the state of the volcanic system during the unrest.

Over 1780 earthquakes were automatically detected beneath the lake over the 13-month unrest period, the highest number recorded during instrumented unrest episodes at the volcano. Four distinct phases were identified based on weekly earthquake detection rates, with relocations suggesting activity was focused around overlapping caldera structures beneath the lake. A rapid 50 mm/yr inflation was detected at a GNSS station located within the lake, peaking during the M 5.7 earthquake with 18 cm uplift and 25 cm horizontal movement. Modelling of the GNSS data suggests the inflation source was located at 4-8 km depth beneath the lake. The lake tsunami was recorded by three water-level gauges and a survey was conducted to record inundation heights around the lake. Analysis suggests the small tsunami was generated by two sources: a sub-lacustrine landslide near the town of Taupō, and upward movement of the lakebed. Altogether, we suggest the 2022-23 unrest episode at Taupō volcano was caused by an intrusion of magma at depth with seismic activity generated by reactivation of faults beneath the lake.

POSTER 76

Imaging the Magma Plumbing System Below Okmok Volcano Using Full-Wave Ambient Noise Tomography

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Volcanic eruptions can pose a substantial threat to society, causing significant impacts on economic and social activities during their eruptive periods. To advance volcano monitoring, eruption forecasting, and hazard assessment, an improved understanding of the magmatic processes and plumbing systems beneath active volcanoes is essential. Okmok Volcano in the eastern Aleutian Arc represents a complex magmatic system, distinguished by decades-long development of eruptive cones and short-term seismicity migrations. Its eruption cycle follows a cyclic pattern of magma reservoir recharge and discharge events with documented eruptions styles ranging from effusive to explosive.

Previous seismic imaging studies imply Okmok has multiple magma sources at varying depths, supported by geodetic observations, yet the structure and geometry of these magma reservoirs remain poorly defined. Our study aims to construct a high-resolution 3-D seismic velocity model of Okmok down to a depth of 15 km below sea level using full-wave ambient noise tomography. The resulting model will enable us to locate possible magma sources beneath the volcano using an expanded seismic dataset. To support our interpretations, we will incorporate the imaging results with geodetic observations, deformation modeling, and volcano seismicity. The results of this multidisciplinary investigation will deepen our understanding of volcanic processes and magma dynamics at Okmok and, by extension, hold relevance for other active volcanoes.

POSTER 77

Crustal Structure of the Laguna Del Maule Volcanic Field Using Receiver Functions

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The Laguna del Maule (LdM) volcanic field in central Chile has had considerable postglacial rhyolitic eruptions supplied by a shallow, crustal magma reservoir. Today, this reservoir is characterized by extensive seismicity and periods of inflation. Geophysical studies have shown there is a low density, high conductivity, low seismic velocity anomaly inferred to contain partial melting up to 14%. Geodetics and seismicity studies also show the likely source of inflation and seismicity coincides with the low velocity anomaly, implying active recharge from a deeper source. While the presence of an upper crustal magma reservoir is consistent in prior geophysical imaging, questions remain regarding the detailed geometry of the reservoir and how it fits within the transcrustal magmatic system feeding LdM. Using seismic stations deployed between 2015-2018, we conduct receiver function analysis to get better constraints on the detailed crustal structure below LdM. Preliminary results show there is heterogeneity across the LdM volcanic field and a weak Moho. There are several strong mid-crustal conversions that are spatially limited. These mid-crustal conversions may indicate a more complex upper-mid crustal reservoir system. A weak moho signature may imply a weak or gradual structural crust-mantle transition.

POSTER 78

Seismological Models and Seismicity Patterns in the Kivu Rift and Virunga Volcanic Province (D.R. Congo)

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The Kivu Rift is located in the bordering region of the Democratic Republic of Congo and Rwanda, in the Western branch of the East African Rift. The active volcanoes Nyamulagira and Nyiragongo in the Virunga Volcanic Province threaten the city of Goma and neighbouring agglomerations. Urbanisation in that region undergoes sustained rapid growth, and the region currently counts 1 million inhabitants today. In 1977, 2002 and 2021, eruptions of Nyiragongo caused major disasters. Destructive earthquakes can also affect the region, as the Kalehe (Mw 6.2) earthquake in 2002 along the western shore of Lake Kivu, or in 2008 in Bukavu (Mw 5.9), south of Lake Kivu.

Between 2013 and 2022, the first dense real-time telemetered broadband seismic network in the Kivu Rift region (KivuSNet) was gradually deployed in the frame of several research projects and was fully operational with a sufficient station coverage (>10 stations) since October 2015. Due to the fundamental importance of monitoring the seismicity in this region, substantial efforts were made for setting up this permanent network with real-time data acquisition, which thus rapidly became the main seismic network of the Goma Volcano Observatory for daily routine monitoring work.

This contribution will present the lessons learned from more than 61/2 years (October 2015–June 2022) of continuous seismic monitoring in the the Kivu basin as well as the current status of seismological information derived from these data, including a robust 1D seismic velocity model and calibrated local magnitude scale for the Kivu Rift region. The complete seismicity catalogue (volcanic and tectonic events) has been relocated and the main seismic patterns will be discussed with a special emphasis on how this new knowledge can help the Goma Volcano Observatory in improving its monitoring tasks.

POSTER 79

Seismicity Classification From Eruptions: Analysis of Hawaiian and Aleutian Island Volcanoes

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Volcanic eruptions produce different types of seismic signals, and monitoring these signals is crucial for understanding underlying processes. Associated seismic signals can be classified as volcano-tectonic (VT), long-period (LP), tremor, explosive, tornillo, and hybrid events. Classification using standard and machine learning algorithms are commonly based on features selected in the time and frequency domain. Such features include, for example, dominant frequency band, power spectral density, energy ratios, duration, peak amplitude, and rate of amplitude decay.

Here, we analyze seismicity associated with major eruptive phases of the Kilauea volcano, Hawaii, Okmok, and Akutan volcano, Alaska. Cyclical pressure variation due to recurring inflation and deflation during caldera collapse is likely to influence the associated seismicity. We are motivated to understand how the caldera collapse sequence and the eruption phases influenced the types of seismic events.

We are focusing on spectrogram analysis based on both spectral and temporal characteristics of events for this study. The selected stations are within 5 to 25km from the caldera, to avoid noise and site effects related to volcanic processes. VT events have a clear P and S wave arrivals. Spectrograms and power spectral density show that the frequency range of VT is above 5 Hz and can be up to 30 Hz. LPs show a lack of distinguishable phase arrivals, and durations are longer than those of VTs. The peak frequency of LP is mostly within 5 to 10 Hz.

The sampling rate of the waveforms is 100 Hz. We computed the energy ratio of spectral energy below a threshold frequency of 3Hz, 5Hz, and 10Hz to the total energy. This energy ratio shows a clear bimodal distribution for 5Hz, which helped to differentiate the VT and LP events based on their energy. Tremors are characterized by relatively consistent amplitude and over very long durations and time periods of minutes to hours. We successfully classified VT, LP, and tremors from the seismic events during the eruption period.

POSTER 80

Analysis of the Seismicity Recorded Before the May 22, 2021 Eruption of Nyiragongo Volcano, Democratic Republic of the Congo

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We present an overview of the different seismic precursors of the Nyiragongo volcano eruption on May 22, 2021, as well as a statistical analysis of the seismic swarms recorded during the pre-eruptive period. The analysis of the seismic activity of Nyiragongo volcano during the pre-eruptive period shows that there was a particular seismicity composed of hybrid and/or volcano-tectonic type events that characterized the long-period seismic swarm recorded about a month before the May 2021 eruption. In February 2016, similar seismic activity was observed at Nyiragongo volcano, which led to the opening of a new vent within Nyiragongo's main crater on February 29, 2016, and which remained active until the May 2021 eruption.

During the period from January 2016 to May 2021, the lava lake remained very active with significant fluctuation as evidenced by the Real Seismic Amplitude measurement at Rusayo and Kibati stations. The increase and stabilization of the lava lake to a higher level resulted in an increase and accumulation of stress on the flanks of the volcano since the lava lake had already reached a higher critical level. Whether in January 2016, November 2016 or April 2021, we show that this particular type of so-called hybrid seismic events recorded during a swarm at Nyiragongo volcano could lead to an eruption either inside the main crater (February 2016) or on the flanks in May 2021.

POSTER 81

Seismic Source Scaling of Volcano-Seismic Events: Tracking Magma Plumbing System Overpressure and Volume Through Macroscopic Seismic Source Parameters

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Volcano-seismic resonances are often manifested as long-period (LP), very-long-period (VLP) events, or volcanic tremors. Unlike tectonic earthquakes and low-frequency earthquakes, volcano-seismic resonance reflects magmatic or hydrothermal fluid dynamics occurring at shallow depths during either quiescent or eruptive episodes. Although experimental and numerical simulations have recognized fundamental microscopic dynamics associated with gas-liquid interaction and fluid-solid interaction in the volcano plumbing system, quantitative assessment of the underlying dynamics is often retrospective. Here we explore source scaling relationship for volcano-seismic events from a global perspective and derive a theoretical model to understand such scaling related to overpressure and pressurized volume in magmatic systems, which could provide crucial information in evaluating the state of the system stability and the potential of incoming eruptions.

In this report, we compile macroseismic source parameters, specifically the peak seismic moment rate and the magnitude of single force from volcano-seismic events in 26 active volcanoes, displaying a prominent scaling trend, i.e., 10^{-3}~10^{-4} s/m. Following the framework developed by Nishimura (1998), we devise a generic framework, which relates the system overpressure and pressurization volume to macroscopic seismic source parameters, as well as the acoustic properties of the fluid near the seismic source (i.e., sound speed and density).

We find that the estimated overpressures associated with volcano-seismic events in the 26 active volcanoes ranges in 10^4-10^8 Pa, clustered at ;10^6-10^7 Pa, whereas the estimated volume ranges in 10^3-10^{11} m^3, clustered at ~10^6 m^3 and ~10^8 m^3, respectively. We will discuss the uncertainties associated with the estimated overpressure and volume and how these quantities vary against magma composition, volcanic activities (e.g., magmatic vs. hydrothermal) and the type of volcano-seismic event (e.g., non-destructive vs. eruptive).

POSTER 82

Eruption Dynamics of the 2022 Mauna Loa Eruption Revealed Through Tremor

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Mauna Loa, Hawaii erupted for 12 days in 2022 following nearly 38 years of repose. The eruption began after several years of intermittent unrest, including inflation and earthquake swarms, however the only actionable precursor was approximately one hour of strong seismicity and tremor before the start of the eruption. The eruption started in the summit and eventually migrated into the NE rift zone over approximately three hours, eventually establishing the dominant fissure eight kilometers from the summit. On December 10, the fissure stopped erupting, ending the eruption.

During the eruption, seismic tremor was common and continuous and thus we can use the characteristics of tremor to reveal details of the eruption throughout the sequence. In particular, we use amplitude-based location methods to track changes in vent location and dike propagation. In the precursory phase of the eruption, we find tremor locations throughout the upper 8 km of the volcano and then immediately before the eruption within the upper 4 km of the volcano. Once the eruption starts, tremor depths shallow to the surface and remain stable for 2.5 hours before tremor locations deepen and shift into the NE Rift Zone. Analysis of tremor spectra show the likely presence of two simultaneous source of tremor, one in the summit associated with lava fountaining, and another deeper source associated with dike propagation. Tremor locations further detail dike propagation downrift until the stable fissure, Fissure 3, becomes dominant. Tremor locations cluster around the Fissure 3 vent until the end of the eruption when locations slowly migrate back uprift toward the summit.

POSTER 83

Using Remote Hydroacoustic Recordings to Track Volcanic Unrest Near the Ta'ū Islands, American Samoa

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A seismic swarm near Taʻū Island, a volcanic island in eastern American Samoa, occurred from July to October 2022. The earliest unrest was noted as felt reports in late July, and instrumentation varied in the beginning of the sequence as the Hawaiian Volcano Observatory responded by installing temporary and then permanent seismometers to monitor the activity. The network variability made it difficult to characterize the earliest seismicity and contextualize the entire sequence to discriminate between an underlying tectonic or volcanic source. Here we present results analyzing hydroacoustic detections from International Monitoring System hydrophone arrays near Wake Island, 4500 km northwest of Taʻū volcano. Using least-squares beamforming analysis, we create a catalog of T-wave detections from the direction of Taʻū volcano to track the earthquake rate. Both the rate and hydroacoustic pressures, which we interpret as a proxy for earthquake magnitude, gradually increased from late July to August, peaking on August 19 (rate) and August 24 (magnitude), before gradually decreasing to background in late September. Minutes-long bursts of tremor were also contemporaneously recorded from the moment the permanent broadband seismometers were installed on August 20. Tremor activity continued throughout the rest of August, peaking on August 25, before ending in early September. These tremor bursts were band-limited to ~1-5 Hz and were recorded as S-waves at a distal station on Tutuila Island, 230 km to the west of Taʻū Island. Our preliminary results do not constrain the earthquake or tremor locations (which may not be co-located), but we interpret the increase in earthquake size and rate, together with the occurrence and characteristics of the tremors, to be the result of magmatic activity beneath Taʻū, volcano.

POSTER 84

Inversion of Multiple Concurrent Resonant Oscillations at Kīlauea Volcano During Very-Long-Period Seismic Events Informs Magma System Properties.

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Kīlauea Volcano in Hawaiʻi (USA) is one of the most active and best studied volcanoes in the world. From 2008-2018, it experienced an open-vent eruption at the summit, allowing for the collection of diverse datasets. Thousands of very long period (VLP) seismic events (signals with periods T >2 seconds) were recorded in the summit region throughout this time. These signals have been inferred to signify perturbations in the shallow subsurface motions of melt and gas, which can provide insight into the evolving geometry of the magmatic system and magma properties such as temperature, viscosity, and volatile content. In this study, we focus on two common modes of resonance: a vertical conduit-magma reservoir sloshing mode (T ~35-43 s) and a conduit organ pipe mode (T ~2-4 s), both excited by rock fall events on the lava lake surface. Over timescales of days-weeks, these modes generally exhibit quasi-constant resonant periods, but the quality factor can be highly variable. We interpret this as a change in magma fluid properties, such as temperature or bubble content, within the shallow (<2 km) summit transport system. We invert the two distinct associated resonant modes from individual VLP events with a petrologically-informed model of wave propagation in a multiphase, viscous, stratified magma column representing the lava lake-conduit-reservoir system to seek further constraints on magma properties and transport geometry during that period. We augment seismic data with geodetic constraints on reservoir geometry/pressure and MgO glass thermometry data to constrain the temperature of the lava lake (1151-1158 range, +/- 10 degC), both of which help define the background state of the magma column prior to VLP events. We use footage of the lake surface to confirm the origin of VLP excitation. This approach will provide us with a well-constrained snapshot of the subsurface geometry and magmatic properties at the times of the VLP events, and thus can better inform our understanding of coinciding eruptive processes.

POSTER 85

Seismic Velocity Changes Across Multiple Eruption Cycles at Shishaldin Volcano in the Eastern Aleutian Arc

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Volcanic eruptions can be disastrous, so understanding the development of eruptive activity has significant implications for volcanic monitoring, prediction, and hazard assessment. One of the critical eruptive parameters is the variation of the subsurface structure (e.g., seismic velocities) before, during, and after the eruption. Previous studies have documented three stages of seismic velocity changes at active volcanoes: pre-eruptive decrease, co-eruptive increase, and post-eruptive decrease. Despite these established patterns, some volcanic eruptions deviate from the observed three stages, raising uncertainties about the repeatability of velocity change patterns at the same volcano across different eruptions. In this study, using ambient noise cross- and auto-correlations, we estimate the seismic velocity changes over two decades (2003-2023) at Shishaldin Volcano in the eastern Aleutian volcanic arc, covering four documented eruptions in 2004, 2014, 2019, and 2023. We utilize continuous records from 9 seismic stations to characterize the spatiotemporal distribution of seismic velocity changes based on same-station and cross-station ambient noise correlations. The seismic velocity changes show a notable pre-eruptive increase and co-eruptive decrease associated with the 2014 eruption, which had the most degassing activities among the four eruptions. The velocity changes may reflect the pre-eruptive pressurization and co-eruptive depressurization associated with magma and gas recharge and discharge events. We will compare the velocity change results with changes in surface deformation patterns from geodetic measurements. The results from this study will help us understand the control of eruptive structural changes and the predictability of eruptive activities.

POSTER 86

Seismicity, Ambient Noise Tomography, and Anthropogenic Noise via the Auckland-Hauraki Node Array in New Zealand

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The Northern North Island of New Zealand (including Auckland) is 400+ km from the Hikurangi Plate margin, making it one of the country's most stable regions. However, it features several active faults and experiences regular seismicity. It is also home to the Auckland Volcanic Field, a collection of ~53 monogenic intraplate eruptions with the most recent occurring ~600 years ago (e.g. Hopkins et al., 2021). The region is also home to the Hauraki Rift, an active continental rift widening oblique to the subduction zone at a rate of ~1 mm/yr (Pickle, 2019). Both these features were investigated in mid-2023 via a 50+ station broadband node array (AHNA, X5, 2023), using SmartSolo BD3C-5 instruments recording for ~30 days. Despite historically wet conditions, the nodes were sensitive to periods upwards of ~15 seconds and were able to resolve crustal structure to depths of 25 km via ambient noise tomography. Over 100 earthquakes were also recorded during this occupation, many of which were associated with an earthquake swarm within the Hauraki Rift that began earlier in the year. The network also was able to characterize trends in anthropogenic noise in and around the greater Auckland region.

Seismology in the Oceans: Pacific Hemisphere and Beyond

Oral Session • Thursday 2 May • 8:00 AM Pacific

Conveners: James Gaherty, Northern Arizona University (james.gaherty@nau.edu); Jianhua Gong, Indiana University (gongjian@iu.edu); HyeJeong Kim, University of Utah (hyejeong.kim@utah.edu); YoungHee Kim, Seoul National University (younghkim@snu.ac.kr); Joshua Russell, Syracuse University (jbrussel@syr.edu); Lindsay Worthington, University of New Mexico (lworthington@unm.edu)

Structure of the Cascadia Margin Offshore Northern Oregon (44.5-46deg N) From Casie21-OBS Wide-Angle Seismic Profiles

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The 2021 Cascadia Seismic Imaging Experiment ocean bottom seismometer deployment (CASIE21-OBS) is an NSF- and USGS-supported controlled-source marine seismic survey conducted offshore Cascadia in May-July 2021 (Carbotte et al., in review; Canales et al., 2023, doi:10.1785/0220230010). The main goal of CASIE21-OBS was to collect a modern, open-access wide-angle seismic reflection/refraction dataset that would enable scientists to develop P- and S-wave velocity models of the structure of the accretionary prism and down-going plate along most of the Cascadia margin between northern Vancouver Island and southern Oregon. In this presentation we report 2-D Vp models obtained from traveltime tomography of sedimentary (incoming and accreted), crustal and mantle arrivals recorded along three of the CASIE21-OBS profiles (PD10, PD12, and PD13). These profiles cross the Cascadia margin offshore northern Oregon between latitudes ~44.5°-46°N in a region that includes the offshore northern edge of the Franciscan terrane and variable offshore extension of the Siletz terrane —both of which are thought to play a role in the deformation characteristics of the accretionary prism and the geometry and deformation of the subducting Juan de Fuca plate (JdF)— as well as a transition from seaward to landward vergence near ~45°N. Profile to profile, our models document important along-strike variability in continental platform seismic velocities arising from the presence/absence of the accreted volcanic terranes. Profile PD13 in the seaward-vergent section of the margin shows more complex and heterogeneous seismic structure in both crustal and accreted sediments when compared to landward-vergent profiles PD10 and PD12. We tentatively attribute this difference to prevalence of fluid drainage fracture networks traversing the down-going JdF crust and slope sediments in seaward-vergent regions compared to stratigraphic-dominated fluid migration patterns in landward-vergent regions (e.g., Johnson et al., 2006, doi:10.2973/odp.proc.sr.204.125.2006).

A Newly Identified Mass-Transport Deposit in the Guaymas Basin, Gulf of California: Implications for Regional Tectonics and Continental Slope Stability

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We report a significant mass transport deposit (MTD) in the southeastern Guaymas Basin, central Gulf of California, Mexico, which is a young marginal rift basin characterized by active seafloor spreading. We interpret 16 high-resolution seismic reflection profiles across the E-SE basin margin. Within these data we identify an ~85-m-thick, wedge-shaped unit with a dominantly transparent seismic reflection character, though containing some small packages of laterally discontinuous reflectors, and a bumpy upper surface. We interpret this unit to be a MTD that originated from the Yaqui Delta region of the Sonoran margin and infer that a combination of high sedimentation rate and active tectonics contributed to the MTD event. The presence of buried 'flower structures' within the data indicates that the MTD buried part of the transform fault separating Guaymas Basin and the continental Sonoran margin. The MTD appears to have occurred near the transform/spreading-center intersection. That intersection and the axial graben, the surface expression of extension, have since jumped northwestward, apparently in response to the MTD emplacement, creating a second, northern seafloor graben, where previously there had only been one in Guaymas Basin. The MTD extends to the NE margin of the northern graben, thins to the SE of the basin, partially fills the southern graben, and has been faulted and overlain by younger sediments since emplacement. These inferences are based on a geological and structural interpretation of ~708 km of high-resolution multichannel seismic reflection data. We estimate the area and volume of the observed MTD to be 3346 km^2 and 303.3 km^3, respectively. Our results contribute to the understanding of the tectonic evolution of the Guaymas Basin and provide new insights into the interaction between continental slope failure at active continental margins, spreading-center tectonics, and high flux of sediment transport into this young spreading system in the Central Gulf of California.

Implications of Multi-Layer High-Vp/Vs Seafloor Sediments Characterized Using Passive Ocean Bottom Seismic Data: Toward Improving Crustal and Mantle Structure Analysis

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Body-wave analysis of the sub-oceanic crust and mantle structure is often challenged by the response of seafloor sediment layers that overwrite propagating body waves. Kim et al. (2023; JGRse) introduced a novel method to characterize the in-situ structure of the seafloor sediment using teleseismic body waves recorded by ocean bottom seismometers (OBSs). The method resolves the impedance and the Vp/Vs value of each sediment layer, which is important in predicting the strength of the shallow layer reverberations. We show that a single layer model explaining PS-P time and a multi-layer model from the new method show different waveforms in both high- (~1 Hz) and low-frequency (< 0.3 Hz) ranges.

We apply the methodology to data from various OBS arrays in the Pacific to estimate in-situ sediment structures. The sediment models show multiple layers in some regions, including the top water-saturated layer with low S-wave velocity and high Vp/Vs values. The scaling relationship of Vp/Vs to Vp shows higher values than the previously discussed ones (e.g., Brocher, 2005; Hamilton, 1979). Furthermore, the sediment layer model constrained from the body waves exhibit agreement in predicted Rayleigh wave admittance with the sediment model from the Rayleigh wave admittance (Bell et al., 2015). In this presentation, we will discuss how the in-situ high-Vp/Vs multilayer sediment model differs in predicting the reverberation effects on receiver function analysis for ocean bottom seismometers. Additionally, we will discuss the potential of integrating Rayleigh wave admittance into our body wave approach to enhance the resolution of crust and mantle structure at depths.

Estimating the Extent of Low-temperature Ductile Deformation in the Lithosphere Using Seismic Anisotropy Measurements Around the Alpine Fault

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How strong is the lithosphere? This simply posed question is central to our understanding of active tectonics, but the answer is not at all simple. Laboratory experiments extrapolated to geologic conditions typically indicate that at temperatures below ~600°C, the lithosphere is strong and deforms in the brittle regime. However, recent novel experiments and dislocation mobility models have suggested that the lithosphere can undergo ductile deformation at relatively low temperatures (<600-800°C). Reconciling these experimental results with geodynamic models indicating that the generation and maintenance of plate boundaries requires a strong lithosphere remains a fundamental challenge for plate tectonic theory. Here, I present preliminary results using seismic anisotropy as a proxy for viscous strain to investigate how the lithosphere deforms at low temperatures around the Alpine Fault in South Island, New Zealand. Previous studies in this region have shown that viscous strain associated with relative motion across the Australia-Pacific plate boundary is accommodated in a zone up to 200 km wide, but have not been able to determine whether that deformation is occurring in the lithosphere or in the warmer asthenosphere due to limited spatial and/or depth resolution. I use existing data from GeoNet stations and a temporary ocean bottom seismometer deployment to calculate receiver functions with harmonic-percussive separation and dereverberation filters to mitigate high noise levels, and apply harmonic decomposition to constrain azimuthal anisotropy in the lithosphere-asthenosphere system across and around the South Island. Receiver functions provide information on local structure beneath each instrument, making it possible to map spatial variations in anisotropy attributed to viscous deformation around the Alpine Fault.

Crustal and Uppermost Mantle Structure North of the Gloria Fault Inferred From OBS-Recorded Surface Waves

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The DOCTAR array encompassed 12 broadband Ocean Bottom Seismometers (OBSs) that operated on the seafloor for ~1 year north of the Gloria fault, at the African-Eurasia plate boundary in the north Atlantic. The array had short inter-station distances of 10-20 km and aimed mainly at the application of array techniques to teleseismic data and to study the seismicity of the Gloria fault. However, the data recorded by this array can also be used to study the shallow Earth structure. Here, we analysed the dispersion of surface waves from both ambient noise (short periods, <14 s) and from teleseismic earthquakes (longer periods, > 14 s). Based on the inferred surface wave dispersion observations, we then computed first a 1D vertically layered model for the entire region, and subsequently a 3D laterally varying model of S-wave velocities.

The 1D Vs model shows a top layer of sediments with a low Vs of 1.05 km/s; this low velocity is in agreement with previous observations for the region and likely results from the presence of water in the sediments. Below the sediments, Vs increases in the crust from 3.3 to 4.5 kms. We find an unusual high velocity of 4.9 km/s in a 20 km thick layer at depths between 16 km and 36 km. We suggest that this unusual fast velocity indicates the presence of harzburgite, which is formed as a residue of enhanced mantle melting. We hypothesize that such enhanced melting might have resulted from the proximity between the slow-spreading mid-Atlantic ridge and the Azores mantle plume. A low-velocity zone is then found deeper, at 70 km depth, which we associate with the LAB. The 3D models shows that the shallow crustal is mostly horizontally layered below the DOCTAR array. However, it also shows some small-amplitude oscillations of the crustal structure.

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Overthickened Lithosphere Beneath the Blanco Transform Faults

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The complex interaction between mid-ocean ridges and oceanic transform faults demands validation of the half-space cooling model for the thermal evolution of oceanic lithosphere at the ridge-transform systems. Seismic tomography is key for accurately deciphering the lithosphere structures in the transform faults. Thanks for the unprecedented opportunity provided by an ocean-bottom seismometer experiment at the Blanco Transform Faults (BTF) of the northeastern Pacific, here we present a three-dimensional seismic velocity tomographic model of the lithosphere and top asthenosphere beneath this fault system. We carried out data pre-processing of the OBS data by removing the tilt and compliance noises for the vertical-component waveforms, correcting for the clock drift via an improved noise cross-correlation function method, verifying the polarity of the vertical component and determining the horizontal orientations via a phase-tracking method. We then extracted dispersion measurements from teleseismic Rayleigh waves and the empirical Green's functions retrieved from ambient noise, as well as the amplitude ratio between the radial and vertical components (H/V ratio) of Rayleigh waves. These measurements were applied to a jointly inversion of phase-velocities and H/V ratios for the S-wave velocity model via surface-wave tomography and a Bayesian Monte Carlo method. The most shocking finding in the model is that high velocities dominate the uppermost mantle of the eastern BTF. We attribute the velocity variation in the mantle primarily to temperature variation and establish new isotherms along the BTF. Unlike previous studies, our 600°C isotherm well correlates the depth extent of earthquake sources beneath the whole BTF. The lithosphere-asthenosphere boundary beneath the eastern BTF indicated by the model-predicted 1200°C isotherm is deeper than that derived from the half-space cooling model. Our results suggest the lithosphere had been thickened for millions of years prior to the formation of a mature oceanic transform system.

The Anelastic Fingerprint of Small-Scale Convection: Grain-Size Reduction in Pacific Asthenosphere Revealed by Regional Shear Attenuation

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The cooling and thickening of oceanic lithosphere as it spreads from the mid-ocean ridge is fundamental to plate tectonics, and the base of this thermal boundary layer represents one of the largest temperature gradients in the planet. Yet, the thermo-mechanical processes that occur below the plate as it interacts with the warmer low-viscosity asthenosphere are still debated, especially at intermediate and old ages. If dynamic processes are present, they should impact the asthenosphere's physical state (temperature, grain size, viscosity, melt fraction) and be seismically observable using regional datasets.

Here, we use Rayleigh waves recorded on broadband ocean-bottom seismometers to constrain profiles of shear attenuation and velocity through the asthenosphere at three experiments in the central and southwest Pacific representing intermediate age (~40–90 Ma) oceanic plate. At all three locations, we observe a high-attenuation peak (low Q_μ) centered at 100–150 km depth corresponding with the low-velocity zone. Two experiments located in the south Pacific display remarkably high attenuation (Q_μ ~ 25–35)—among the highest observed to date beneath ordinary oceanic plate—and both locations exhibit lineations in the gravity field. The magnitude of the attenuation peak varies between sites but does not simply covary with seafloor age, suggesting heterogeneity in dynamic processes within the low-viscosity zone beneath the Pacific plate that persist to at least ~90 Myr.

By jointly inverting our observations within a Bayesian framework that considers melt stability and uses laboratory-derived relations for mantle anelasticity from the Very Broadband Rheology calculator (VBRc), we show that the high-attenuation, low-velocity zone can be explained by grain-size reduction (≤ 5 mm) consistent with active deformation within a low-viscosity channel. This channel is also damp (~150–500 ppm H_2O) and contains low-degree partial melt (< 0.3%). We consider a ~50 km thin layer of remarkably high attenuation in the asthenosphere to be an anelastic hallmark of sub-lithospheric small-scale convection.

An Ocean-Bottom View of Mantle Convection Beneath the Pacific Basin

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The Pacific basin provides an outstanding natural laboratory to study a range of tectonic and upper-mantle dynamic processes, including seafloor spreading, midplate volcanism, and multiscale thermal convection. Historically, geophysical insights into these processes were limited to low-resolution, long-wavelength imaging due to the restriction of instrumentation to continents and islands. Recent advances in ocean-bottom seismometry have now enabled high-resolution investigation of these processes using localized (few 100s-km aperture) broadband arrays. We present emerging results from the ORCA (OBS Research into Convecting Asthenosphere) project, comprising two 12-month seismic arrays in the central and southwest Pacific. ORCA was designed to image upper-mantle wavespeeds in two regions where satellite-derived gravity variations display linear structures suggestive of small-scale upper-mantle convection, one at intermediate plate age (30-40 Ma), and one at old plate age (90 Ma+). At the younger site, we find linear blobs of fast and slow material (~250–300 km wavelength), parallel to the gravity features, that we infer to represent cold sinking and warmer rising material beneath the plate. Preliminary results from the older site show similar velocity heterogeneity, but perhaps less linear structure and longer wavelength (>400 km). Both regions are characterized by a narrow (50–75 km), low-velocity (~4.2 km/s), low-Q (~25–35) asthenosphere, suggesting grain-size reduction combined with a small amount of partial melt (<0.3%) play an important role in controlling rheology. Seismic anisotropy varies strongly within and between regions, with distinctive variations with depth that suggest regional differences in the scale and strength of deformation controlled by seafloor spreading, lithosphere-asthenosphere coupling, and pressure- and temperature-driven asthenospheric flow. By combining these results with previous analyses from across the Pacific, we are gaining an improved understanding of the processes controlling the formation and evolution of the ocean plates and the highly dynamic convective system beneath them.

Deep Learning for Deep Earthquakes in Oceans: Insights From Obs Observations of the Tonga Subduction Zone

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Applications of machine learning in seismology have greatly improved our capability of detecting earthquakes in large seismic data archives. Most of these efforts have been focused on continental shallow earthquakes, but here we introduce an integrated deep-learning-based workflow to detect deep earthquakes recorded by a temporary array of ocean-bottom seismographs (OBSs) and land-based stations in the Tonga subduction zone. We develop a new phase picker, PhaseNet-TF, to detect and pick *P*-,*S*-, and *PS*-wave arrivals in the time-frequency domain. The frequency-domain information is critical for analyzing OBS data, particularly the horizontal components, because they are contaminated by signals of ocean-bottom currents and other noise sources in certain frequency bands. PhaseNet-TF shows a much better performance in picking *S* waves compared to its predecessor PhaseNet. The predicted phases are associated using an improved Gaussian Mixture Model Associator GaMMA-1D and then relocated with a double-difference package teletomoDD. We further enhance the model performance with a semi-supervised learning approach by iteratively refining labeled data and retraining PhaseNet-TF. This approach effectively suppresses false picks and significantly improves the detection of small earthquakes. The new catalog of Tonga deep earthquakes contains more than 10 times more events compared to the reference catalog that was analyzed manually. This deep-learning-enhanced catalog reveals Tonga seismicity in unprecedented detail, and better defines the lateral extent of the double-seismic zone at intermediate depths and the location of 4 large deep-focus earthquakes relative to background seismicity. The newly picked arrivals offer new potentials for deciphering deep earthquake mechanisms, refining tomographic models, and understanding subduction processes.

Earthquakes and Slab Morphology in Southern Mariana and Yap Subduction Zones

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The Southern Mariana and Yap subduction zones have attracted enormous attention of scientific investigators and explorers during recent decades. Since late 2016, near-field active and passive source seismic experiments has been carried out by deploying Ocean Bottom Seismographs (OBS) in various terms. Both active and passive source tomographic images clearly indicate a well hydrous incoming Pacific plate, which is consistent with the observed pervasive normal faults in the out-rise region. Numerous earthquakes have been detected from the OBS recordings, and their locations delineate the subducting plate as well as deep out-rise faults. The slab geometry in southern Mariana shows significant along-trench variations, with earthquake depths ranging from 120 to 240 kms. In comparison, the slab beneath the Yap trench exhibits a steep dip angle, with earthquakes concentrated in depths less than 80 km. The contrasting slab morphology in southern Mariana and Yap is likely resulted from subduction of the Caroline ridge, a buoyant oceanic plateau that was formed during Oligocene-Miocene. After collision with the trench, the subducting slab beneath the Yap trench gradually steepened. However, the dip angle of the slab beneath southern Mariana is relatively gentle, possibly due to the oblique subduction direction.

Seismology in the Oceans: Pacific Hemisphere and Beyond [Poster Session]

Poster Session • Thursday 2 May

Conveners: James Gaherty, Northern Arizona University (james.gaherty@nau.edu); Jianhua Gong, Indiana University (gongjian@iu.edu); HyeJeong Kim, University of Utah (hyejeong.kim@utah.edu); YoungHee Kim, Seoul National University (younghkim@snu.ac.kr); Joshua Russell, Syracuse University (jbrussel@syr.edu); Lindsay Worthington, University of New Mexico (lworthington@unm.edu)

POSTER 23

Upper Mantle Velocity Structure Beneath the Galapagos Archipelagos From the Analysis of Pn Wave Recorded by Broadband Seismic Instruments and Mermaids

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Over the past two decades, global scale seismic velocity models have improved thanks to increased seismic station density and advancements in high-performance computing infrastructure and algorithms. However, the oceanic domain, accounting for 3/4 of the earth's surface, shows lower resolution in comparison to the continental domain. The deployment of Mobile Earthquake Recorder in Marine Areas by Independent Divers (MERMAIDs) around the Galapagos in 2014 and in the South Pacific in 2018-2019 demonstrated the potential of this new generation of data acquisition in the Ocean and their ability to generate reliable seismic data. To map the extension of the Galapagos mantle plume beneath the oceanic crust, we merged data from eight MERMAIDs and broadband seismic stations. This improved the resolution of the seismic velocity model and expanded data coverage throughout the ocean domain. We use travel times of refracted waves Moho from regional shallow events (<40 km) with epicentral distance between 2° and 16°and Mw>5.5 to image the 3-D uppermost mantle velocity structure. This contribution will highlight the new Pn velocity anomalies maps and compare them with recent models like the Regional Seismic Travel Time model. We will discuss the potential and limitations of our approach, specifically in regards to data selection and modeling. Additionally, we will discuss geodynamic implication associated with the Galapagos mantle plume and its interaction with the spreading ridge.

POSTER 24

Seismic Structure of the Young Oceanic Cocos Plate From the Ridge to the Trench Axis Offshore the Mexico Subduction Zone

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Characterizing the seismic structure of oceanic plates is crucial for assessing hazards in subduction zones, including earthquakes and volcanic eruptions. Moreover, it also contributes to our understanding of biodiversity and the evaluation of resources in proximity to the ridge axis or seamounts. Several key locations globally present a unique opportunity to investigate the evolution of oceanic plates from accretion to subduction at the trench axis along a single seismic profile with consistent acquisition parameters and processing schemes. Here, we focus on two active-source seismic profiles acquired in 2022 aboard the R/V *Langseth* as part of the ¡ME GUSTA! Seismic Experiment. These profiles explore the region from the East Pacific Rise to the trench axis offshore of the Guerrero seismic gap—an area that remains largely unexplored. These profiles, acquired with slightly different orientations to follow a flow line, sample a 0-12.5 Ma oceanic crust accreted at fast to ultra-fast spreading rates. The processing of the multibeam and the multichannel seismic data allows for the characterization of a very thin sediment cover (< 50m), small changes in basement roughness, and intraplate features such as a small rift. Velocity models from traveltime tomography of the 15-km long streamer data reveal reduced upper crustal velocities near the ridge axis between 0 and 2.5 Ma, attributed to vigorous hydrothermal circulation. Farther away from the ridge axis and flanks, upper crustal velocities increase due to the closure of pores and precipitation of hydrous minerals and are very similar to the global average. A modest reduction in velocity in the bending area suggests slight reactivation of favorably oriented abyssal hill faults, consistent with slightly higher fault throws measured approaching the trench axis. We propose that the reactivation of abyssal hill faults is only modest due to the inherent weakness of the young Cocos crust. Comparison with other young plates such as the Juan de Fuca plate will allow us to further refine our understanding of accretionary and evolutionary processes.

POSTER 25

Adjoint Waveform Tomography of the Cascadia Subduction Zone Using CASIE21 Controlled-Source Data

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We apply adjoint waveform tomography to CASIE21-OBS data to produce a 2D velocity model crossing the seismogenic zone of the Cascadia Subduction Zone offshore Washington. Cascadia is capable of producing large (M~9) earthquakes and tsunamis. Slab and velocity models exist for Cascadia, but, prior to the 2021 controlled-source Cascadia Seismic Imaging Experiment (CASIE21), higher-resolution models were restricted to a few profiles or small 3D volumes. Regionally comprehensive 3D models also exist, but are generally low resolution and/or inaccurate, particularly under the submarine forearc where variations in shallow fault structure and material properties can have significant effects on earthquake rupture. CASIE21 airgun shots along profiles crossing the submarine forearc offshore Oregon, Washington, and Vancouver Island were recorded by a towed streamer, ocean-bottom seismometers (OBS), and onshore seismic arrays. We tested the feasibility of applying the SPECFEM code's adjoint waveform tomography capability to image Vp and Vs using these controlled-source data. Here, we show results from a 2D test case using OBS data. Sensitivity kernels calculated from first-break traveltime delays show strongest sensitivity at basement depths, and up to ~15 km depth in the seismogenic zone. After a preliminary inversion, travel times of first-break phases were ~16% more consistent with OBS data compared to a velocity model based on the streamer data alone. Future targets include an inversion of amplitudes from several seismic phases and their reverberations, comparison with results from conventional wide-angle traveltime tomography, and 3-D application using more lines from CASIE21.

POSTER 26

Seismicity of the Atlantis Massif Oceanic Core Complex: 2005-2006 OBS Data Revisit

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An oceanic core complex (OCC) forms through the exhumation of lower-crustal and upper-mantle rocks on the seafloor via slip on detachment faults rooted below mid-ocean ridges. Due to the challenges of seafloor observation, few studies have investigated dynamic processes of OCC at depth, such as hydrothermal circulation, faulting, and magmatic activities. The Atlantis Massif OCC, situated at approximately 30°N, 42°W along the Mid-Atlantic Ridge, was monitored by a network of five ocean bottom seismometers (OBS) from 6/5/2005 to 3/25/2006. In this study, we leverage recent advancements in machine-learning methods for earthquake detection and location to reprocess the OBS data, aiming to gain insights into magmatic, faulting, and fluid flow processes beneath the OCC.

We implement a machine-learning-enabled workflow using four open-source software to detect and locate microseismicity at Atlantis Massif OCC. PhaseNet, a deep-neural-network-based seismic arrival time picking method, returned over 100,000 picks for both P and S phases for four stations. Nearly 160,000 total phase picks were then used by GaMMA, a machine-learn phase associator, to associate phases with seismic events. Only events with more than seven total P and S picks are saved, which results in 31,118 associated events. COMPLOC was used for earthquake location, yielding ~25,700 locatable events. The vast majority of events located in this stage appear to be under the Mid-Atlantic Ridge valley between 5 and 13 km depth, with a fair number of events located under the oceanic core complex itself. Relative relocation of earthquake hypocenters based on waveform cross-correlation data was performed using GrowClust to refine initial location estimates and determine clusters of events. Two main sequences of events along the ridge can be observed and account for about 35.5% of the total events. Our preliminary location result is consistent with previous study of Collins et al, 2012, but has more than two times of total events. We will first focus on the two main sequences along the ridge to understand faulting and magmatic activities at the OCC-ridge system.

POSTER 27

P-Wave Anisotropic Velocity Model of the Galápagos Plume

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The Galápagos plume and nearby spreading center create a novel setting to study how hot mantle plumes interact physically and chemically with mid-ocean ridges. This area is well studied geochemically, geophysically, and geodynamically (e.g., Schilling, 1982; Hooft et al., 2003; Ito & Bianco, 2014). Geodynamic models reproduce many aspects of the region, but there remain discrepancies between observations and geodynamic predictions. The IGUANA teleseismic experiment (1999-2003) used 12 seismometers on the islands to image the plume and found anomalously low Vs material that near 200 km depth, well below the thermal lithosphere, tilts northward toward the spreading center (Villagómez et al., 2014). This is not predicted by geodynamic models and may be driven by pressure gradients or small-scale convection in the asthenosphere. However, features consistent with S-wave imaging results are notable absent from unpublished isotropic P-wave tomography models. One possible explanation is the trade-off between thermally-induced velocity variations that can reduce seismic velocities and mantle upwelling that can increase seismic velocities for vertically traveling P waves. Here, we analyze the IGUANA data to determine if including seismic anisotropy in the tomographic inversion produces P-velocity models consistent with prior S-wave imaging. We jointly invert cross-correlated P and S delays for hexagonal anisotropic elastic parameters with an arbitrarily oriented symmetry axis. By leveraging both datasets and accounting for the anisotropic properties of the mantle, we aim to better constrain the geometry of the Galápagos plume and associated mantle flow field.

POSTER 28

Shear Wave Velocity Structure of the Upper Mantle Beneath the Oldest Pacific Seafloor Revealed by Finite-Frequency Traveltime Tomography

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This study presents the first three-dimensional S-wave velocity structure of upper mantle beneath the oldest Pacific seafloor using finite-frequency traveltime tomography. We use teleseismic records from the Oldest-1 experiment, which deployed eleven broadband ocean-bottom seismometers on the oldest Pacific baisin in the west Pacific. We measure relative traveltime residuals of the traverse S waveforms filtered at three frequency bands between 8–32 s, using a multichannel cross correlation method. The obtained S-wave traveltime residuals show peak-to-peak variations of ±3 s across the array. S tomography results reveal S-wave velocity anomalies ($\delta \ln V_S$) ranging within ±6%. We find a fast-V_s anomaly at depths of 100–190 km beneath eastern part of the array. Additionally, slow-V_s anomalies are found to the southwest and northeast, at approximately 100–250 km and 100–300 km in depth, respectively. The overall distribution of slow- and fast-velocity anomalies of S tomography model is found similar with P tomography model. Our preliminary V_p/V_s model shows elevated V_p/V_s values ($\delta \ln(V_p/V_s) > 2\%$) for the slow-Vs anomalies, whereas relatively moderate V_p/V_s values ($\delta \ln(V_p/V_s) = 1–2\%$) are found for the fast-V_s anomaly. The differences in V_p/V_s may imply compositional variation of upper mantle across the Oldest-1 array site.

POSTER 29

A New 3D Reference Velocity Model for Offshore Cascadia Based on CASIE21 Data

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We developed a new 3D reference velocity model for the offshore portion of the Cascadia Subduction Zone based on controlled-source seismic data from the 2021 Cascadia Seismic Imaging Experiment (CASIE21). This initial model has two main goals: (1) provide a next-generation 3D velocity model of the submarine forearc and shallow subducting plate and (2) prototype a 3D model building approach that can integrate constraints from a variety of mostly-2D, controlled-source seismic datasets. The input constraints to this initial model are CASIE21 2D Vp models built for pre-stack depth migration of ultra-long offset multichannel seismic data. The 3D model is constructed by defining velocity and surface geometry control points and then interpolating between them. Surfaces are interpolated first and then used to guide 3D interpolation of velocities. Selection of the control points is inherently subjective, but the model building process itself is automated, enabling objective and quantitative evaluation of control point quality and influence on the 3D model via validation tests (e.g. travel-time misfits). Interpolation can use conventional (e.g., kriging) and/or machine learning (e.g., random forest and neural network) methods. Output models consist of surface and material meshes with material parameter values and geostatistical uncertainties assigned. Meshes can use different geometries (e.g., tetrahedral, hexahedral) and have uniform or variable resolutions, depending on the interpolation method. Currently, efforts are focused on Vp modeling, but a future model could expand to other material parameters (e.g., Vs, density, resistivity). Output meshes can be produced in common formats (e.g., VTK) with the resolution and mesh geometry needed for specific applications (e.g., travel-time tomography, waveform modeling, ground-motion simulation).

POSTER 30

Seismicity Observation in the Oldest Pacific Plate Using Pacific Array (Oldest-1) Data

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The oldest part of the Pacific plate (the "Pacific triangle"), located approximately 900 km east of the Mariana Trench, has been considered the most stable oceanic intraplate region due to its age (~170–180 Ma). Seismic records recorded by the Oldest-1 Array, consisting of 11 broadband ocean bottom seismometers (BBOBS) and 12 pressure gauges, provide a great opportunity to investigate the stress state in the old oceanic lithosphere from the local to regional seismicity in the oldest Pacific. Although the array geometry is originally designed to probe upper-mantle seismic properties, high-quality BBOBS data (Kawano et al., 2023) made the detection and location of microseismicity possible. In this study, we present a one-year catalog of intraplate seismicity that includes 17 earthquakes with mb(Sn) magnitudes ranging from 0.9 to 3.7 in and around the array. This earthquake records can serve as an important dataset to clarify the relationship between seismicity, tectonic stresses and geological setting in the oldest Pacific.

Based on locations, a total of 17 events are grouped into two with one group of ten events and the other of seven. The first group of ten events forms two clusters with five events per group. One cluster shows a high degree of waveform similarity (correlation coefficient exceeding 0.92), and their epicenters are located in close proximity to 200-300 m high knolls with the location uncertainty of 100 m. The other cluster is located 16 km apart from the Ogasawara fracture zone, but aligns closely with its strike. Seven earthquakes for the second group are sparsely populated within the array; in particular, three events exhibit clear T-phase and are located near seamounts which might contribute to the T-phase excitation. Although the seismicity is low overall, their spatial scattering and clustering might suggest meaningful correlations between the seismicity and preexisting zones of weakness or geological features on the seafloor.

POSTER 31

The Upflow Experiment: Data Report for 49 Ocean Bottom Seismometer Deployment in the Azores-Madeira-Canaries Region, Atlantic Ocean

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UPFLOW has been one of the largest ocean bottom seismometer (OBS) experiments targeting mantle upwelling so far. Its goal is to constrain upward mantle flow, which is crucial to understanding global mantle flow. UPFLOW deployed 50 and recovered 49 OBS in a ~1,000 x 2,000 km^2 area in the Azores-Madeira-Canaries region with an average station spacing of 150-200 km,starting in July 2021 for ~13 months. The experiment included institutions from five different countries: Portugal (IPMA, IDL, Univ. of Lisbon, ISEL), Ireland (DIAS), UK (UCL), Spain (ROA) and Germany (University of Potsdam, GFZ, GEOMAR, AWI). Most of the instruments had three-component broadband seismic sensors (mostly T~120 s) and hydrophones, but three different designs of OBS frames were used. Our analysis shows 94% data completeness and overall high-quality data, notably a substantial noise decrease in vertical component long-period data (T>30s) compared to previous experiments. Horizontal component data show reasonable quality, enabling the estimation of seismometer orientations using body and surface waves from 149 earthquakes. Earth's free oscillations with frequencies as low as ~1.8 mHz following two Mw > 8 earthquakes are observed on vertical components, after applying tilt and compliance corrections they are visible at nearly all sites. We show illustrative recordings of teleseismic and local events, and non-seismic signals (whales, instrument resonances)., demonstrating the potential of the UPFLOW dataset to address many outstanding questions not only in solid Earth sciences but also in oceanography and marine biology.

POSTER 32

Using Deep Learning Algorithms to Study Seismicity Changes Preceding and Following the 2021 Central Hikurangi Slow Slip Event, New Zealand

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Slow Slip Events (SSEs) are aseismic events that release strain built up along faults. Resolving the mechanisms that drive these events and understanding the physical changes they cause to a fault zone, are important in improving our forecasts of when a fault will fail. Subduction zones around the Pacific regularly host SSEs of varying magnitudes and recurrence intervals, but offshore seismic and geodetic instrumentation is required to appropriately characterise their occurrence. The PULSE project (Physical processes UnderLying Slow Earthquakes) aims to better understand the processes driving slow slip by building a 2-year microseismicity catalogue offshore New Zealand on the Hikurangi subduction zone. This will allow us to observe and characterise the physical changes to a fault zone prior and following slow earthquakes. The PULSE network consists of 55 onshore (48 seismic, and 7 geodetic) instruments, and 26 offshore (10 seismic and 16 geodetic) instruments and is focused on the Pōrangahau region in the central Hikurangi, where SSEs occur approximately every 5 years. This dense PULSE Network will allow us to generate a high resolution, high precision microearthquake catalogue spanning the slow-slip and inter slow-slip period.

To build the catalogue, we employ the deep learning automatic earthquake picker EQTransformer (Mousavi et al., 2020) to pick the data. The picks are then associated into distinct events by GaMMA (Zhu et al., 2022). These events are then first absolutely located with NonLinLoc (Lomax et al., 2010) and relatively relocated with GrowClust3D (Trugman et al., 2022). We target the Pōrangahau SSE that occurred between May-June 2021. The national GeoNet network finds ~500 earthquakes in our deployment region over the SSE period. We can resolve over 4 times as many seismic events and are able to resolve seismicity offshore near to and underneath the slip patch. This has allowed us to better understand how seismicity evolves preceding and following SSE activity, with increases in seismicity occurring concurrent with SSE onset and movement of seismic activity across the SSE period.

Six Decades of Tsunami Science: From the Source of the 1964 Tsunami to Modern Community Preparedness

Oral Session • Thursday 2 May • 2:00 PM Pacific

Conveners: Dmitry Nicolsky, University of Alaska Fairbanks (djnicolsky@alaska.edu); Anthony Picasso, Alaska Division of Homeland Security & Emergency Management (anthony.picasso@alaska.gov); Barrett Salisbury, Alaska Division of Geological & Geophysical Surveys (barrett.salisbury@alaska.gov); Elena Suleimani, University of Alaska Fairbanks (ensuleimani@alaska.edu)

The 2021 Antarctic (South Sandwich) Tsunami as Recorded in the North Pacific

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On 12 August 2021, a major earthquake occurred in the Antarctic sector of the Atlantic Ocean near the South Sandwich Islands. This was a complex event that was initially reported as a magnitude 7.5 at 18:33 UTC at a deep depth of 47 km followed, three minutes later, by a M_w 8.1-8.3 main shock due to rupturing of the shallow subduction zone. The main shock generated a global tsunami that spread throughout the World Ocean, where it was recorded at such remote regions as Kamchatka, the Aleutian Islands, Alaska and British Columbia roughly 17,000–18,000 km from the source area. To examine this event, we used data from a number of coastal tide gauges located within these regions, along with data from 14 DART stations in the North Pacific and 9 ONC NEPTUNE cable stations offshore of Vancouver Island. The first tsunami waves arrived at the southern coast of British Columbia (BC) about 23 h after the earthquake and at the northern coast of BC and southeastern Alaska about 1.0-1.5 hours later. Our numerical model simulations of the event based on the known seismic parameters and Okada's equations agree remarkably well with the open-ocean DART and ONC records, including the recorded tsunami wave amplitudes and periods. This case clearly demonstrates that even highly distant tsunamigenic events with source areas located in remote

oceanic regions can reach the coasts of Alaska and British Columbia and be reliably reproduced by the modern numerical models.

Re-evaluating Global Threat of Tsunamis Generated by Air-pressure Waves from Volcano Explosions

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The eruption of Hunga Tonga-Hunga Ha'apai (HTHH) on January 15, 2022, unexpectedly triggered a global tsunami. While the waves had a significant impact along Pacific coasts, they were also detected at gauges worldwide, extending beyond the Pacific region. A similar phenomenon occurred globally on August 27, 1883, when the Krakatau explosion generated one of history's most devastating tsunamis, which was observed and recorded across the world.

Both these global tsunamis were partly caused by air pressure waves resulting from the volcanic eruptions. The HTHH tsunami provided valuable observational data, enabling a thorough quantitative assessment using modeling techniques. Tsunami models, constrained by atmospheric pressure wave (Lamb waves) measurements demonstrated very good comparisons with sea-level recordings globally. We apply the modeling expertise obtained from the analysis of the HTHH volcanic tsunami generated by the air-pressure waves to re-examine the global tsunami generation by the Krakatau volcano. Analyzing these events lays the groundwork for evaluating the potential threat posed by this new type of tsunami, which volcanoes and other large-scale explosive events could produce.

Multi-Scale Geophysical Characterization and Tsunami Modeling of Active Listric Normal Faults Offshore Grays Harbor, Wa

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Understanding the role of upper plate crustal faults in subduction zone strain accumulation and release is fundamental to improving earthquake and tsunami hazard characterization and risk mitigation. Here we take a closer look at a series of active listric normal faults located ~70 km offshore NW of Grays Harbor, Washington, to determine how these structures accommodate strain and how they may contribute to earthquake and tsunami hazards along the coast. We provide new constraints on the shallow structure and activity of these faults and use these observations to develop a suite of tsunami models that capture a range of possible rupture scenarios including those with and without megathrust rupture.

Analysis of multibeam bathymetry and high-resolution sparker and chirp seismic data collected between 2017 and 2023 document two areas of active faulting near the heads of Quinault and Grays canyon with individual fault trace lengths between 5 and 25 km. The faults are characterized by distinct seafloor scarps (heights ranging from 23-57 meters) cutting across the outer shelf and upper slope in water depths ranging from 160-600 meters. Interpretations of crustal-scale seismic data suggest these structures go listric at shallow depth (~3-4 km). We explore the tsunamigenic potential of these faults using estimates of fault rupture area derived from a combination of near-surface and crustal-scale seismic data. Preliminary GeoCLAW models of tsunami propagation and inundation resulting from listric normal fault sources predict maximum wave amplitudes along the coastline of less than one meter, with arrival times varying from 35 to 55 minutes. However, the modeled tsunami impacts from the listric fault source are overshadowed by those from megathrust sources. While these listric faults alone may not pose a significant tsunami hazard to coastal Washington, their presence may reflect repeated large-scale co-seismic seaward motion of the outer wedge, enabling large amounts of shallow slip and tsunamigenesis similar to that observed during the 2011 Tohoku earthquake in Japan.

Real-Time Prediction of Tsunami Amplitude Using Gaussian Process Regression

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Tsunami Warning Centers depend on coastal tide gauges to measure tsunami wave heights for rapid decision making and alerting. To isolate the tsunami signal from the tidal background, a physics-based harmonic analysis model is often used to predict the tides. This prediction is then subtracted from observed data, ideally leaving a tsunami-only waveform plus noise. However, this model is less accurate in waterways where complex bathymetry and freshwater input introduce complications that are not accounted for in the model. In such cases, determining tsunami wave height is challenging because the tide is poorly modeled, making it difficult for Tsunami Warning Centers to produce accurate measurements.

Data-derived methods such as Gaussian processes may be used to address this need. Gaussian processes are a nonparametric, Bayesian approach that avoids issues with traditional physics-based analyses. This method uses a radial basis kernel function to capture data structure, and its properties are determined directly from tide data through a set of hyperparameters. The study demonstrates improved algorithm performance using tide data recorded in Valdez, AK, during the February 27, 2010 Chilean tsunami; the March 11, 2011 Tohoku tsunami; and the January 15, 2022 Tonga tsunami.

A Behavioral Theory Framework for Tsunami Preparedness

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As stated in the session description "educating the public, counteracting disaster amnesia and preserving the memories of tsunamis for future generations are all important tasks that the tsunami community will be working on for decades." Perhaps the biggest challenge is motivating coastal communities and individual residents to ACT on the education, knowledge and memories to prepare for future tsunamis. Social scientists developed the Protective Action Decision Model to describe how individuals are motivated to take action to protect themselves from natural and other hazards. Public health researchers have developed and tested health behavior theories for application in campaigns to improve public health. These theories include the health belief model, ecological model and self-efficacy model. According to the health belief model, there are several factors that motivate a change in behavior when a person is faced with a threat. These factors include the extent to which a person feels vulnerable, the perceived danger or severity of the threat, the real or perceived barriers to taking action, and the perceived effectiveness of taking action. The self-efficacy model includes a sense of control, which overlaps with factors in the health belief model. The ecological model of behavior focuses on the social environment, including individual "intrapersonal", interpersonal, institutional and community factors, as well as public policy. A health promotion program would incorporate elements of these 3 models to motivate behavioral change. A typical health promotion campaign would have the following elements that are directly relevant to tsunami risk reduction: 1) Belief in personal threat, e.g. "I am susceptible to tsunami"; 2) Belief in response efficacy, e.g. "There is something I can do that will lessen tsunami threat"; 3) Belief in personal efficacy, e.g. " I am capable of taking action"; and 4) Belief that new behaviors are consistent with group norms, e.g. "My peers support this action".

Six Decades of Tsunami Science: From the Source of the 1964 Tsunami to Modern Community Preparedness [Poster Session]

Poster Session • Thursday 2 May

Conveners: Dmitry Nicolsky, University of Alaska Fairbanks (djnicolsky@alaska.edu); Anthony Picasso, Alaska Division of Homeland Security & Emergency Management (anthony.picasso@alaska.gov); Barrett Salisbury, Alaska Division of Geological & Geophysical Surveys (barrett.salisbury@alaska.gov); Elena Suleimani, University of Alaska Fairbanks (ensuleimani@alaska.edu)

POSTER 168

Depth Variation in Megathrust Rupture Leads to Mature Tsunami Gap in Metropolitan Chile

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"Seismic gaps" refer to segments along active geologic faults that have not ruptured in a time period comparable with the recurrence intervals of past earthquakes, and are therefore expected to rupture at any time. This concept usually describes spatial variations in earthquake recurrence in the strike dimension. However, modern seismological observations show that rupture can occur at a variety of depths, so that the lack of a seismic gap in the strike direction may not indicate the lack of a seismic gap in the dip direction. This recognition has important hazard implications. For example, within a given strike segment of a subduction megathrust, an earthquake may rupture only one depth section, with another section still accumulating energy for a future large earthquake. Here, we present unambiguous historical evidence for the presence of such an unruptured depth section in metropolitan Chile. In this area, four earthquakes greater than magnitude 8 (1730, 1822, 1906 and 1985) were documented in the written history, but only the first (1730) of this sequence was accompanied by a large tsunami. By combining newly found first-hand accounts of coastal uplift and tsunamis with coupled deformation-tsunami models, we show that the three post-1730 earthquakes failed to produce large tsunamis because their rupture zones were confined to relatively large depths beneath land. In contrast, the large tsunami in 1730 was the consequence of large slip of the shallow section of the megathrust beneath the sea. Because the shallow section has not ruptured in a time period comparable with the recurrence intervals of prehistoric tsunamis (2-6 centuries), it creates a "tsunami gap" today along Chile's most populated coast that could be filled by a large tsunami at any time. Similar tsunami gaps are likely present in other subduction zones and should be addressed in hazard analysis and risk mitigation.

POSTER 169

Constraining Offshore Coupling in the 1946 Tsunami Earthquake Rupture Area

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One of the most important challenges currently in geodesy is accurately modeling the coupling behavior offshore in subduction zone environments. This is largely because most observations of coupling-induced deformation are made on land, where geodetic data are largely unable to resolve the behavior more than about 40 km offshore. This includes the near-trench region, making seafloor geodetic methods vital for capturing such behavior that leads to large earthquakes and tsunamis, like the 1946 Aleutian "tsunami earthquake" that generated an unexpectedly large tsunami presumably because of enhanced near-trench slip. In this region, both community- and PI-driven projects are underway to capture such deformation in Alaska using GNSS-Acoustic methods. Here, we evaluate the proposed distributions of the seafloor equipment, planned for deployment in Summer 2024 surrounding the 1946 tsunami earthquake inferred rupture area. Some of these sites will be located as close to the trench as possible (rated to 6000 m water depth), providing new information on current elastic deformation that cannot be obtained any other way. From our results, we determine the resolvability of the subduction deformation of this specific region, by analyzing the improvement provided by the spatial distribution among the stations in the current proposed geometric distribution. With this analysis, we expect to answer the extent to which questions regarding the current coupling state of the 1946 Aleutian tsunami earthquake area can be answered given the planned instrument distribution.

POSTER 170

Efficient Forward Modelling of Tsunamis Using the Spectral-Element Method

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We developed an open-source tool for the forward modelling of tsunamis. We utilize the spectral element method, aiming to enhance the accuracy and efficiency of tsunami simulations. The spectral element method is a higher-order finite element method that is extensively used in forward and adjoint modelling of seismic wave propagation due to its inherent advantages, such as higher accuracy, stability, and efficiency. Specifically, we solve the shallow water wave equation on curvilinear coordinates to accommodate Earth's curvature. We employ ETOPO 2022 as a reference for the bathymetry. We perform comprehensive simulations of the Indian Ocean tsunami induced by the 2004 Sumatra-Andaman Earthquake and the Pacific Ocean tsunami induced by the 2010 Chilean earthquake.

POSTER 171

Adding Tsunami Observations and Modeling to the USGS Finite Fault Modeling Procedure

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The U.S. Geological Survey National Earthquake Information Center (NEIC) is expanding its earthquake finite fault modeling capabilities to include tsunami modeling and the inversion of tsunami observations. In preliminary testing, we find that the quality of the earthquake source characterization is improved by consideration of offshore data from Deep ocean Assessment and Reporting of Tsunamis (DART) buoys. We demonstrate new tools within the NEIC's finite fault modeling software (Wavelet and simulated Annealing SliP; WASP) developed to interact with the tsunami modeling software, GeoClaw. These updates support forward modeling of the expected tsunami from an offshore finite fault model, allowing early estimates of the ocean response to fault motions. However, earthquake source characterization from terrestrial observations alone is not always compatible with the resulting tsunami (e.g., 2020 M7.6 Sand Point, Alaska), which motivates operationalizing joint inversion of earthquake and tsunami observations. Tsunami amplitudes provide critical constraints on the updip extent of slip, the kinematics of rupture, and the amplitude of vertical deformation. Updates to WASP seamlessly call on GeoClaw to facilitate the calculation of tsunami Green's functions. WASP then inverts DART observations of the tsunami alongside terrestrial seismic and geodetic observations of the causative earthquake. GeoClaw is then called once again to enable tsunami propagation modeling. In this presentation, we showcase the implementation of the updated WASP software package and share results from joint inversions of tsunamigenic earthquakes, demonstrating the gains afforded by including DART observations.

POSTER 172

The What, When and Whys of Alert Progression During Tsunamigenic Events: A Simple Generative Approach to Forecasting Decision Points and Developing Heuristics

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Due to the possibility of imminent tsunami inundation after large earthquakes, tsunami warning centers make fast, real-time decisions about which regions to alert. For initial alerts, the centers typically assume a worst-case scenario as there often aren't sufficient preliminary constraints to resolve event tsunamigenesis. This strategy mitigates the risk posed by the tsunami and simplifies the decision making process. However, it also communicates serious impacts that may not come to pass, and can thereby be a source of frustration for alerted populations. These populations, some of whom may have evacuated, may have to wait hours before the worst-case assumptions can be refuted and the event resolved. Here, in order to alleviate the uncertainty inherent in event progression and to better explain/simplify event decision-making, we propose a method focused on identifying when, where, and why plausible hazard likelihoods are expected to update during an individual event. We develop a simple generative model that maps event observations to a probabilistic description of future impacts at the coast, and show how the model can be used to both highlight upcoming decision points and develop straightforward event-specific heuristics (rules of thumb) that simplify the decision making process. For example, the model can recognize that a specific open ocean water-level observation exceeding some threshold will be the first determining factor in whether or not a warning level observation (>1 m waves) will be realized at a coastal location. The model is trained using an array of precomputed Alaska Tsunami Forecast Model (ATFM) outputs, including forecasted tsunami amplitudes for large subduction zone earthquakes in the Pacific. This model does not improve final forecast accuracy, but rather provides a real-time, decision-first framework to highlight what amplitude thresholds need to be measured when in order to reduce initial forecast uncertainty and crystallize anticipated impacts. The goal of this model is to provide a basic, explainable, robust, data-oriented framework that informs the decision making process.

POSTER 173

Estimating Tsunami Vulnerability along Western Coast of India

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India has a long coastline of roughly 1500 km along its western margins. Tsunami hazards along western coast of India have been under-studied, comparative to the eastern coast. The major hazard of tsunami along western coast comes from Makran subduction zone. However, other features in Arabian sea and Western and Northern Indian ocean may pose also pose a threat, in terms of tsunami. Seafloor topography reveals various tectonic features that can possibly trigger tsunamis. These comprise of Indian ocean mid-oceanic ridge including carlsberg ridge, owen fracture zone, among others. These features primarily have earthquakes of strike-slip in origin. It has been shown that stirke-slip earthquakes have potential of generating tsunamis, contrary to popular belief. Slope failure, favourable bathymetry, large dip angle, are some of the feature which faciliates tsunamigenic nature of strike-slip earthquakes. Another common reason of tsunami is underwater landlslides. One such region is Indus canyon, in the north western indian ocean. In this study, possible tsunami harzard estimation for the western coast of India have been done, by taking hypothethical earthquake scenarios along several features in Arabian sea and North and North west Indian ocean. Inundation and Run-Up for each case has been discussed, higlighting vulnerability of the region.

POSTER 174

Precise Point Positioning of Ships to Detect Tsunamis

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Precise Point Positioning (PPP) of ships could be a useful addition to existing tsunami detection frameworks. Leveraging Global Navigation Satellite System (GNSS) data to precisely track the movements of marine vessels can unveil anomalies in sea surface height indicative of tsunamis. Results are presented for the R/V Sikuliaq, a research vessel commissioned by the University of Alaska Fairbanks that has operated an external Trimble MPS865 Modular GNSS Heading Receiver since 2019. Raw RINEX GNSS data files with a sampling rate of 1 Hz from the ship were processed with PRIDE PPP-AR, an open-source software for PPP applications developed by the GNSS Research Center of Wuhan University. Utilizing this software, in tandem with further post-processing, we demonstrate the efficacy of harnessing ship positioning data for tsunami detection in two case studies: (1) the M8.2 earthquake that occurred offshore Chignik, Alaska on July 29, 2021, when the ship was in transit in the Pacific Ocean (kinematic), and (2) the Lowell Point landslide near Seward, Alaska on May 8 (UTC), 2022, when the ship was in port in Resurrection Bay (stationary). For both instances, orthometric height (height above mean sea level) was calculated from the ship elevation data, tides were modeled through OSU Tidal Prediction Software (OTPS) and removed from the resultant time series data, and signal processing techniques were employed for further analysis. The tsunami generated by the earthquake was not detectable, given its small size (synthetic models give 2 cm tsunami height at ship location); however, the diurnal and semidiurnal tides were well-observed using GNSS receiver data from the moving ship. Conversely, the tsunami was detectable for the landslide event the clear signal suggests dominant wave periods of less than one minute and an amplitude of approximately 5 cm. The standard deviation of the post-processed vertical position time series differed in both cases: 1.3 cm for the stationary case and 4 cm for kinematic case; noise in these readings can be attributed to wind and other atmospheric disturbances, as well as movement of the ship.

POSTER 175

Testing Crustal Fault Tsunami Sources in the Salish Sea: Comparing Modeled Inundation With the Geologic Record at Discovery Bay, WA

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Crustal faults across the Salish Sea are capable of producing M7+ earthquakes and hazardous tsunamis in Puget Sound and the Strait of Georgia. A better understanding of the history of Salish Sea tsunamis and their sources will improve tsunami hazard assessments in Washington State and British Columbia. The Seattle and Tacoma faults are well-studied tsunami sources, but other Salish Sea crustal faults are just starting to be evaluated for their tsunami hazard. One way to advance our understanding of crustal fault tsunami hazards is to compare modeled tsunami inundation from various sources with geologic evidence for past tsunamis. The tidal marsh at Discovery Bay, Washington, is an excellent geologic recorder of past tsunamis because of its wave-amplifying funnel-shaped morphology, an abundant sediment supply, and a terminal tidal marsh that has preserved tsunami deposits in the marsh stratigraphy. With at least 10 tsunami deposits of thicknesses between 2-10 cm thick, and at least 6 thinner layers under 1 cm thick spanning the last ~3,000 years, the deposits at Discovery Bay likely represent not only tsunamis generated by the Cascadia subduction zone, but also those generated by crustal faults, landslides, or tsunamis from other Pacific subduction zones. To better understand potential crustal fault sources of Discovery Bay tsunami deposits, we test high-resolution tsunami inundation models of the Skipjack Island, Darrington-Devils Mountain, South Whidbey Island, Seattle, and Tacoma fault zones. We also test tsunami inundation models of the 1700 C.E. Cascadia subduction zone and 1964 Great Alaskan earthquake tsunamis, both of which have probable deposits at Discovery Bay. Some of the crustal fault sources we tested appear to be more likely to cause flooding at Discovery Bay than others and may be the sources for deposits whose ages do not align with known Cascadia earthquakes.

POSTER 176

KOERI Activities in Tsunami Early Warning and Risk Mitigation System in the Eastern Mediterranean and Its Connected Seas

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Kandilli Observatory and Earthquake Research Institute (KOERI) tsunami warning system provides services in the Eastern Mediterranean, Aegean, Marmara and Black Seas under the UNESCO Intergovernmental Oceanographic Commission (IOC) - Intergovernmental Coordination Group (ICG) for the Tsunami Early Warning and Mitigation System in the North-Eastern Atlantic, the Mediterranean and Connected Seas (NEAMTWS). KOERI's Regional Earthquake and Tsunami Monitoring Center (RETMC) was established on the foundations of the KOERI National Earthquake Monitoring Center (NEMC) by adding observation, analysis and operational capability related to tsunami early warnings after an extensive preparatory period between 2009 and 2011. The center initiated its test-mode 7/24 operational status as a national tsunami warning center in 2011, and after a one-year period it became operational as a candidate tsunami warning center for NEAMTWS on 1 July 2012. KOERI continues monitoring and disseminating messages in the NEAM region together with other TSPs; CENALT (Centre d'Alerte aux Tsunamis-France), NOA (National Observatory of Athens-Greece), INGV (Instituto Nazionale di Geofisica e Vulcanologia-Italy), and IPMA (Instituto Português do Mar e da Atmosfera-Portugal), completing full coverage of the tsunami-prone regions monitored by NEAMTWS. KOERI issued 45 tsunami warning message disseminated since 1 July 2012, including the remarkable events, such as the 20 July 2017 Bodrum–Kos Mw 6.6, 30 October 2020 Samos–Izmir Mw 6.9, 06 February 2023 Gaziantep Mw7.7 and 20 February 2023 Hatay Mw6.3 earthquakes. KOERI monitors 28 tide gauge stations operated by General Directorate of Mapping and KOERI in Türkiye and nowadays enlarges its sea-level network with inserting an additional 20 stations along the coast of the Marmara Sea. This presentation will focus on

the KOERI's Tsunami Early Warning and Risk Mitigation Activities in NEAM region.

POSTER 177

Estimation of the Tsunami Hazard for the Bering and Chukchi Seas Based on Numerical Modeling of Trans-Oceanic and Local Tsunamis

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The tsunami hazard for the Bering and Chukchi seas has been estimated based on numerical modeling of eight major far-field earthquakes in the Pacific Ocean (1946 Aleutian, 1952 Kamchatka, 1960 Chile, 1964 Alaska, 1965 Rat Islands, 1957 Andreanof Islands, 2011 Tohoku, and 2012 Haida Gwaii), and one near-field earthquake in the Bering Sea (2017 Commander Islands). Tide gauge records of the 2011 Tohoku tsunami from St. Paul Island, Port Moller and Nome in the Bering Sea were used to validate the model. According to our numerical simulations, the tsunami generated by the M_w 9.5 1960 Chilean earthquake would have produced the strongest response in the Bering Sea wave amplitudes up to 2.7 m, while for the 1952 Kamchatka tsunami (the second strongest response) the maximum wave amplitudes would have been up to 1.5 m. The 1964 Great Alaska earthquake (M_w 9.2) did not produce a substantial tsunami in the Bering Sea because the Alaska Peninsula sheltered the region from incoming tsunami waves. We have also estimated the penetration effectiveness for the distant tsunamis into the Bering Sea and then into the Chukchi Sea/Arctic Ocean. According to our computations, a typical attenuation coefficient for the straits through the Aleutian Islands is 0.75, on average, while the corresponding coefficient for the Bering Strait is 0.29. Based on these estimates, we conclude that the likelihood of tsunami penetrating into the Arctic Ocean from remote Pacific sources is low. Even for a powerful event, such as the 1960 Chilean tsunami, the tsunami wave amplitudes in the Chukchi Sea leading into the Arctic Ocean would not exceed a few centimeters. However, for the Bering Sea, tsunami waves from major distant earthquakes can be significant.

POSTER 178

Real Time Tsunami Run-Up Estimation From Real Time Finite Fault Models

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Often, Tsunami Early Warning relies on a precomputed set of scenarios for places near the tsunami generation zone. These scenarios are non realistic and are computed from a uniform constant slip over the rupture surface, because of the short reaction time for the local authorities to manage the threat. Here, we present a new development to be implemented on Early Warning Systems, that allows real time tsunami modeling using the W-Phase solution of the seismic source and the finite fault model inversion to evaluate tsunami threat levels. A fast linear approximation of shallow water equations turns into a numerical solver that can be implemented on a parallel thread. As a case study, the proposed method is applied in Chile. The results show that it is possible to obtain consistent and realistic threat levels and arrival times for the tsunami in progress within times useful for Tsunami Early Warning, since the earthquake origin time.The proposal considers realistic heterogeneous and kinematic fault models of seismic sources obtained rapidly using continuous GPS, strong motion and broadband records, expanding the evaluation capabilities of Early Warning Systems and diminishing the bias imposed by precomputed scenarios, by using the source solution for the particular earthquake that generated the tsunami in progress.

POSTER 179

Measuring and Forecasting the Background Open Ocean Tsunami Spectrum

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he background open-ocean tsunami spectrum (BOOTS) is an under-studied topic in the tsunami sciences. It describes the spectrum of oscillations that occur out in the open-ocean within the tsunami band (1 min-2 hrs). It plays a key role in understanding the local site response at coastal sea level stations, which can be extended to show the tsunami site response at locations where no sea level data is available. The objective of our research is to measure the BOOTS and its noise and forecast these variables using a graphical neural network.

For the analysis, we use data from the recovered bottom pressure recorders of DART stations, which have a sampling rate of 15 seconds. With this sampling rate, it is possible to measure the BOOTS over the full tsunami band. The quality-controlled de-tided pressures are used in the calculation of power and amplitude spectra. These spectra are computed every two weeks for each DART station for as long as fidelity data are available. Tsunami events anywhere in the Pacific and Atlantic basins over the time frame of 2000-2022 are filtered out to ensure that the spectra are mainly that of the background oscillations. Spectra generally have a simple log-linear decay, so we utilize a least-squares inversion to compute the slope and intercept of the spectra— e.g., the energy and noise of the background state. From these spectra, we construct a time-series of the two parameters that shows the temporal variation for each DART station. We then use these data as inputs to forecast these parameters via a graphical neural network.

POSTER 180

The Role of Climate-Change Sea Level Rise Exacerbating California's Tsunami Hazards

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A new era of engineering is arising in which coastal risk assessments are carried out in a more holistic manner. One key improvement is the incorporation of compounding processes. New tsunami hazard evaluations, for example, shall integrate the influence of tides and climate-driven sea level changes. In terms of magnitude, they could be comparable to tsunamis of interest at certain regions, such as those threatening the Southern California coast. New non-stationary probabilistic tsunami hazard assessment (nPTHA) methods are developed to incorporate the mean sea level changes due to a warming climate and the uncertainty of the tidal phase at the moment of tsunami occurrence. Results show that sea level rise shifts hazard curves towards greater values, while tides cause a diffusion making the tails of hazard distributions heavier.

As an illustration, the developed nPTHA is employed for assessing tsunami hazards in San Francisco, Long Beach and San Diego due to earthquakes in the Alaska-Aleutian and Cascadia subduction zones. The nPTHA is carried out by generating synthetic random earthquakes, by simulating tsunami scenarios in the framework of a stochastic reduced order model (SROM) and by employing a surrogate model that simulates the effects of tides and sea level rise. When analyzing the Maximum Considered Tsunami (MCT) results, defined as the sea level exceeded with a probability of 2% in 50 years in building codes, we observe significant exacerbation of the hazard at the assessed regions. MCT maps in Long Beach Port, for example, exhibit an increase beyond 60% when considering the NOAA's moderate-high sea level rise projection. These results suggest that critical coastal infrastructure, projected to serve several decades in the California coast, shall incorporate a nPTHA in the design process.

POSTER 181

In Search of the Missing Tsunami: Is There a Tsunami Threat to Anchorage?

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The historic tsunami events have led to a common misconception that the Upper Cook Inlet (UCI) is completely immune to tsunami impacts. A coordinated effort to evaluate tsunami hazards in the area, as a part of the Alaska tsunami inundation mapping program, has been recently completed.

Tsunamis were not reported in Anchorage during the Great Alaska earthquake. One possible explanation was that the 1964 rupture did not produce a substantial amount of slip in the presently creeping Kenai segment of the plate interface, which resulted in a relatively small amount of energy entering Cook Inlet. Another potential reason for the unreported tsunami was the timing of the arrival of the wave: after midnight at low tide.

Tsunami inundation models used in hazard assessment studies usually employ static-tide runs with the Mean High Water vertical datum, because dynamically coupled tsunami-tide models are hard to implement. However, UCI is a shallow water body with extreme tidal ranges of up to 10 meters, which makes tsunami-tide interactions crucial for accurate hazard assessment. We perform numerical modeling of the 1964 tsunami in UCI by dynamically coupling the tsunami model with tides, and suggest that a 3-meter high tsunami did occur, but was unnoticed in Anchorage due to its arrival on low tide that was 5 meters below Mean Sea Level. Our further modeling shows that the inundation zone, corresponding to the tsunami calculated on a high static tide, is larger than that computed with dynamically coupled tide, therefore our tsunami inundation maps do not underestimate potential hazard due to static-tide modeling.

Our understanding of the tsunami threat in UCI has been significantly revised since 1964. We considered tsunami sources similar to that of the 2011 Tohoku tsunami, and included tsunami-tide interactions in the tsunami hazard analysis due to extreme tidal ranges in UCI. Our future task is to educate coastal residents and various stakeholders about this rare but real tsunami threat. The public outreach campaign is now underway in Anchorage and other communities in UCI.

Special Applications in Seismology

Oral Session • Wednesday 1 May • 4:30 PM Pacific

Conveners: Heather McFarlin, Alaska Earthquake Center (hlmcfarlin@alaska.edu) and Nate Murphy, Alaska Earthquake Center (nwmurphy@alaska.edu)

Is Dynamically Triggered Seismicity Comparable to Background Seismicity?

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Earthquakes can be dynamically triggered by the passing waves of events from distant faults. Identifying dynamic triggering mechanisms offers tangible hope in revealing earthquake nucleation processes. Delayed dynamic triggering is frequently observed, and such cases are likely driven by nonlinear processes that differ from typical stress triggering. This brings into question whether or not they reflect the same nucleation processes. Here we investigate the physical mechanisms of triggered seismicity in southern California using a variety of independent datasets related to faulting environments and earthquake source characteristics. Within the spatial and temporal resolution afforded by these data, we find weak correlations between triggering occurrence and surface fault trace complexity, focal mechanism diversity, and fault type. Such low correlations suggest similar faulting environments for the triggered and background seismicity. We find that the triggered seismicity may have lower stress drop and b-value estimates compared to background seismicity. The lower stress drops and b-values imply that the driving mechanisms might be different between triggered and background earthquakes. Additionally, about 85% percent of triggered sequences do not begin with the largest event. About 50% of these triggered sequences have migration velocities above 0.25 km/hr and Omori p-values below 0.75. These characteristics suggest that the triggered seismicity is akin to earthquake swarms, which are often driven by aseismic slip or fluid migration. These processes are likely reflected in the lower stress drops and b-values of the triggered seismicity. Our findings suggest that the triggered seismicity are likely by-products of additional, localized processes activated by the passing waves, such as aseismic slip or fluid movement.

Ligabue—Large Induced Ground Amplitudes by Urban Excitations, as Recorded by a 7c-Station

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We deployed a *7C-station* as a multiparameter recording setup, composed by a classical broadband seismometer (Nanometrics Trillium Compact Horizon 120s), a rotational motion sensor (iXBlue, blueSeis-3A) plus an infrasound sensor (Chaparral 64 UHP2). Here, we understand *Urban Excitations* as the daily anthropogenic noise (car and railway traffic, power lines, hydraulic pumps, washing machines, etc.) in the city of Florence, temporarily superposed by large oscillations generated during a public performance of the Italian rock musician Luciano Ligabue. The 7-component station, installed approximately 650 m eastwards from the concert hall "Nelson Mandela Forum", include three translational and three rotational components, which recorded large amplitudes of seismic ground motion. These 6 degrees-of-freedom, in combination with an additional infrasound sensor (0.015-50 Hz, Nyquist frequency), allowed us to identify the generated wave types, to distinguish between the respective propagation paths, and to discriminate between the seismic and the acoustic source(s).

The largest seismic amplitudes observed during the two-hours rock concert appear as discrete monochromatic wave-trains in a predominant frequency range of 2-3 Hz. A parallel and synchronized video recording of the musical event proves that these oscillations correspond exactly to the master beat of the respective song (refrain) and are caused by the rhythmically jumping spectators. The seismic *beat amplitudes* are not amplified due to local site effects, as suggested by the spectral ratios curve computed on the quiet part of ambient noise, but can be correlated with the number of *enthusiastic* spectators. Being recorded on the vertical and the radial (E-W) component, the *master beat* signals are composed by Rayleigh waves. This is confirmed by data from the rotational sensor, which hardly records signals below 8-9 Hz due to its self-noise level. However, the large seismic amplitudes on the HJ2-component between 2-3Hz stand out from the self-noise-dominated rotation rate spectra. Unexpected was the recording of the departing traffic after the end of the concert.

#Utequake: An Outreach Project Combining Real-Time Large Crowd Seismology and Football

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The #Utequake project is an outreach initiative from the University of Utah Seismograph Stations that bridges the gap between science and Athletics. For this project, we deployed a strong motion station in Rice-Eccles Stadium to record and correlate in real-time the signals generated by the crowd during University of Utah football home games. In this work, we showcase the visibility and impact of the project on social media, the University, and local media, and we will show some comparisons of the largest amplitude signals during the 2023 season. #Utequake showcases the powerful intersection of science and sports, creating a platform for education, entertainment, and community engagement.

Enhancing Classification Reliability With Anomaly Detection for Operational Monitoring of Continuous Seismic Data

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With the ever-growing amount of seismic data collected, the role of artificial intelligence (AI) for processing and analyzing those recordings becomes indispensable. Recent years have seen a surge in seismic detection and classification applications. However, the robustness of classification models poses a challenge: the complexity of continuous incoming stream of data is never *fully* represented in a training set, and a classification model does not have the ability to detect unexpected behavior and to say "I do not know". Consequently, it will erroneously classify unknown samples in one of the predefined classes. In current work, we improve the reliability of seismic data detection and classification in two different aspects. Using a 32-month seismic dataset from 43 French stations, identifying six classes, a single convolutional neural network (CNN) analyzes the entire multi-stational dataset. Firstly, we explored strategies to mitigate bias in a multi-class classification model due to class-size imbalances. Best results are obtained by optimizing the loss function regarding class-size, enhancing balanced accuracy by 47%. Secondly, we propose the

implementation of an anomaly detection module to mitigate the problem of misclassification of unknown samples by providing the model the opportunity to say "I do not know where this sample belongs". We considered four semi-supervised anomaly detection algorithms, namely one-class SVM, elliptic envelope, isolation forest and local outlier factor. Our findings reveal that incorporating an anomaly detection module effectively mitigates the misclassification of most novelties as predefined classes. Furthermore, it allows for detecting unexpected behaviors such as anomalies, class drifts and ambiguous samples. Thereby enhancing the trustworthiness and reliability of predictions. Our study indicates that the isolation forest method yields best results for our specific application.

Towards the Automatic Relocation of Intermediate-Depth Earthquakes Using Adaptive Teleseismic Arrays

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The accurate location of intermediate-depth earthquakes has proven to be one of the more enduring problems in global seismic location studies. Complicated in many cases by a paucity of near-field observational data, the determination of accurate source depths for such earthquakes, in particular, has proven to be elusive. As a result, and despite improvements in recorded seismic data density and quality, the distribution and controls of these events remain poorly understood.

Depth phases (near-source surface reflections, e.g. pP and sP) are crucial for the accurate determination of earthquake source depth using global seismic data. However, such phases are often difficult to detect, suffering from low signal-to-noise ratios, and are disguised in the P-wave coda, and often suffer from an ambiguity as to which depth phase has been observed.

To address this limitation, we develop an automated approach to group globally-distributed stations at teleseismic distances into *ad-hoc* arrays with apertures of 2.5 degrees, before optimising and applying phase-weighted beamforming techniques to each array. We then use the resulting vespagrams from each medium-aperture array to automatically pick phase arrivals for the direct and depth phases, and determine differential arrival times between the depth phases and their corresponding direct arrival. These are subsequently used to invert for a new hypocentre location. We demonstrate this method by relocating all intermediate-depth events above a magnitude 4.7 associated with a region of northern Chile and the Peruvian flat slab region of the subducting Nazca plate. We demonstrate that our approach leads to a radical increase in the number of depth phases detected, particularly for smaller-magnitude events, and makes a substantial difference to the location of seismicity in intraslab settings, and to the resolution of the seismogenic structure of the slab.

Receiver Functions in the Los Angeles Basin

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The Los Angeles Basin (LAB) is of interest to study because its subsurface geometry and composition can increase the seismic hazard in this metropolitan area. Sedimentary basins can amplify seismic waves and prolong their shaking. Virtual simulations from an M7.2 event on the San Andreas Fault show a longer and amplified shaking in the Los Angeles area, which is fed through channelization of the northern Los Angeles basins. We apply the time-domain deconvolution methods to exploit the density of the station along the two linear lines across the LAB and scattered nodal stations. Our results improve the model of the Los Angeles Basin by applying modern geophysical methods to a newly acquired dataset that densely spans the basin.

Resolving the Structure of the Los Angeles Basin Through High-Resolution Seismic Tomography

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The urban area of Los Angeles is located within a large-scale deep sedimentary basin that during large earthquakes can considerably amplify the recorded seismic amplitudes, which in turn may result in considerable damage to buildings and infrastructure. The accurate prediction of earthquake ground motion relies heavily on understanding the basin's geometry and the seismic properties of its filling material. Therefore, the accurate characterization of sedimentary basins is crucial to correctly estimating shaking intensity in these geological scenarios. Los Angeles stands as one of the most densely monitored urban areas where a remarkable increase in continuously operated seismic stations occurred since the 1980s. The Southern California earthquake catalog, comprising over 800,000 events derived from hundreds of thousands of P- and S-wave arrival times, reflects this extensive seismic network. In addition to the traveltime picks from conventional stations, we also include arrival times obtained using PhaseNet-DAS applied to distributed acoustic sensing (DAS) datasets collected over a year using preexisting telecommunication fibers within the urban area. The conventional station data yields more than 16 million P-wave travel times and 8 million S-wave picks, while the DAS data comprises approximately 1 million and 3 million arrival times for P- and S-waves, respectively. To fully exploit this vast dataset, we apply a matrix-free Eikonal tomography and double-difference relocation workflow to the traveltime picks accumulated for more than 40 years. The combination of the high-spatial density of DAS with the substantial number of cataloged events from the conventional station dataset allows us to significantly enhance the existing velocity models and capture structural details at an unprecedented level of details. Our new model would have important implications for the evaluation of the seismic hazard within Los Angeles and its surroundings.

Upper-Plate Seismicity and Focal Mechanism for Studying the Stress State in the Mendocino Triple Junction

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The Mendocino Triple Junction (MTJ) is the place where the North America, Pacific and Gorda plates meet. The interaction between the three plates results in frequent and damaging earthquakes that occur not only at major plate boundaries but also within each plate, with the largest and most destructive one ever recorded being the 1992 M7 Petrolia earthquake within the overriding North America. Intriguingly, North America plate hosts faults with diverse orientations near MTJ. The 1992 M7 Petrolia earthquake occurred on a westward, shallow dipping thrust fault at about 10 km depth, while most of the shallow Quaternary faults are strike-slip dominated, oriented in the N-S and NNW-SSE directions. Such spatially varying fault orientations indicate that large spatial stress gradients exist in the overriding plate. To better quantify earthquake hazards of the upper plate, a more detailed picture of the stress field is needed to understand under what conditions these faults are operated. In this study, we use focal mechanism of upper-plate earthquakes in the MTJ region to infer the state of stress within the overriding plate and how it changes spatially. We select events between -125.5° to -123° W and 39.5° to 41.5° N from 2008 to 2022 with a magnitude >2 using the USGS ANSS Comprehensive Earthquake Catalog and separate earthquakes that are above the slab interface of the Slab2 model, which results in 816 total events. Three component seismic waveforms are downloaded from IRIS and Northern California Data Center. The number of available stations near MTJ increases from 72 in 2008 to 92 in 2022 with a total of 188 permanent and temporary stations active at different times. Those events are relocated using 3D velocity model for the MTJ region. We manually pick P wave first motion polarities in Pyrocko and calculate focal mechanism using HASH program. Our preliminary result shows that there is a range of focal mechanism solutions from mostly strike-slip near the coast and mostly normal faulting further inland. We will invert these focal mechanisms to quantify the stress fields within the upper-plate.

Complex Deformation of the Northern Deep Tonga Slab

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Two-thirds of global deep earthquakes occur within the subducting Tonga slab. The resulting dense seismicity provides important constraints on slab deformation and deep earthquake rupture mechanisms. We explore the type and distribution of deformation and earthquakes in the northern Tonga slab using relative earthquake relocation and focal mechanism cluster analysis. Roughly 1000 earthquakes were relocated using a hypocentroidal decomposition method. The arrival time dataset consisted of more than 400,000 arrival times, including regional arrivals from temporary land and ocean bottom seismometer deployments as well as a variety of teleseismic arrival phases sourced from the International Seismological Centre (ISC). 345 earthquakes were grouped into commonly occurring focal mechanism types using

K-means cluster analysis of their P, T, and B axis orientations from the Global Centroid Moment Tensor (CMT) catalog. The result of combining accurate relative locations with CMT cluster analysis demonstrates unique seismicity patterns. An extremely dense plane of seismicity aligns with steeply dipping focal mechanism nodal planes along the top (southwest) portion of the slab, indicating a shear zone of less than 5 km width. This near-vertical shear zone is potentially localized in the subducted crustal layer, and indicates oblique, left lateral, and downward motion of the main part of the slab. To the northeast of the shear zone., This region of the slab shows along-strike extension, with a lower seismicity rate. However, The largest earthquakes in the northern deep Tonga slab do not occur within the highly seismic shear zone but in the extensional region of the slab. These observations are difficult to fit within the framework of a metastable olivine wedge associated with transformational faulting because of the complex pattern of deformation and the large width of the seismic region compared to the that of the predicted olivine wedge.

Using Machine Learning Algorithms to Explore the Seismoacoustic Wavefield at an Industrial Facility

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Operational activities at industrial facilities generate a diverse array of seismic and acoustic signals, providing valuable insights into the characterization and monitoring of these activities. In an effort to enhance our understanding, nodal seismic stations were strategically deployed intermittently at an industrial facility in Texas. Given the intricate nature of operations and the involvement of high-frequency vibrations, seismic and acoustic sensors were configured to operate at a high sampling rate, exceeding 1000 samples per second. Over the span of multiple data collection campaigns conducted between 2021 to 2023, a substantial seismic and acoustic dataset was amassed, surpassing a size of 10 TB. While traditional physics-based analysis and modeling have been carried out, we have also leveraged machine learning algorithms to delve into the complex seismoacoustic wavefield at the site. A hierarchical clustering algorithm was applied to seismic signals originated from high-explosive (HE) detonations. A remarkable total of 39 signals related to detonations were recorded at a single station. The clustering algorithm categorized similar waveforms into cohesive clusters, enhancing our ability to discern patterns within the data. A self-supervised machine learning technique has been developed to learn representative characteristics embedded within continuous seismograms, which can then be used to detect anomalies in the seismogram and contribute to a more comprehensive understanding of the operational dynamics at the facility.

Special Applications in Seismology [Poster Session]

Poster Session • Wednesday 1 May

Conveners: Carl Tape, University of Alaska Fairbanks (ctape@alaska.edu); Michael West, University of Alaska Fairbanks, (mewest@alaska.edu)

POSTER 166

Sub-Daily Gnss Denoising Using Graph Neural Network

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Global Navigation Satellite Systems (GNSS) time series have become increasingly precise, enabling researchers to study tectonic motion and transient deformation, such as Slow Slip Events (SSEs). While daily GNSS data permit analysis of such events with good accuracy, they lack temporal resolution. On the other hand, sub-daily GNSS data have lower signal-to-noise ratios making it challenging to identify small amplitude signals. Current GNSS denoising methods, such as stacking, filtering, or common-mode filters (CMFs), are efficient at removing noise from the whole network. However, applying these methods to a heterogeneous network of stations with spatially varying noise patterns, time-dependent network topology changes, and data gaps can lead to a misrepresentation of the noise, introducing bias.

Here we use a Graph Neural Network (GNN) approach, already applied to the daily time series, for denoising the high rate GNSS. The GNN's strength lies in its ability to handle the spatial heterogeneity of the stations within the network and accommodate varying numbers of available stations. Neural networks have also shown robustness in addressing temporal gaps, making them suitable for GNSS time series. To construct the graph, we connect multiple stations based on rules. It enables the GNN to capture the spatiotemporal structure of the noise at different levels, from individual stations to sub-networks and the entire network. We can remove unwanted noise by identifying correlations between stations experiencing similar signal character. To evaluate our method, we apply it to our high-rate GNSS data processed with the PRIDE-PPP ar positioning software, with the goal of resolving large-scale secondary slip fronts in the high-rate GNSS data.

POSTER 167

Analysis of Characteristic Repeating Earthquakes in the Tehuantepec Triple Junction, Mexico

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Analysis of the characteristics repeating earthquakes has been extensively used to examine the fault behavior of plate interfaces in a wide variety of tectonic settings. It is believed that they are the result of reiterative ruptures from a common asperity in an otherwise creeping region. Therefore, resulting in a set of two or more events that produce almost identically waveforms with similar magnitudes and recurrence times. In this study, we focus on the temporal variations of the repeating earthquakes in the Tehuantepec triple junction. On September 8th, 2017, this area was hit by a large M8.2 intraslab earthquake that significantly redistributed the stress of this region. In a former study, we found a set of 426 sequences along the flat segment of the subduction zone in the states of Guerrero and Oaxaca. Furthermore, we observed a sustained activity between two nearby large asperities resulting in magnitude M7+ earthquakes. Here, we perform a more extensive search of repeating earthquakes for all events reported by the National Earthquake Center between 2001 through 2022 by using all the permanent broadband stations including those around the triple junction in the Tehuantepec region. This search consists of nearly ~1 million waveforms from the 217,285 cataloged events ($3.2<M<4.5$). This study complements our studies along the flat portion of the in Guerrero-Oaxaca where repeating earthquakes showed a good agreement with geodetic observations.

POSTER 168

Nodal Seismometer Recordings of Aftershocks of the 11 May 2023 Mw 5.5 Lake Almanor Earthquake

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On May 11, 2023, an Mw 5.5 earthquake occurred near Lake Almanor, California, followed by an Mw 5.2 aftershock 19 hours later. Starting on May 13, the US Geological Survey deployed 34 nodal seismometers (nodes) in the vicinity of Lake Almanor to compliment the local permanent Northern California Seismic Network (NCSN) stations. As there is only one active strong-motion station in the immediate vicinity of Lake Almanor and no other strong-motion stations with 25 km of the epicenter, addition of the nodal stations represents a large temporary increase in local stations that recorded the aftershock sequence. The nodal stations were spaced approximately 2-3 km apart and consisted of SmartSolo IGU-16HR 3-component nodes that recorded continuously at a 2-ms sampling interval from May 13 through July 25, 2023. One of the nodal stations was coincident with a station (CGS ID#L 87053) of the permanent network operated by the California Geological Survey. The nodal stations, combined with the permanent network, provided more densely spaced recordings of events in the area, with the combined network recording 25 Mw 2.5+ aftershocks, 5 of which were greater than Mw 3.0, as determined by the permanent network. The combined dense nodal and permanent network stations expanded the recording azimuth (nodal stations surrounded most aftershocks) and is expected to significantly increase the number of events in and the accuracy of the current earthquake catalog for the region during the deployment period, particularly when evaluated with machine- learning-based methods (Yoon et al., 2015; 2023). From

the improved catalog, we expect to develop detailed 3D P- and S-wave velocity models and to better identify subsurface faults in the vicinity of Lake Almanor.

POSTER 169

Machine Learning as a Tool to Build a Comprehensive Seismic Catalog for the Island of Hispaniola

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The island of Hispaniola, located on the northeastern boundary between the North American and Caribbean plates, is shared by Haiti and the Dominican Republic. In this region, the convergent margin to the east transitions to the transform fault system in the west, leading to frequent earthquakes. Despite a history of devastating seismic events, existing catalogs lack crucial information concerning earthquake hazard, including fault lengths and seismogenic potential. Building a comprehensive earthquake catalog, including both small and large magnitude events across the entire region, is essential for reliable estimates of seismic hazard. Traditional seismic detection methods are time-consuming and susceptible to errors. Recent advances in machine learning provide an opportunity to enhance seismic catalogs and produce a better understanding of earthquake behavior and more accurate hazard assessment.

In this study, we employ machine learning techniques, utilizing the easyQuake Python package, to analyze seismic data continuously recorded on Hispaniola from 2014 to 2023. The Earthquake Transformer deep-learning picker was applied to over 35 seismic stations across the island and its surroundings, successfully detecting and locating more than 121,000 seismic events. This represents a sixfold increase in the number of identified seismic events compared to catalogs from the seismic networks of the Dominican Republic over the same period. The program Hypoinverse was used to relocate these events, and filters were applied to remove poor locations, ensuring a reliable catalog. Most earthquake locations cluster around faults that are known to be active, but others reveal patterns that may provide new insights into earthquake dynamics on Hispaniola. The next steps in this research involve refining locations with HypoDD and employing other machine learning techniques, such as PhaseNet and Generalized Phase Detection, to compare the effectiveness relative to Earthquake Transformer.

POSTER 170

Assessment of Atmospheric-Driven Ground Noises for Dragonfly's Seismic Observation on Titan

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Dragonfly is one of NASA's New Frontiers program missions, which is going to explore the largest Saturn's moon, Titan in the mid-2030s. The main focus of the mission is "extraterrestrial habitability", and Titan was selected because of its high similarity to our planet compared to other accessible bodies. In order to deepen our understanding of Titan's environment and discuss the possibility of extraterrestrial life, a quadcopter-type spacecraft is going to fly to various sites on Titan and conduct chemical, meteorological, and geophysical observations on every landing occasion. As a part of the Dragonfly Geophysics and Meteorology Package (DraGMet), our short-period seismometer (DraGMet SEIS) will be installed on the spacecraft to investigate the internal environment of Titan.

The assessment of environmental noises is an important step in seismic observation because they directly control the quality of the data. On Earth, owing to a dense and worldwide seismic network together with meteorological stations, we can easily evaluate the noise level. However, due to a limited source of information on extraterrestrial planetary bodies, we are forced to rely on numerical modelings or extrapolation from Earth's analog observations. In this study, we are trying to model a seismic noise induced by atmospheric activities on Titan, referring to terrestrial examples and the InSight seismic observation on Mars (2018–2022). In the presentation, followed by introducing the theoretical background and an example of the application to Martian seismic observation, we will share a preliminary environmental noise model of Titan. In addition, we will discuss how the atmospheric-induced signals can be used for the subsurface investigation.

POSTER 171

Ground Deformation Caused by Atmospheric Gravity Waves on Mars: An Independent Assessment of Martian Crustal Rigidity

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Seismic observations on extraterrestrial bodies always face challenges because we are forced to perform single-station seismology or sparse network seismology. The former is exactly the case of the NASA InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) mission, which conducted seismic and meteorological observation on Mars (2018–2022). In such a case, simultaneous observation of seismic and meteorological data (such as atmospheric pressure) is useful for estimating the internal structure of a planet. On Earth, the measurement of the ground deformation due to background pressure variations allows us to assess ground rigidity, known as Sorrells' theory. Nowadays, this theory is applied to event-driven signals (e.g., convective vortices, gravity waves) not only on Earth but also on Mars.

Previous studies on Mars estimated the rigidity structure down to tens of meters, focusing on convective vortices, which excite energy around 0.5–1.0 Hz. To retrieve structure information from greater depth, this study pays attention to atmospheric gravity waves, whose energy range is around 1 mHz. In the analysis, we retrieved InSight's seismic and pressure data for windows containing atmospheric gravity waves, computed the transfer function (the spectral ratio between pressure and horizontal acceleration), and then estimated Young's modulus of the Martian crust. In the presentation, followed by an example of analysis for terrestrial gravity waves (especially the Lamb wave from the Hunga-Tonga eruption in 2022), we will present the results for Martian gravity waves and discuss the consistency with the structure obtained from analyses of Martian quakes.

POSTER 172

Efficient Cataloging of Low-Frequency Earthquakes With Deep-Learning Model and Template Matching

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Low-frequency earthquakes (LFEs) are small-magnitude earthquakes that are depleted in high-frequency content relative to traditional earthquakes of similar magnitude. Typically associated with slow slip events (SSEs), LFEs offer insights into the space-time evolution of SSEs. However, due to their weak signals and computationally expensive identification methods, LFEs are not routinely cataloged in most places. Here, we develop a deep-learning model trained on an existing LFEs catalog to detect LFEs in 14 years of continuous waveform data in southern Vancouver Island. The result shows a significant rise in detection rates at individual stations, with over 1 million LFEs during the study period located by using a grid search approach in a 3D regional velocity model. Our resulting catalog is consistent with the tremor catalog during periods of large-magnitude SSEs. However, there are cases where it registers far more LFEs than the tremor catalog. We highlight a 16-day period in May 2010, our model detects nearly 3,000 LFEs, whereas the tremor catalog contains only one tremor in the same region. This suggests the possibility of hidden small-magnitude SSEs that are undetected by current approaches.

In addition to the presented work, we extend the investigation into LFEs by employing template matching as a validation method for the detections outlined in the existing catalog. These detections serve as templates subjected to cross-correlation across signals from various stations on southern Vancouver Island. The cross-correlation method facilitates the identification of new detections based on coefficients exceeding a predetermined threshold. The newly defined detections are then stacked and utilized as refined templates, building a base for an iterative process, enhancing the signal-to-noise ratio (SNR). The emergence of clear P- and S-wave arrivals from the noise during this template matching procedure validates the initial detections as LFEs. This methodology aims to validate the deep-learning model's detections, contributing to the confirmation of LFEs and uncovering potential hidden seismic activity.

Structure and Behavior of the Alaska-Aleutian Subduction Zone

Oral Session • Friday 3 May • 8:00 AM Pacific

Conveners: Grace Barcheck, Cornell University (grace.barcheck@cornell.edu); Julie Elliott, Michigan State University (ellio372@msu.edu); Ronni Grapenthin, University of Alaska (rgrapenthin@alaska.edu); Donna Shillington, Northern Arizona University (donna.shillington@nau.edu); Xiaotao Yang, Purdue University (xtyang@purdue.edu)

Forty-Five Years of the Shumagin Gap: What Recent Earthquakes Tell Us About This Seismic Gap

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McCann et al. (1979) identified the 200-km long section of the Alaska-Aleutian Islands subduction zone near the Shumagin Islands as a "seismic gap"—an area that had not hosted a recent M 8.0+ megathrust earthquake and was thus likely to do so in the future. Since then, interpretations of the Shumagin Gap have ranged from this initial view of it being overdue for a large event, to it being poorly coupled and unlikely to ever rupture in a large earthquake. A sequence of large earthquakes starting in 2020 updates our understanding the seismotectonics of the region. The July 2020 M 7.8 Simeonof megathrust event, the October 2020 M 7.6 Sand Point intra-slab strike-slip event, the July 2021 M 8.2 Chignik megathrust event, and the M 7.2 megathrust event in July 2023 all illuminate aspects of plate interface coupling and its effects on earthquake cycle strain accumulation and release. We combine observations of these earthquakes with finite element models of subduction zone locking to revisit the nature of the plate interface in the Shumagin Gap. Together, these allow us to develop a pattern of coupling in the Shumagin Gap that satisfies seismic, geodetic, and geologic datasets. We find a lateral transition from high coupling on the plate interface east of the Shumagin Gap to low coupling in the Shumagin Gap. The Shumagin Gap megathrust is therefore unlikely to rupture in a tsunamigenic, M 8.0+ earthquake. This low coupling is not uniform over the depth extent of the Shumagin Gap plate boundary—the downdip edge of the plate interface in the Shumagin Gap hosts moderate (up to M ~7) earthquakes, indicating some locking in this region. Recent offshore GNSS observations support low coupling on the shallow megathrust across the entire area. The poorly coupled areas of the plate interface in the Shumagin Gap and the shallow megathrust accumulate partial slip deficit because of their proximity to nearby locked zones, and can participate in co-seismic and/or post-seismic slip associated with nearby large events rupturing those locked zones.

Putting the Pieces Together: A Kinematic Coseismic Model of the Mw 7.2 Alaska Earthquake

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A Mw 7.2 earthquake occurred in July 2023 offshore the Alaska Peninsula, rupturing a western portion of the Shumagin Gap. Three years prior in July 2020, a Mw 7.8 event ruptured the eastern portion of the gap, previously known for being devoid of large earthquakes over the last century and characterized by low geodetic coupling. Later in 2020, a Mw 7.6 event strike-slip earthquake potentially ruptured the central portion of the gap as evidenced by tsunami data, updip of the July, 2020 Mw 7.8 earthquake. Deeper postseismic deformation was evident after the July, 2020 earthquake. Here we investigate the kinematic rupture of the July, 2023 Mw 7.2 event using a joint inversion of high-rate GNSS, strong motion data, and static offsets recorded during the event. We utilize MudPy, an open-source, multi-data source modeling and inversion toolkit available on GitHub, with an 800-patch mesh of the subduction slab to assess the slip distribution. We analyze the full sequence of these events to understand the release of accumulated strain at certain depths in this portion of the Alaska-Aleutian Subduction Zone. With the recent > Mw 7 events in the Shumagin Gap, we investigate how this Mw 7.2 event fits in relation to the other events within the past three years to gain an understanding of the coupling of the region and the partial filling of the Shumagin seismic gap to enhance hazard mitigation and assessment in the region.

A Joint Coseismic and Early Postseismic Study of the 29 July 2021, Mw 8.2 Chignik Earthquake

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Understanding the coseismic slip distribution of a megathrust earthquake and the postseismic mechanisms that follow is a task of both critical importance and notable difficulty. For the coseismic slip, due to the sparseness of data and regularization in the inversion, it's common that models that fit the data vary considerably from one to another. Postseismic models can receive bias from the coseismic slip models, especially for those physically based stress-driven models. Second, it's difficult to separate viscoelastic relaxation and afterslip because of the similarity both in time history and spatial pattern, especially in the early postseismic period. Third, there are tradeoffs between parameters in simulation models, for example, the stress change and frictional properties in afterslip simulation, and the geometry and viscosity in viscoelastic models.

In this study, we show how a joint study of coseismic slip and the postseismic mechanisms of the 29 July 2021, Mw 8.2 Chignik earthquake helps to resolve these difficulties. We use a joint seismic-geodetic coseismic inversion to determine the coseismic slip distribution, and varying assumptions about the slip area. We use stress-driven models based on regularized rate-strengthening law to simulate afterslip, and we use the VISCO2.5D software to simulate viscoelastic relaxation. We find that viscoelastic relaxation models are not sensitive to variations in the coseismic slip models, but afterslip models provide new constraints on the coseismic slip distribution, as fitting the postseismic data requires that there be coseismic shear stress increases at particular places. We find the afterslip and viscoelastic relaxation models are complementary in the horizontal component but make opposite predictions in the vertical component, and that the viscoelastic relaxation vertical predictions are very sensitive to features of the assumed geometry like the thickness of the lithosphere and the existence of a cold nose to the mantle wedge. By treating the horizontal and vertical components separately, we can more confidently determine a postseismic model.

Estimating Slip Models and Ground Motion for the 1964 Mw 9.2 Alaska Earthquake

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We revisit the 1964 Mw 9.2 Alaska earthquake rupture using a reviewed dataset of seismic, tsunami, and geodetic observations, including an extended set of leveling-line measurements. This new dataset motivates us to consider a fault model that follows the Slab 2.0 subduction interface and extends further east from previous models (Plafker, Ichinose) to better match the spatial distribution of the known aftershocks. In addition to the updated fault geometry and additional data, we also used improved and higher-resolution bathymetric effects as well as an advanced tsunami model that computes arrival times more accurately. For the leveling data, we also solve for a baseline correction, and for all Green's functions, we correct for the large topographic variations from trench to shore. Even with the additional data, there is still a large range of solutions consistent with the data. Rather than focusing on a "best" fitting solution, which is highly subjective in this case, we develop a suite of solutions that are consistent with the data and span a range of inversion constraints such as rupture speed, rise-time, and weighting. We use this suite of inverted rupture models to compute realistic static deformation scenarios, using 3D spectral-element waveform modeling. This allows us to evaluate the slip distribution over the whole region, which we can compare with the existing coseismic offset maps and geodetic observations.

Earthquake Location Improvements for the Aleutian-Alaska Subduction Zone by Using Waveform Cross-Correlation Data

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Alaska is one of the most seismically active states in the United States, with more large earthquakes than the rest of the country. The adjacent Aleutian Subduction Zone, serving as a convergence boundary between the North American Plate and the Pacific Plate, has had several notable earthquakes, some of which were associated with tsunamis. In this presentation, I show the high-precision earthquake relocation results by using waveform cross-correlation data and characteristics of seismicity in the Aleutian-Alaska subduction zone. The current work is focused on the 43,000 earthquakes in 2020. The majority of these earthquakes occur above 150 km depth and the magnitudes range from -0.5 to 7.8. In order to improve absolute location accuracies, I first perform the three-dimensional earthquake relocation based on phase arrival times through the AKEP model by Nayak et al. (2020), which covers southern-central Alaska. Given the large amount of seismic data, waveforms are only downloaded for AK, TA and AV network stations from the Incorporated Research Institutions for Seismology (IRIS). Before cross-correlation, the seismograms are pre-processed (e.g., filter, resample, etc.) to ensure the best correlation results. The calculation is performed for each event with its closest neighbors up to 200 within 20 km distance. The final waveform cross-correlation relocation shows dramatic improvements in relative locations and correlates with the geological structures significantly better compared with the initial locations. The relocation catalog can provide updated constraints on subduction zone earthquake mechanisms, fault geometries, regional deformation, and ground motion models, which are all essential for assessing seismic hazards.

Upper Plate Stress in the Alaskan Continental Crust: Spooky Interactions at a Variety of Distances

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To understand the impacts of Alaska-Aleutian subduction on the overlying crust and far-field continental interior, we compile moment tensors from 3048 earthquakes in the Alaskan continental crust. Inverting these provides the first comprehensive statewide stress map, first Alaskan stress model update in 15 years, and the first to take advantage of improved coverage from the Earthscope Transportable Array.

Subduction controls near-field stress. Reverse-oblique faulting accommodates radial crustal shortening around the flat-slab segment in south-central Alaska, from Cook Inlet to the northern Alaska Range foothills and all along the Denali/Totschunda fault system. Similarly, radial shortening around the Yakutat block occurs by reverse faulting. Above the slab tear between these two, however, NW–SE lower crustal extension may result from increasing buoyancy due to heating and underplating beneath Prince William Sound, the western Chugach and Talkeetna Mountains. The Queen Charlotte-Fairweather system transitions from oblique shortening near Yakutat Bay to strike-slip and then to oblique extension south of Haida Gwaii; tsunamigenic potential cannot be fully understood without accounting for this along-strike transition in faulting style.

Plate-boundary compression wanes with distance into the continent, controlling maximum stress directions but giving way to variable intraplate deformation. Strike-slip with secondary N–S contraction dominates the upper Yukon basin and eastern Brooks Range. Between the Tintina and Kaltag faults, maximum stress is consistently NNW–SSE, yet secondary extension replaces contraction. This trend continues westward: Despite compressive boundary tractions, oblique extension is widespread across western Alaska. In the Purcell and Baird Mountains, Seward Peninsula and diffusely across southwest Alaska, primarily strike-slip motion includes significant NNE–SSW stretching roughly parallel to the distant plate boundary, suggesting escape tectonics. Equal parts normal and strike-slip faulting accommodate NW–SE extension in the western Aleutian backarc and ESE–WSW extension in the Bering Sea.

A Chicken and Egg Dilemma: Forearc Strain Field and Seismic Behavior in the Andreanof Segment.

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What determines megathrust slip behavior in subduction zones is still under debate, and the relationship between the preferred slip style over short, earthquake-cycle time scales and long-term patterns of deformation also remains poorly understood. We collected multichannel seismic data, USGS legacy reflection data, and gravity data in the Andreanof segment of the Aleutian Islands to address these questions. This region presents contrasting seismic and locking behavior from west to east. There is a higher recurrence of large earthquakes and tsunamis and higher coupling in the western section. Moreover, the oblique subduction leads to strain partitioning. As a consequence, the upper plate developed strike-slip faults and rotating blocks, impacting the distribution of compressional and extensional stress.

Observations indicate distinct forearc deformation styles in the eastern region (Atka) and the western region (Adak). Atka has a wide forearc basin with flat layers, whereas Adak shows more compression by uplifting the frontal prism and forearc basin shortening, which correlates with the higher recurrence of megathrust earthquakes. Adak shows intracrustal reflectors that could be magmatic intrusions, underplating, or old deformational features.

The incoming plate properties, sediments, and trench infill show similar characteristics in the entire Andreanof segment. Thus we propose that overriding plate properties contribute to the different seismic and deformational styles. The combination of differences in rheology due to magmatic intrusions, underplating, and/or pre-existing deformation and differences in tectonic stress associated with rotating blocks and the strike-slip systems could impact fault development and changes in forearc permeability. We explore the hypothesis that the higher shortening in the western section could be more efficient in releasing pore fluid pressure, increasing the effective stress, which promotes coupling and deformation.

Structural and Compositional Controls on Megathrust Slip Behavior Inferred From a 3D, Crustal-Scale, P-Wave Velocity Model of the Alaska Subduction Zone Spanning the Incoming and Overriding Plates

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Earthquake hazard assessment in subduction zones requires an understanding of how large-scale features of both the downgoing and overriding plates influence megathrust slip behavior. However, questions remain regarding the role of broad structural variability in modulating complex behaviors of megathrust faults. The Alaska subduction zone offshore the Alaskan Peninsula exhibits along-strike variations in geodetic plate coupling, seismicity, and earthquake rupture style, making it an excellent location for studying these structural influences. Here, we focus on the Semidi segment and SW Kodiak Asperity of the Alaska subduction zone. Plate coupling is typically high in our study area, with the largest degree of locking inferred near Kodiak Island which hosted part of the 1964 Mw 9.1 event. Coupling decreases to the west, with recent modeling showing a reduction in size of persistent asperities associated with past (1938-1964) and recent (2021) great earthquakes.

In this presentation, we will explore potential structural and compositional controls on spatial variations in megathrust slip behavior by analyzing a 3D P-wave velocity model within a 400- by 400-km area with resolution down to 25-30 km depth. The model was computed by traveltime tomography inversion of wide-angle first-arrivals interpreted from active-source ocean bottom seismometer data acquired as part of the Alaska Amphibious Community Seismic Experiment (AACSE). Results underscore the heterogeneity of the incoming plate marked by hotspot magmatism, fracture zones, and uneven sediment cover. Landward of the trench, variations in backstop geometry and

slab velocities appear correlated with changes in sediment input and the possible downdip persistence of structural features of the incoming plate. In the overriding plate, velocity changes provide clearer evidence of differences in metamorphic grade between terranes and intrusions therein. This presentationwill focus on reconciling these observations with corresponding changes in megathrust plate coupling as well as with past and recent large earthquakes in the area.

A Late Miocene to Pliocene Increase in Soft-Sediment Deformation in Cook Inlet Nonmarine Forearc Basin Strata—potential Evidence for Larger Magnitude Earthquakes Associated With Increased Sedimentation in the Alaska Trench

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Previous analyses of compiled megathrust earthquake data have revealed a statistically significant positive correlation between great events (>M_w8.0) and thicker sediment fill in the trench. This has been interpreted to reflect the important role sediment can play in muting bathymetric relief and smoothing the subduction interface. The reduction in potential asperities may allow ruptures to propagate for longer distances, increasing the total energy released. Seismological studies in southern Alaska have imaged a low velocity zone beneath the Kenai Peninsula, consistent with underplated sediment. This material in the subduction channel is likely sourced from the east, where immense volumes of glaciogenic sediment have been routed into the trench since Late Miocene time (~7 Ma), reflecting rapid uplift and exhumation of the Chugach–St. Elias orogen during collision of the Yakutat terrane.

The 1964 M_w9.2 earthquake in southern Alaska produced a variety of liquefaction features in terrestrial settings, including sedimentary dikes that fed surface sand volcanoes. Potentially analogous soft-sediment deformation is locally observed in the Lower and Middle Miocene Tyonek and Beluga formations along the lower Kenai Peninsula. The relative abundance of these features increases dramatically in the overlying latest Miocene to Pliocene Sterling Formation, ranging from complexly folded, convolute bedded sandstone to zones where disrupted laminations grade laterally into structureless units. These facies are often closely associated with vertical pipe-like features that are collectively interpreted as evidence for liquefaction during intense, prolonged seismic shaking. We suggest the notable rise in soft-sediment deformation at ~ 5–7(?) Ma may reflect an increase in the frequency of very large megathrust earthquakes promoted by greater Neogene sediment flux into the trench. If correct, our study significantly extends the possible record of large megathrust earthquakes in southern Alaska into deep geologic time and highlights the value of forearc basins as long-term archives of subduction zone dynamics.

Variations in the Alaska-Aleutian Subduction Megathrust Properties Along Strike Using Several Seismic Imaging Techniques

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The Alaska-Aleutian subduction zone is one of the most seismically active plate boundaries in the world. Many of the subduction zone characteristics are linked to the shear zone at the top of the subducting plate. However, our interpretation of this region is limited by the discrepancy observed between seismic imaging techniques. We investigate this discrepancy and changes in the Alaska subduction zone properties along strike using a combination of seismic imaging techniques. We analyze data from 34 onshore and offshore broadband seismic stations from the Alaska forearc, recorded by the Alaska Amphibious Community Seismic Experiment (AACSE; 2018-2019) and surrounding permanent stations. At each station, we identify high-frequency P to S (PS; 1-10 Hz) mode conversions from local in-slab earthquakes at the subducting plate interface. We also generate receiver functions (RFs) from teleseismic earthquakes (0.03–1.5 Hz) to identify the PS arrivals associated with the subducting plate. The PS arrival time is dictated by the depth of structures to which the local and RF PS arrivals are sensitive. Using 3D ray tracing, we find local PS arrivals are sensitive to structures 10 km shallower than RF PS arrivals. The depth of structures seen by local PS corresponds to the top of the high reflectivity shear zone in co-located active source profiles, while the RFs illuminate the oceanic Moho. These results and full waveform modeling indicate that local PS arrivals are sensitive to finer-scale structures within the shear zone, while RFs respond to longer-wavelength structures. Therefore, the discrepancy observed between seismic imaging techniques is explained by frequency-dependent sensitivity to structure. Local Ps arrivals are observed across the Kenai, Semidi, and Shumagin segments but are absent around Kodiak. The lack of local PS conversions below Kodiak could indicate the shear zone and upper plate have similar seismic properties, or that there is no shear zone present. Along-strike variability in PS arrivals provides valuable insight into changes in shear zone properties.

Implications of Yakutat Oceanic Plateau Buoyancy Versus Variable Interface Coupling on Deformation in South-Central Alaska

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The subduction margin of south-central Alaska is marked by oblique flat slab subduction and subduction-collision of the Yakutat oceanic plateau beneath North America. Both subduction of young seafloor and subduction of an oceanic plateau may cause an increase in slab buoyancy that can lead to increased resistance to subduction as well as significant upper plate deformation. However, the trade-off between flat slab subduction of young lithosphere versus oceanic plateau subduction on overriding plate deformation in Alaska is still not well understood. Here we present three-dimensional numerical models of subduction in Alaska to examine: 1) the effects of flat slab subduction geometry, 2) a localized increase in coupling along the plate boundary interface in the flat slab region, and 3) buoyancy of an oceanic plateau in controlling upper plate deformation. Simulations of flat slab subduction with variable plate boundary coupling (10^20-10^21 Pa s) and with a simplified compositional buoyancy of the Yakutat oceanic plateau are analyzed. To determine which set of parameters are most representative of the Alaska subduction system, model results are compared to observations of Wrangell block motion, differential motion across the Denali fault, and with along-strike variations in mountain building. We find that the positive buoyancy from the Yakutat oceanic plateau increases Wrangell block velocity, differential motion across the Denali fault, as well as the extent of far-field deformation. Models with both the Yakutat buoyancy and a local increase in plate coupling, however, cause a greater resistance to subduction causing a significant reduction in downgoing plate motion. This suggests a trade-off between the degree of plate coupling and oceanic plateau buoyancy. Nonetheless, the geodynamic simulations show that the inclusion of the buoyant oceanic plateau is important for producing positive dynamic topography above the flat slab and increasing Wrangell block velocity, suggesting that subduction of the Yakutat oceanic plateau is an important driver of overriding plate deformation in south-central Alaska.

Controls on Bending-Related Faulting Offshore of the Alaska Peninsula

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Oceanic plates experience extensive normal faulting as they bend and subduct, enabling fracturing of the crust and upper mantle. Debate remains about the relative importance of pre-existing faults, plate curvature and other factors in controlling the extent and style of bending-related faulting. The subduction zone off the Alaska Peninsula is an ideal place to investigate controls on bending-related faulting as the orientation of abyssal-hill fabric with respect to the trench and plate curvature vary along the margin. Here we characterize bending faulting between longitudes 161°W and 155oW using newly collected multibeam bathymetry data. We also use a compilation of seismic reflection data to constrain patterns of sediment thickness on the incoming plate. Although sediment thickness increases by over 1 km from 156°W to 160°W, most sediments were deposited prior to the onset of bending faulting and thus have limited impact on the expression of bend-related fault strikes

and throws in bathymetry data. Where magnetic anomalies trend subparallel to the trench (<30°) west of ~156°W, bending faulting parallels magnetic anomalies, implying bending faulting reactivates pre-existing structures. Where magnetic anomalies are highly oblique (>30°) to the trench east of 156°W, no bending faulting is observed. Summed fault throws increase to the west, including where pre-existing structure orientations do not vary between 157-161oW, suggesting that the increase in slab curvature directly influences fault throws. However, the westward increase in summed fault throws is more abrupt than expected for changes in slab bending alone, suggesting potential feedbacks between pre-existing structures, slab dip, and faulting.

Outer-Rise Earthquakes and Their Contribution to Tsunami Hazards Across the Alaska Subduction Zone

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We compare the Shumagin, Semidi, and Kodiak sections of the Alaska subduction zones in terms of their outer-rise seismicity, faulting, and potential tsunami hazard. We use data from land and ocean-bottom seismometers deployed during the Alaska Amphibious Community Seismic Experiment (AACSE) and other land-based networks to relocate earthquakes. Seismicity is highest in Shumagin, with normal faulting extending to 25 km below the seafloor and confined within 50 km of the trench. Semidi has less seismicity extending further from the trench, and the focal mechanisms transition to strike-slip in the Kodiak segment. In Kodiak, we determine relative locations of aftershocks from the 2018 Mw 7.9 offshore Kodiak earthquake with a hypocentroidal decomposition program. The aftershocks form multiple N-S oriented lines consistent with right-lateral faulting along the N-S nodal plane of the focal mechanisms. TOPAS sub-bottom profiler records show numerous closely-spaced (~ 5 km) N-S faults throughout the aftershock zone, but no NE-SW faults. These results demonstrate that the 2018 mainshock consisted of strike-slip faulting along numerous en echelon N-S faults. The along-strike transition in outer-rise focal mechanisms indicates a change in tectonic stress regimes. Normal faulting earthquakes in Shumagin transition to right-lateral strike-slip earthquakes by the boundary of the Kodiak segment. This transition approximately corresponds to the western extent of the 1964 Alaska earthquake rupture zone, suggesting it may result from increased seismic coupling along the megathrust to the east. For Shumagin, assuming a maximum normal faulting depth of 25 km and the observed maximum seafloor fault length of 48 km (Clarke et al, in press), earthquake scaling laws predict a maximum outer rise earthquake magnitude ~ M_W 7.3, which is insufficient to produce a damaging tsunami. However, if ruptures propagate across fault segment boundaries, tsunamigenic events of up to ~ M_W 8.2 could occur. The transition to strike-slip faulting in the Kodiak segment and eastward suggests very limited outer rise tsunami hazard in these regions.

High-Resolution Rayleigh-Wave Tomography Constraints on Hydration in the Incoming Plate Along the Alaska Subduction Zone

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Subduction zones are known to drive the water cycle on our planet, and water that penetrates the subduction zone influences fundamental geological processes like the occurrence of large earthquakes and the generation of arc magmas. However, the initial water content of many subducting slabs is poorly known. Here we provide new constraints on the distribution of hydration in the incoming Pacific plate offshore of the Alaska Peninsula. We image crust and shallow-mantle shear velocity and azimuthal anisotropy using short-period Rayleigh waves derived from 15 months of ambient seismic noise recorded by 32 ocean-bottom seismometers that were deployed from outboard of the outer rise to just inboard of the trench during the Alaska Amphibious Community Seismic Experiment. After correcting for tilt and compliance effects on the short-period Rayleigh waves, we observe first-overtone Rayleigh waves with high signal-to-noise ratios at periods of 5-10s. These data are useful for constraining velocity in the incoming oceanic crust and uppermost mantle. We measure inter-station phase velocities using a spectra-fitting technique, and invert for 2-D phase velocity maps and 1-D and 2-D estimates of azimuthal anisotropy. Phase velocity maps are then inverted for a 3D model of shear velocity in the crust and upper mantle. Shear velocities show >5% lateral variations on the incoming plate in both the crust and shallow mantle, with localized low velocities outboard of the Shumagin gap, the Semidi segment, and the Kodiak region. Across the region, we find slower velocities than expected for normal oceanic mantle and crust, suggesting pervasive hydration. We also find variations in crustal thickness associated with heterogenous plate history. Where well constrained, we find weak azimuthal anisotropy with peak-to-peak amplitudes of 0-2%, and fast directions that are oblique to the orientations of both expected seafloor-spreading mantle fabric and observed bending faults. These observations may be consistent with the competing anisotropic effects of fault-induced structural heterogeneity, and seafloor-spreading-induced olivine fabric.

Slab Dehydration Linked to Great Earthquake Rupture Barriers Along the Alaska Peninsula

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The amount of water entering subduction zones and how this water is stored within the slab is debated. This limits our understanding of where exactly fluids are released during subduction and thus how the presence of fluids and changes in pore pressure influence slip behavior along megathrusts. Here we present 3-D compressional and shear-wave velocity models, and their ratio Vp/Vs, of the Alaska Peninsula subduction zone derived from local earthquake tomography of the Alaska Amphibious Community Seismic Experiment dataset. We use these models to investigate the hydration of, and fluid release from, the downgoing plate, and how this impacts megathrust rupture. First, we identify a wide-spread water reservoir within the upper mantle, characterized by elevated Vp/Vs resulting from fluid-filled low-aspect ratio crack porosity. Second, slab dehydration is inferred from seismic velocity anomalies along the plate interface that we interpret as regions of high pore fluid pressure. These regions bound the rupture zones of the recent 2020 M_w7.8 Simeonof and the 2021 M_w8.2 Chignik earthquakes, demonstrating how locations of fluid release and elevated pore pressure impact the frictional properties of the megathrust and act as rupture barriers.

Seismic Structure of Arc Crust in the Andreanof Segment of the Aleutian Arc from Wide-angle Refraction Data

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Arc crust is thought to be the source of new continental crust at this stage of Earth's history. However, the basic structure of arc crust, the processes by which arc crust bulk composition evolves to match that of continental crust, and the pathways of melt migration and magma storage which control arc geochemistry are not well understood. The Andreanof segment in the central part of the Aleutian Arc is a relatively undeformed and unrifted segment, making it an excellent place to study the processes and factors influencing the construction and composition of arc crust. Further, geochemical variations in arc lavas vary along strike within the segment, suggesting that there may be variations in tectonically controlled volcanic plumbing systems and/or differences in the incoming plate which influence arc construction over relatively short length scales.

We conducted an active-source seismic study of the Andreanof segment in August-October 2020, with the goal of imaging the arc in sufficient detail to characterize the structure of the crust and any variations in that structure with potential links to the geochemistry of volcanic products. Here we present a quasi-three dimensional velocity model for a seismic refraction line collected along-strike of the segment, incorporating data from active-source shots surrounding several islands and recorded both on 33 short-period ocean bottom seismometers and 34 AVO broadband stations. Notable features include a seismically slow carapace layer up to ~2 km thick, likely comprised of volcanic flows and rubble; and anomalously slow crustal velocities, especially beneath the Amlia basin.

Along-strike Variations in Sub-arc Melting Beneath the Alaska Peninsula Revealed by Body Wave Attenuation

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The diverse volcanic activity at the Alaska Peninsula potentially indicates substantial variations in mantle melting processes beneath the arc. Here we investigate sub-arc melting beneath the Alaska Peninsula by measuring seismic attenuation in the mantle wedge as attenuation is sensitive to fluids, temperature, and partial melting. Our preliminary findings show high attenuation anomalies at varying depths in the mantle wedge, with notable distinctions in their lateral extent. In the northeast, high-attenuation anomalies are imaged beneath major volcanoes and also at greater depths beneath the back arc. In contrast, beneath the Pavlof volcano in the southwest, high attenuation is imaged at shallower depths down to 60 km. The observed variations suggest along-strike changes in the thermal structure of the mantle wedge, hydration of the subducting plate, and mantle flow patterns.

A Possible Slab Window Along the Alaska Subduction Zone Imaged by Full Wave Ambient Noise Tomography

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Along-strike heterogeneities of subduction zones have been observed globally with variable behaviors in seismicity, locking fraction, slab dip, and volcanism. The Alaska subduction zone is an ideal natural laboratory to study the processes controlling the along-strike variability of subduction systems. Previous studies have demonstrated differences in slab dip, megathrust seismicity, seismic anisotropy, plate interface locking fraction, and variations of slab hydration partly related to changes in oceanic plate fabrics. However, the relationship between these observations and the 3-D structural segmentation remains poorly constrained. Here we use full-wave ambient noise tomography to generate a 3-D shear-wave velocity model of the Alaska subduction zone in the Alaska Amphibious Community Seismic Experiment footprint along the Alaska peninsula. Our velocity model reveals strong variations in the geometry and velocity of the subducting Pacific slab. Low-velocity anomalies are present in regions of active volcanism and sediment subduction while fast-velocity anomalies are observed in the subducting slab. At mantle depths, low-velocity anomalies correlate with the projected changes in plate fabrics and the gap of intermediate-depth earthquakes, indicative of a potential slab window. Our findings suggest that, at the intersection of two plate fabrics, the slab might be relatively weak, which may facilitate tearing of the slab, allowing the sub-slab asthenosphere to flow through.

The Structure of the Alaskan Mantle: A Full Waveform Inversion Approach

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Alaska has a complex subduction history, the remnants of which should be present down to the lowermost mantle. However, using existing tomographic images it has been difficult to trace the long-term subduction patterns. This partly results from inconsistencies between different global and regional tomographic models of the area due to methodological limitations and limited sampling. Moreover, travel time tomography has known limitations when resolving complex mantle structure, particularly when anomalies are strong and localised. In contrast, Full Waveform Inversion, which seeks to explain every wiggle of the seismogram, can account for multipathing and wavefront healing that mask strong heterogeneity like slabs and mantle wedges. Therefore, Full Waveform Inversion can help improve our understanding of the tectonic history of the Northern Pacific. In particular, it can aid in resolving the thickness of the Yakutat terrain and the width of the subducted slab.

Reducing the computational cost of Full Waveform Inversion is a major challenge in its application. With this aim in mind, Masson and Romanowicz (2017, GJI) proposed a methodology, called "Box tomography", in the framework of regional tomography, that allows the coupling of any solvers outside and inside the target region. With this approach now available for use at large scale with both sources and stations outside the target region (Adourian et al., 2023), it becomes possible to take into account teleseismic wavefields recorded at stations located beyond the boundaries of the target region. Thus, we apply Full Waveform Box Inversion to Alaska. Our inversions so far have resolved a stronger and narrower seismic anomaly associated with the subducted Pacific plate than resolved with past methods. We aim to map the subduction history from the surface to the core mantle boundary.

Upper Mantle Velocity Structure and Anisotropy of the Alaskan Subduction Zone from Surface Wave Tomography

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The subduction zone along the southern margin of Alaska is home to numerous active volcanos, and is the most seismically active portion of the United States. It has hosted several megathrust earthquakes, including the 1964 Great Alaskan Earthquake, the second largest earthquake in recorded history. The seismic and volcanic behaviors of the subduction zone, however, undergo dramatic changes along strike, with some areas slipping in great (M>8) events while other regions deform primarily through creep. Understanding the origins of this variability could lead to important insights into subduction zone processes and global geophysical hazards. Recent studies have highlighted the role that hydration of the subducting slab and the mantle wedge may play in governing these behaviors. In this study, Rayleigh and Love waves from teleseismic earthquakes recorded on OBS and broadband land stations from Alaska Amphibious Community Seismic Experiment are combined with similar data from the Alaska Transportable Array and other regional arrays are used to build Rayleigh and Love wave velocity models. These surface wave models are inverted for Sv and Sh velocities to solve for radial and azimuthal anisotropy in the upper mantle beneath the Alaskan subduction zone. These models of velocity and anisotropy show considerable variation along strike and support the hypothesis that hydration of the mantle wedge varies with the Alaskan subduction system.

Structure and Behavior of the Alaska-Aleutian Subduction Zone [Poster Session]

Poster Session • Friday 3 May

Conveners: Grace Barcheck, Cornell University (grace.barcheck@cornell.edu); Julie Elliott, Michigan State University (ellio372@msu.edu); Ronni Grapenthin, University of Alaska (rgrapenthin@alaska.edu); Donna Shillington, Northern Arizona University (donna.shillington@nau.edu); Xiaotao Yang, Purdue University (xtyang@purdue.edu)

POSTER 104

A Re-Evaulation of Slip During the 2021 M8.2 Chignik, Alaska Earthquake

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Along the Alaska-Aleutian subduction zone, there have been more large earthquakes during the past century than at any other subduction zone, including four large M7+ earthquakes since 2020. The largest among these is the 2021 M8.2 Chignik earthquake, which ruptured part of the Semidi segment. This rupture started just to the east of a transition from lower to higher coupling on the megathrust. The Chignik earthquake has raised questions about earthquake triggering, relationships between coupling and earthquake rupture, and possible loading of the shallow megathrust. To answer these questions, a robust understanding of the coseismic slip distribution is needed. Multiple coseismic models have been published, but they show variations in the amplitude and location of slip. To improve our picture of the coseismic slip distribution, we will present new coseismic models of the 2021 Chignik earthquake that incorporate a larger dataset, including campaign GNSS measurements, and use two different slab models to test the influence of slab geometry.

The campaign GNSS measurements have been corrected for post-seismic afterslip with existing InSAR data that has been tied with static GNSS offsets, high rate GNSS data, and teleseismic waveforms. To test how different slab models affect slip estimates, we develop models that use both Slab2 and an interface model based on active source seismic imaging (ALEUT model).

At intermediate depths of the megathrust, where the Chignik earthquake occurred, the ALEUT model suggests a plate interface several kilometers deeper than the Slab2 model, which coincides with the USGS hypocenter depth.

POSTER 105

Take the Cook Inlet DAS Earthquake Challenge!

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Our interactive poster illustrates some features of including real-time DAS seismic array data into regional and local earthquake monitoring using the increasingly novel approaches of HL (Human Learning) and NI (Natural Intelligence). Our goal is to stimulate thought and discussion about possible roles of DAS within regional networks...and to have some serious FUN! From July 2023 through January 2024 we interrogated two dark fiber arrays on the seafloor of southern Cook Inlet, Alaska producing time series of strain at seismic frequencies (*i.e.,* seismograms). The interrogator is located in Homer on the Kenai Peninsula and the fibers cover about 170 linear km of seafloor in two fiber spans. The arrays record earthquake ground motions, a variety of ambient signals ("noise"), and vigorous energy emanating from movement in the seawater column. The channel and gauge lengths were 9.57m and 23.9m, respectively. The sampling frequency of earthquake data shown is 25 sps.

GAME SETUP: Virtual gathers of the >17,000 strain seismograms for 10 earthquakes are presented surrounding a map showing epicenters of 10 earthquakes (origin details from the Alaska Earthquake Information Center) each producing one of the displayed seismogram gathers. GAME ACTION: The player fills out and returns a "contest card", attempting to match each epicenter with its corresponding and correct data image. The viewer may ask the presenters/authors questions about the array(s), the interrogator, the fiber and its emplacement, details about acquisition, processing and the individual earthquake source parameters. However, questions about which earthquake source corresponds (or not) to which display figure are "out of bounds" SCORING: Each correct answer is worth 2 points; each incorrect answer is worth 1 point (there is value in thinking through the issues!); each null answer earns no points. WINNING and PRIZES: The contestant with the highest numerical score wins and receives a fabulous prize (yet to be determined—don't get too excited). In the event of a tie, a random drawing (or largest bribe) will determine the unique winner.

POSTER 106

Searching for Microseismic Precursors to the July 2020 Mw 7.8 Simeonof, Alaska Earthquake in a Machine-Learning Enhanced Catalog

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Examining patterns of small earthquakes within subduction zones has the potential to provide insights into the physical processes that control the initiation of great (magnitude $M > 7$) megathrust earthquakes. The use of machine learning has enhanced our ability to detect these small events. This study explores offshore seismic activity in the months leading up to the 22 July 2020 M_w 7.8 Simeonof earthquake in the Alaska-Aleutian Subduction Zone (AASZ) by using a locally-trained machine learning picking model to detect and catalog small seismicity. Detecting small earthquakes in subduction zones presents a challenge due to their offshore location, where land-based seismic networks have low sensitivity. Fortunately, recent advances in machine learning-driven detection methods enable the creation of more-complete seismic catalogs compared with traditional methods, even for offshore seismicity. We use an EQTransformer picking model trained on 6,764 earthquakes (~123,000 waveforms) recorded on land by the Alaska Amphibious Community Seismic Experiment to construct an earthquake catalog spanning October 2019 to July 2020. Using match filter, we will further expand the catalog, lowering the magnitude of completeness. Looking forward, this catalog, along with an improved understanding of earthquake locations in the AASZ (see Nolan et al., this session), will enable us to analyze microseismicity patterns relative to mainshock hypocenters and asperities, and reveal fault zone processes in the AASZ leading up to a major seismic event.

POSTER 107

Introducing the Alaska Broadband Accessory Deployment for Geophysical Research (BADGER): A New Seismic Dataset for Investigating Slow Slip and Subduction Zone Structure

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The Cook Inlet region of the Alaska-Aleutian subduction zone spans two areas of recurrent Slow Slip Events (SSEs). The northern zone, coincident with subduction of the Yakutat terrane, has been associated with seismic tremor, while the southern SSE zone has not. Both tremor and slow slip have been linked to physical properties of the subducting plate, including crustal fluid content and variations in lithology and/or metamorphic facies. Seismic observations are key to understanding how these properties vary spatially, and how they influence slip rate and seismicity style. Thus far, the northern Cook Inlet SSE zone has been more heavily instrumented. Therefore, we have deployed the Alaska Broadband Accessory Deployment for GEophysical Research (BADGER) experiment to enhance data coverage above the southern SSE zone. Eleven broadband seismometers were installed with dense (10-20 km) spacing on the western Kenai Peninsula in November 2022 for a planned two-year deployment. This campaign emphasized inclusive fieldwork practices by choosing accessible sites and involving community members and K-12 schools.

Scattered-wave imaging, including receiver functions and P wave coda autocorrelations, constrains seismic wavespeed contrasts across the subduction interface and the subducting plate Moho. Wavespeed can then be linked to variations in fluid content, lithology, and anisotropy of the subduction zone. Here we present synthetic tests demonstrating the ability of these imaging methods to distinguish between end-member models of fluid saturation conditions and metamorphic facies. Subsequently, we present preliminary results for teleseismic Ps receiver functions and P wave autocorrelations using the first year of Alaska BADGER data. High noise levels due to the Cook Inlet, basin reverberations, and near-surface natural and anthropogenic sources, present challenges. A concurrent Distributed Acoustic Sensing (DAS) experiment on fiber optic cables beneath the Cook Inlet provides exciting opportunities for augmenting the land-based dataset, and for exploring bridges between DAS and broadband seismic experiments.

POSTER 108

Mapping the Alaskan Lithosphere Based Upon Joint Full-Waveform Inversion of Ambient Noise and Local Earthquake Data

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Alaska is one of the most tectonically active regions in North America, with unique and complex geologic structures shaped by multiple episodes of tectonic processes in the geologic history. We aim to construct a high-resolution shear-velocity model of the entire Alaskan lithosphere to better understand the tectonic evolution of this region.

We use high-quality broadband seismic data, bolstered by the USArray deployment in Alaska, to image the shear velocity of the crust and uppermost mantle. To resolve both shallow and deep structures in the lithosphere, we jointly use ambient noise data and local earthquake data to perform full-waveform seismic inversion. For ambient noise data, continuous seismic records are collected and processed to extract the three-component empirical Green's functions (EGFs) between station pairs, and frequency-dependent travel-time shifts are measured between the EGFs and the simulated Green's functions. For local earthquake data, instead of directly using the absolute travel-time shifts, we measure the difference of the frequency-dependent travel-time shifts between station pairs, known as double difference (Yuan et al. 2016), to enhance receiver-side resolution and mitigate the effect of inaccurate event centroid times. The waveforms are filtered at a period band of 12-50s for ambient noise data, and 25-120s for local earthquake data, for measurements, which are then inverted using the adjoint tomography method to obtain the structural model. The forward and adjoint simulations are carried out using the SPECFEM3D_Cartesian package on a mesh customized to the dimension of the study region. The dynamic mini-batch technique (van Herwaarden et al. 2020) is used to accelerate the inversion process.

We present our model from the surface down to 150km depth, revealing the variation of crustal thickness in this region, magmatic activities and a segmented subducted slab in Southern Alaska. At broad scale, the tomographic image shows that the Alaskan lithosphere can be divided into three blocks, each with a distinct tectonic feature.

POSTER 109

Insights Into Inherited Crustal Features and Southern Alaska Tectonic History From Sp Receiver Functions and Seismicity

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The deformation history of the crustal blocks across southern Alaska and geometric history of the bounding faults reflect both inherited features and subsequent convergent margin events. Multiple dense (<20-km spacing) arrays of broadband seismometers across southern Alaska have previously allowed for imaging of crustal structure across the region using various seismic imaging methods. Here, we employ S-to-P receiver functions to investigate the crustal structure of southern Alaska for signals of dynamic tectonic activity. The subduction zone plate interface and subducting slab Moho are imaged dipping at shallow (<60-km) depths across the southernmost part of the subduction zone, in agreement with previous P-to-S receiver function imaging. Along two different transects, an inland-dipping (~15°) boundary is imaged intersecting the trace of the Border Ranges Fault at the surface. This feature may represent an unrotated paleo-subduction (Mesozoic) interface. This observation is combined with previous seismic imaging along both the Border Ranges Fault and the next seaward terrane-bounding fault—the Contact Fault—to examine along-strike gradients in the dip of these structures and the relationship between their variable rotation and the history of convergent tectonics along the margin. Along with large (>10-km) crustal thickness offsets imaged across both the Denali Fault system and the Eureka Creek Fault, these features provide a test of previous hypotheses for subduction polarity in the region. Additionally, a sharp positive velocity gradient with increasing depth is imaged at ~25-km beneath the Copper River Basin, which is most easily explained as a shallow Moho and may be related to the generation of a new Wrangell Volcanic Field volcano, resulting from the underlying tear in the subducting slab. New tremor and low-frequency earthquake locations across the Copper River Basin region contrast with these seismic imaging results and raise questions about the structure and dynamics surrounding the tear in the subducting Yakutat slab.

POSTER 110

Examining the Distribution of Earthquakes Within the Alaska-Aleutian Subduction Zone Using Events Detected by the Alaska Amphibious Community Seismic Experiment

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Small earthquakes in subduction zones indicate where deformation is taking place and can help us understand why regions exhibit differences in plate coupling and rupture behavior; however, knowledge of precise earthquake locations relative to large-scale structure is critical for interpretations. Between May 2018 and September 2019, the Alaska Amphibious Community Seismic Experiment (AACSE) deployed 30 land stations and 75 ocean-bottom seismometers (OBS) within the Alaska-Aleutian Subduction Zone (AASZ). The AACSE array in combination with the nearby Earthscope Transportable Array and permanent stations led to the detection of over 7,200 earthquakes. These events were located using the same parameters the Alaska Earthquake Center routinely uses for events detected on their permanent array of land stations. The routine catalog placed many events in the general vicinity of the interplate thrust zone, indicating activity on that fault, but large depth uncertainties allow for other interpretations. In particular, many of these earthquakes may be within the downgoing plate as has been observed farther east in the 1964 rupture zone. Inspection of travel times to OBSs directly above earthquakes confirms that the apparent thrust-zone earthquakes lie well below the plate interface, showing deformation within the downgoing plate. An additional 15,000 events have been detected within the AACSE dataset using EQTransformer trained on the AACSE land data. To better understand the distribution of earthquakes within the AASZ, we conducted a joint velocity-hypocenter inversion to relocate all the events detected by the AACSE array. A 3D velocity model and station corrections are used in the inversion to account for the complex sedimentary structure beneath the OBSs. This catalog in combination with one being developed between the end of AACSE in October 2019 and the July 22, 2020 Mw 7.8 Simeonof earthquake (see Friedman-Alvarez et al., this session) will help improve our understanding of how the distribution of earthquakes relates to subduction zone structure and seismic cycles.

POSTER 111

Searching for Tectonic Tremor Along the Lower Cook Inlet Portion of the Alaska-Aleutian Subduction Zone

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The origin of tectonic tremor along the eastern Alaska-Aleutian subduction zone remains poorly understood. Tremor has been detected along the subduction interface in the Upper Cook Inlet (UCI) vicinity, where the inferred Yakutat microplate is undergoing subduction. This tremor is approximately coincident with slow slip events (SSEs). However, tectonic tremor has not been observed in the Lower Cook Inlet (LCI) during SSEs through 2012. We investigate whether the absence of tremor is intrinsic to SSEs in the LCI during more recent events using automatic detection. Here we present preliminary results from this effort, focusing on a likely SSE in the LCI after the 2016 Old Iliamna earthquake. We selected stations from the Southern Alaska Lithosphere and Mantle Observation Network (ZE), Alaska Regional Network (AK), and the USArray Transportable Array (TA) within and near the Cook Inlet that were operating during the SSE. Several months of continuous data were analyzed to identify and locate any instances of tremor, using the automated location tool *Enveloc*. We filtered seismic waveforms, computed envelopes, and determined event locations through a 3D grid search that optimized cross-correlations of envelopes between stations. If tremor is absent in the LCI during the 2016 SSE, this would suggest that there is a fundamental difference between how slow slip proceeds in the LCI vs. the UCI, which may be related to physical properties within the subduction zone. Conversely, the presence of tremor would provide a new seismic observation that can be used to understand the structure of and interactions between the overriding and subducting plates in this region. This investigation will help us understand how seismicity varies temporally and spatially along the Alaska-Aleutian subduction zone, which will contribute to understanding slow slip events, tremor, and megathrust hazards globally.

POSTER 112

Probabilistic Teleseismic Tomography of the Alaskan Mantle With Corrections for Distant Structure

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Seismic tomography provides a window into the mantle expressions of the tectonic processes that assembled Alaska. Tomographic models have been used to constrain the accretion of the Yakutat Terrane, the origin of the Denali Gap and Wrangell Volcanic Field, and the long-term history of the subduction. In order to estimate the uncertainty in models of the Alaskan mantle and the geometry of structures within it, we apply regional-scale transdimensional Bayesian tomography. This approach has several advantages, including accurate amplitudes and measures of uncertainty for velocity variations. Targeting the mid-mantle beneath Alaska requires the use of teleseismic data, but seismic structure outside the area of study introduces traveltime variance that is not constrained by a regional-scale model. This results in pessimistic error bars for velocity and reduces the confidence of conclusions drawn from the model. It is therefore necessary to find a means of compensating for uncertainty introduced by distant structure.

We present a method for estimating these effects and apply it to the reduction of error bars on a new model of the Alaskan mantle. We demon-

strate the effectiveness of the method with data calculated in existing global models before applying it to USArray, global, and local array data. With the corrected traveltimes, a new model of the Alaskan mantle with improved uncertainty estimates will be produced, enabling the testing of hypotheses about mantle structure.

POSTER 113

Building a 3D Seismic Velocity Model for the Gulf of Alaska

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Offshore regions in tectonically active margins such as Alaska or southern California exhibit extreme structural complexity and produce a wide range of earthquake mechanisms and ground motions. A significant challenge in modeling ground motion at coastal cities is the lack of offshore stations near the offshore earthquakes, which poses challenges both for understanding the offshore earthquakes and for imaging the offshore structure. In south-central Alaska, the active collision and accretion of Yakutat microplate beneath North America plate creates an extremely complex regional structure, including low-velocity accretionary strata. The onshore region has been imaged using permanent stations installed during the STEEP project and augmented by stations from the EarthScope Transportable Array. Most of these tomographic models include inherent smoothing that cannot capture the sharp interfaces of the offshore setting. By comparison, the offshore region of the Gulf of Alaska has been studied only with a sparse array of high-resolution 2D velocity models derived from marine studies conducted between the 1980s and 2000s. Here we leverage these 2D models to create experimental 3D velocity models with known geological features, such as a low-velocity accretionary wedge and the Yakutat block. We then perform 3D seismic wavefield simulations of earthquakes and virtual sources derived from ambient noise cross-correlations on our experimental models and three tomographic models from the EarthScope IRIS EMC repository. These simulations provide insights into the complexity of the recorded seismic wavefield, as well as the limitations of our experimental velocity models. The results of this study should enable us to build a comprehensive 3D seismic velocity model for the Gulf of Alaska.

POSTER 114

Investigating Temporal Velocity Changes and Plate Interface Structure in the Southern Mw 9.2 1964 Great Alaska Earthquake Rupture Area: A Comparative Study of Ambient Noise and Earthquake Observations Using a Dense Node Array

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We present latest findings beneath the Kodiak array employing seismic ambient noise and p-wave coda autocorrelations. Temporal variations observed in noise records offer the potential for high-precision monitoring of changes in elastic properties. These fluctuations, mainly influenced by long-period ocean waves, lead to clear shifts in observed seismic velocities. Our analysis indicates fractional variations in the order of 0.01%. We further demonstrate the influences of external phenomena such as tides, temperature, and precipitation on velocity changes.

Prior studies utilizing the Kodiak node array with receiver functions have successfully depicted a clear image of the subducting slab. Our research conducts a detailed comparative analysis between receiver functions, P-wave coda, and ambient noise autocorrelations. The autocorrelation methods reveal unique reflectors not previously observed in receiver functions, establishing it as a valuable complementary imaging technique.

POSTER 115

Upper Plate Structure in the Alaska Subduction Zone Across the 2020 and 2021 Ruptures From 2D Wide-Angle Seismic Data

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The rigidity and permeability of the overriding continental plate are proposed to influence megathrust behavior in many subduction zones. Here we use 2D wide-angle seismic data acquired in 2011 to evaluate upper plate controls on megathrust behavior across the Semidi and Shumagin sectors of the subduction zone off the Alaska Peninsula. The Semidi segment is strongly locked and regularly ruptures in great (M>8) megathrust earthquakes, such as the M8.2 in 2021. The Shumagin segment is weakly coupled and appears to host regular M7.x events, such as the M7.8 in 2020, but has not hosted a M>8 in at least ~170 years. We present 2D P-wave seismic velocity models across these segments obtained from joint reflection and refraction tomographic inversion. Model uncertainty was estimated using a Monte Carlo approach. The resulting P-wave velocity models display large-scale velocity variations in the overriding plate that are interpreted to represent the extent of the accretionary prism and accreted crustal terranes that form the overriding plate: the Prince William and Chugach terranes. In the Semidi segment, recently recognized shallow slow slip and afterslip appear to be focused beneath the accretionary prism and younger, lower velocity Prince William Terrane while rupture in the 2021 earthquake is concentrated below the higher velocity Chugach terrane. In the Shumagin Gap, slip in the 2020 earthquake straddles the Moho of the overriding plate. Correlations between the downdip extent and style of slip events and overriding plate structure suggest an upper plate influence on megathrust behavior here.

POSTER 116

Comparison of Crustal Magmatic Storage at Aleutian Volcanoes, Gareloi and Kanaga, using Teleseismic Receiver Function Analysis

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The Aleutian arc is of considerable interest for geophysical and geologic investigations due to an abundance of 53 historically active volcanoes with several eruptions per year. Characterization of crustal magma storage depths and establishing ties to laterally variable subduction processes along the arc have been challenging due to the remote and harsh environment. In 2019, the Alaska Volcano Observatory conducted upgrades to the seismic network on Gareloi and Kanaga volcanoes in the Andreanof Islands. These upgrades increased the number of three-component broadband seismometers at these volcanoes to five and six, respectively. While these volcanoes are located only ~100 km from each other, there are key differences in observed seismic activity. Both have seismicity persistent through the upper- to mid-crust, but Gareloi's rate of low-frequency seismicity is higher, and it is relatively devoid of volcano-tectonic earthquakes. To better understand what this might imply for crustal magma storage, we use the receiver function (RF) technique to provide independent constraints on subsurface magmatic system geometry.

We calculate RFs from teleseismic earthquakes with >M5.5 from 2019 to 2023. We use the P-to-S converted phases to constrain depths and velocities of abrupt boundaries in the crust related to magmatic structure. Both Gareloi and Kanaga provide good targets for this technique; each station produced on average ~419 RFs with overlapping ray path coverage between stations. We observe arrivals consistent with features in the mid-to-deep crust (~12–25 km depth) at both volcanoes. In addition, the RFs display complex patterns of back azimuthal variability that vary across stations at an individual volcano. We aim to interpret these complex arrivals and compare magma storage at the two volcanoes through forward modeling constraining crustal velocities.

POSTER 117

Cook Inlet DAS (CI-DAS): A Year-Long Experiment Studying Structure, Seismicity, Ocean Waves, and Acoustics Offshore Southern Alaska

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Since June 8, 2023, a Sintela Onyx interrogator unit from the University of Washington FiberLab has recorded continuous DAS data across two 85-km spans of buried seafloor telecom fiber in Alaska's Lower Cook Inlet: one span running NW from the city of Homer to Iliamna Bay, near Augustine Volcano, and the other running SW towards Kodiak Island. The DAS was deployed with a NAS for local data storage and both CPU and GPU servers, enabling real-time edge computing on the continuous data without file transfer. The DAS data is augmented by a land-based experiment, the Alaska Broadband Accessory Deployment for GEophysical Research (Alaska BADGER), which supplies 3C broadband data from the western Kenai Peninsula. Over the first 6.5 months, the DAS system recorded 2881 regional and local earthquakes, spanning a wide range of magnitudes (Ml 0.6 to Mww 7.2) and depths (~0 to 196 km). Our open-source edge compute software automates daily extraction of earthquake waveforms for USGS ANSS cataloged events and transfer of the event data to a server at the University of Washington. Daily reports are also automatically generated and pushed to researchers by email, summarizing recording statistics in order to monitor data quality. Work is ongoing to implement a machine-learning based phase picking and denoising workflow, for eventual use in source studies and travel-time tomography. We are also cross-correlating both ambient noise and earthquake coda waves to construct multi-modal Scholte wave dispersion curves along each cable and invert for the shallow velocity structure of Cook Inlet sediments. Results show an extremely soft sediment layer with a power-law shear-wave velocity profile overlying a stiff basement, the depth of which varies systematically across the inlet. We also record the quasi-static deformation of the seafloor from ocean surface gravity waves. By comparing DAS data with a CDIP wave buoy located ~500 m from the cable in 40 m water depth, we demonstrate that it is possible to measure common wave statistics, including mean wave period and significant wave height, using an empirical transfer function approach.

POSTER 118

Investigation of Magmatic Systems Through Novel Seismic Receiver Function Analysis at Alaska-Aleutian Arc Volcanoes

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The Alaska-Aleutian Arc exhibits along-arc variability in subduction parameters such as sediment input, subduction obliquity, and regional stress states. Thus, it provides an opportunity to investigate relationships between subduction parameters and crustal magma storage. In recent years, teleseismic receiver function (RFs) analysis has been increasingly applied at arc volcanoes to extract mid- to lower-crustal (>10 km) magmatic structure. Recent expansion of broadband instrumentation in the Alaska-Aleutian arc enables systematic application and further development of this technique to constrain variability in arc magma storage. Here, we focus on seven target volcanoes: Pavlof, Shishaldin, Westdahl, Akutan, Makushin, Okmok, and Cleveland. We extract back azimuthal patterns in receiver functions using both classical and novel methods, including harmonic decomposition and unsupervised machine learning, to assess the presence of complex, heterogenous crustal structure, and to assess its correlation to the volcanic edifice. Data at Akutan, Cleveland, and Okmok indicate significant local heterogeneity and a high correlation to the volcanic edifice, likely indicating local magmatic storage. Data at Westdahl and Pavlof indicate less heterogeneity and a low correlation to the volcanic edifice, possibly indicating more sensitivity to regional structure. Finally, data at Makushin and Shishaldin express a moderate correlation to the edifice, likely a result of a superposition of local magmatic and regional structures. This work contributes to the further development of a versatile RF workflow for quantiative comparison of observed crustal structure at arc volcanoes, supporting broader efforts to study arc volcanoes comparatively.

POSTER 119

Testing Machine Learning Phase Pickers to Develop a High-Resolution Earthquake Catalog With a 398-Instrument Nodal Array on Kodiak Island, Alaska

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Portable seismic node instruments enable spatially dense seismic data acquisition for high-resolution imaging and event detection in diverse field areas. The Kodiak node array, deployed during the Alaska Amphibious Community Seismic Experiment (AACSE), consisted of 398 nodal seismometers deployed along roads at - 200–300 m spacing on northeastern Kodiak Island for four weeks in May-June 2019. The network overlies the southern asperity of the 1964 Mw9.2 Great Alaska earthquake and offers a high-resolution snapshot of thrust zone microseismicity several decades after a large megathrust earthquake. Compared with collocated AACSE broadband stations, the node array is far more numerous and closely spaced, providing an opportunity to detect small events which are critical for understanding fault zone structure and earthquake interactions.

Here we create an earthquake catalog using a machine-learning (ML) workflow. To test existing ML picking models on the node data, we first create a node waveform dataset by manually picking 2,467 P and 2,392 S from 23 small and local events using event times from the AACSE catalog. We then use the dataset to test performance on node waveform of 29 pretrained ML picking models available from Seisbench. The picking models have variable performance on the node waveform dataset. Overall, PhaseNet pretrained with INSTANCE, EQTransformer pretrained with INSTANCE, and EQTransformer retrained with local AACSE data resulted in the highest recalls, smallest median residuals, and reasonable number of picks. We are using these three models as starting models for transfer learning, and will apply the re-trained models to continuous node data to detect more regional and low-magnitude earthquakes compared with the AACSE catalog.

Structure, Seismicity and Dynamics of the Queen Charlotte-Fairweather Fault System [Poster Session]

Poster Session • Wednesday 1 May

Conveners: Collin Brandl, University of New Mexico (cbrandl@unm.edu); Andrew Gase, Western Washington University (gasea@wwu.edu); Emily Roland, Western Washington University (rolande2@wwu.edu); Lindsay Worthington, University of New Mexico (lworthington@unm.edu)

POSTER 154

Transpression Along the Southern Queen Charlotte Fault: Underthrusting and Strain Partitioning of the Queen Charlotte Terrace

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The Queen Charlotte Fault (QCF) is a part of the Pacific-North America plate boundary, one of Earth's fastest slipping continent-ocean transforms, and the source of some of Canada's most significant earthquake hazards. The 2012 M7.8 Haida Gwaii thrust earthquake reinvigorated interest in the QCF, especially in its southern section. Mechanisms to accommodate the extremely oblique convergence (from ~5-20-) fall into two end members: oceanic crustal thickening or incipient subduction. Both mechanisms could produce the Queen Charlotte Terrace, an uplifted complex west of the QCF offshore Haida Gwaii. The Queen Charlotte Terrace's crustal structure is crucial for understanding the tectonics and seismic hazards of this region, but previous imaging is limited to shallow penetrating, low-resolution studies that leave most of the deep crustal structure largely unknown. We use multichannel seismic reflection data acquired with a 15 km-long hydrophone streamer to image the crustal structure offshore Haida Gwaii, including the Pacific plate, the Queen Charlotte Terrace, the QCF, and the North American continental shelf. Our images reveal a downwarped and faulted Pacific plate, a Queen Charlotte

Terrace with sub-parallel ridges underlain by landward dipping thrust faults, a localized strike-slip fault that coincides with the surface trace of the QCF, and minimally deformed shallow (<2 km) sediments along North American shelf. Beneath the Queen Charlotte Terrace, continuous underthrusting Pacific plate crust and sediments, topped by a décollement, indicates that recent convergence is accommodated by underthrusting. Thrust faults branch off the décollement and accrete oceanic sediments, building up the Queen Charlotte Terrace. Oblique slip on the frontal thrusts implies that strain is partially partitioned along Haida Gwaii, so the QCF may be slipping at less than the full plate rate. Older oblique strike-slip faults close to the western side of the QCF suggest that the system may have begun with distributed strike-slip on oceanic basement-cutting faults before evolving towards its current configuration as a crustal sliver.

POSTER 155

Local Earthquake Monitoring of the Central Queen Charlotte Fault With an Ocean-Bottom Seismic Array

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High-resolution bathymetry data show that most Holocene slip along the central Queen Charlotte Fault (QCF) has occurred along a narrow fault zone near the edge of the North American continental shelf. Local seismicity along the central QCF is poorly determined because the fault is offshore, and the nearest permanent networked seismic station is >70 km away. Yet, this fault can generate large, hazardous earthquakes. From August 2021 to September 2022, we deployed an array of 28 broadband ocean-bottom seismometers (OBS) along the central QCF within the rupture zone of the 2013 Craig earthquake. Winter storms and strong tidal currents generate significant noise that complicates signal detection and characterization on shallowly deployed (<300 m water depth) seafloor instruments, however, 19 of these instruments recorded useful data for locating nearby earthquakes. We use these stations and 8 networked seismometers to produce an earthquake catalog, using a deep-neural network-based picking routine. Our preliminary earthquake catalog (~1300 earthquakes) shows strong seasonal variation in the number of events. This seasonality may be due to strong secondary microseism noise from winter storms (0.1-3 Hz) and fin whale calls (15-30 Hz) that are more frequent in winter months; both mask portions of the local earthquake spectrum. Most earthquakes are found <10 km from the Queen Charlotte Fault, confirming that most modern tectonic deformation is in a narrow fault zone that dips gently to the northeast. Preliminary locations show a degree of vertical clustering and most earthquakes are in the mid- and lower-crust (~5-20 km). These results suggest that the central QCF is deforming under simple shear in comparison to more oblique, pure shear deformation to the south. Earthquake depth distributions and the degree of localization represented the new seismicity catalog should provide new insight into the rheological conditions along the ocean-continent plate boundary fault. This dataset is also valuable as a prototype for seismic deployments in shallow-water regions of high wave, winter storm and whale activity.

POSTER 156

Morphologic Expression of Shallow Volcanics and Ice Sheet Extent Along the Queen Charlotte Fault, Se Alaska and British Columbia

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Transform faults represent one of the three types of major plate boundaries on Earth and are the least associated with volcanism. The Queen Charlotte fault (QCF) is the fastest-slipping ocean-continent transform fault in the world at 50-57 mm/yr (Brothers et al., 2020). It hugs the continental slope along western North America for >900 km between southern B.C. and southeast Alaska, roughly coincident with the location of the western extent of the Cordilleran ice sheet (CIS) during multiple Pleistocene glaciations. Young (Quaternary) volcanic features exist within 25 km on both sides of the fault, but the mechanisms driving this volcanism remain uncertain. Coupled with recent fault trace mapping and lithospheric-scale geophysical imaging of the plate boundary from the Transform Obliquity along the Queen Charlotte and Earthquake Study (TOQUES) experiment, we explore how the distribution of volcanism relative to fault structural variations and former ice sheet limits may provide new insight into the timing and mechanisms of volcanic activity in southeast Alaska and British Columbia. Using previously published and legacy seafloor geophysical data, as well as new multibeam bathymetry and sub-bottom profile data along the QCF, we synthesize diverse evidence for young and active volcanic features along the QCF. We also reassess seafloor morphology for evidence of the extent of the CIS relative to the location of the plate boundary and currently active fault trace. Mapping the distribution of volcanic activity along the QCF will provide a more robust explanation of 'leaky transform' magmatism at conservative boundaries like transform faults.

POSTER 157

Crustal Velocity Structure of the 2013 m7.5 Craig Earthquake Source Region With Joint Ocean-Bottom Seismometer and Streamer Tomography

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Fault damage zones are regions of fractured rock that surround a fault's main slip interface. Numerical studies show that the presence and depth exent of fault damage zones can influence rupture processes and large, pervasive damage zones may promote complex modes of slip. The Queen Charlotte Fault (QCF), located offshore of southeastern Alaska and western British Columbia, accommodates ~5 cm/yr of right-lateral strike-slip between the Pacific and North American plates along a highly localized fault trace. The QCF has generated several Mw >7 earthquakes in the last century, the most recent being the 2013 Mw 7.5 Craig earthquake. To better understand the structure and material properties of the QCF, including the presence and characteristics of a fault damage zone, we conducted first arrival traveltime tomography with crustal refractions recorded on an ultra-long offset marine seismic streamer and an array of 16 ocean bottom seismometers in the region of the Craig earthquake. Our high-resolution P-wave velocity model constrains the upper crustal structure across the QCF revealing multiple velocity anomalies through the upper seismogenic zone in the Craig earthquake region. A prominent low velocity anomaly lies west of the QCF in the Pacific plate crust, implying past damage in response to oblique collision and flexure. We see no indication of a pervasive damage zone surrounding the main slip interface of the QCF, as is reported in studies at oceanic transform faults that use similar methods. The highly localized nature and lack of an extensive damage zone at the QCF may contribute to large earthquakes.

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Crustal Structure Crossing the Queen Charlotte Fault and Trough in the Region of the Haida Gwaii 2012 m7.9 Thrust Earthquake Using P-Wave Tomography

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In 2012, a M7.8 earthquake ruptured offshore the Haida Gwaii region of British Columbia and generated a small tsunami. The earthquake occurred in a region of the Pacific-North American (Pac-NA) plate boundary where >5 cm/year of transform plate motion is accommodated on the Queen Charlotte Fault (QCF). Along the southern portion of the QCF, a bend in the plate boundary leads to ~15° of convergence. This convergence has been hypothesized to be accommodated by either crustal shortening, particularly along the Queen Charlotte Terrace (QCT), a prism-like structure just offshore Haida

Gwaii, or through underthrusting, more similar to a subduction zone. In the summer of 2021, the Transform Obliquity on the Queen Charlotte Fault and Earthquake Study (TOQUES) collected wide-angle seismic refraction data along the QCF, including a ~75 km-long transect that crosses the plate boundary near the epicenter of the 2012 earthquake. Here we present P-wave tomography from this transect, where 5-km-spaced OBS recorded airgun shots of the R/V Marcus G. Langseth. Records of high-quality crustal and mantle refractions exist along the full offset of the line, as well as reflections from the Pac Moho and NA Moho or lower crust. Refractions were also recorded on a station on Moresby Island. Arrival-time tomography shows variation in seismic velocities transitioning from the eastern-dipping Pac lithosphere to the seismically fast and heterogeneous QCT offshore Haida Gwaii. Velocities support underthrusting of the Pacific slab beneath the QCT but do not show evidence of continued underthrusting east of the where the QCF has been mapped as a through-going, high-angle fault. The shallow structure does show a clear increase in seismic velocities east of the fault at the seafloor, consistent with Miocene uplift of Haida Gwaii, but does not show fault damage. Evaluating the relative contributions of underthrusting vs. crustal shortening is not straightforward, as both the shallow dip of the apparent underthrusting Pac and fast nappe-like structures in the wedge seem to require some of both deformation modes to accommodate convergence.

POSTER 159

Crustal Architecture Across the Queen Charlotte Fault Zone North of Haida Gwaii, British Columbia From 2d Tomography

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The Queen Charlotte fault (QCF) is a 900-km-long dextral strike-slip fault system separating the Pacific Plate from the North American Plate offshore western British Columbia and southeastern Alaska, and is one of the fastest-slipping strike-slip faults in the world, accommodating ~50-57 mm/yr of slip along a highly localized fault zone. While dominantly a dextral transform system, there remains considerable debate about mechanism(s) of oblique convergent strain accommodation ranging from incipient subduction to intraplate deformation. Additionally, seismogenesis along the active fault zone may be partially controlled by material contrasts across the fault, but little is known about the velocity structure at seismogenic depths. Ocean-bottom seismometer (OBS) seismic refraction data collected as part of the 2021 Transform Obliquity on the Queen Charlotte fault and Earthquake Study (TOQUES) project were designed to 1) determine the extent of potential Pacific Plate underthrusting beneath North America and 2) provide insight into the material contrast across the fault at seismogenic depths. We modeled refracted arrivals recorded by 25 OBS located along a >200-km-long linear transect crossing the QCF just north of Haida Gwaii, British Columbia. Our resulting 2D tomographic model images the velocities across the fault zone at up to ~30 km depths, providing the first-ever constraints on the lithospheric architecture in this key tectonic region. We observe high P-wave velocities (> 6 km/s) at relatively shallow depths (<5 km), and greater velocity heterogeneity on the North American side of the plate boundary that we attribute to the seismically fast Wrangellia and Alexander accreted terranes. We also find that the QCF aligns with a relatively sharp contrast in seismic velocity, with the slower velocities on the Pacific side of the plate boundary at seismogenic depths (~5-20 km in this area). Lastly, our velocity models do not present strong evidence for underthrusting north of Haida Gwaii, but we do show seismic reflections within the North American crust at <30 km depths.

POSTER 160

New Constraints on Crustal Structure and Fault Zone Architecture in the m7.8 2012 Haida Gwaii Earthquake Source Region, Offshore British Columbia

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The Queen Charlotte Fault (QCF) transform plate boundary offshore western Canada and southeast Alaska accommodates >50 mm/yr of dextral strike-slip motion between the Pacific (PAC) and North America (NA) plates. Transpressional deformation occurs offshore Haida Gwaii in the southern QCF, generating the Queen Charlotte Terrace fold and thrust belt and a M7.8 thrust type earthquake and tsunami in 2012. Multiple existing hypotheses seek to explain oblique convergence in the southern QCF, ranging from oblique subduction to crustal shortening and buckling as leading end members, but crustal-scale imaging in the region has been limited. In 2021-2022, the Transform Obliquity along the QCF and Earthquake Study (TOQUES) collected active-passive marine seismic data along a ~450 km-long section of the QCF. Here, we focus on long-offset (15-km streamer) multichannel seismic reflection data collected aboard the R/V Marcus G. Langseth that samples the 2012 earthquake epicentral region. We observe extensive crustal-scale normal faulting on the PAC, with vertical offsets up to 500 m at the oceanic Moho and active deformation up to the seafloor, through 2-3 km-thick sediments. These features indicate significant bending of the PAC plate as it enters the deformation zone and are consistent with normal faulting aftershock sequences from the 2012 event. The data show evidence for multiple stages of deformation and reworking within the sediments of the Queen Charlotte Terrace. A narrow region of thrust faulting occurs west of the main QCF trace within a deformed sedimentary section up to ~8 km thick. The main QCF is expressed as a near-vertical structure imaged at up to ~4 km depth. East of the QCF, strata within the upper ~1.5 km are minimally deformed, suggesting that compressional deformation in the shallow terrace is decoupled from the NA backstop. Bright, low-frequency reflectors beneath the sediments of the QCT potentially represent deformed oceanic basement. We suggest that PAC-NA convergence is accommodated via underthrusting and PAC plate deformation with minimal shallow deformation within the NA plate.

Structure, Seismicity and Dynamics of the Queen Charlotte-Fairweather Fault System

Oral Session • Wednesday 1 May • 4:30 PM Pacific

Conveners: Collin Brandl, University of New Mexico (cbrandl@unm.edu); Andrew Gase, Western Washington University (gasea@wwu.edu); Emily Roland, Western Washington University (rolande2@wwu.edu); Lindsay Worthington, University of New Mexico (lworthington@unm.edu)

Aftershock Regions of Mw > 6.7 Earthquakes on the Queen Charlotte–Fairweather Plate Boundary, 1929 to 2013

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For large, early-instrumental (pre-1960) earthquakes, the spatial region of aftershocks offers the best approximation for the rupture area of the mainshock. This link, introduced by Fedotov (1965) and Mogi (1968), was applied by Sykes (1971) to a large set of major earthquakes rupturing the northern Pacific plate boundary, from the westernmost Aleutians to south-central Alaska (1965, 1957, 1946, 1964) and along the Queen Charlotte-Fairweather (QCF) strike-slip fault system (1958, 1927, 1949). We recently relocated the historical aftershocks and updated the aftershock regions for the Aleutian-Alaska subduction zone (Tape and Lomax, 2022). Here we focus on the Mw > 6.7 earthquakes rupturing the QCF plate boundary. Using a probabilistic approach (NonLinLoc), we relocated 150 aftershocks arising from 11 mainshocks spanning from 1929-05-26 Ms 7.0 (northwest of Vancouver Island) in the south to 1979-02-08 Mw 7.4 (St. Elias Mountains) in the north. The analysis of the QCF aftershocks is much more difficult than the analysis of Aleutian-Alaska aftershocks because the mainshocks are smaller, resulting in fewer detectable aftershocks based on globally distributed recording stations. With fewer arrival times and aftershocks, the resulting relocations have higher uncertainties and pose challenges for establishing aftershock regions. Applying a similar approach to all 11 events (early-instrumental and modern), we establish revised aftershock regions, using the known plate boundary location for guidance. We compare our findings with previously published detailed studies dedicated to one or more of these earthquakes.

Kinematics of the Fairweather-Queen Charlotte Transform System and Deformation Across the Broad Pacific-North America Plate Boundary Zone

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The Fairweather-Queen Charlotte system is a 1200-km long onshore-offshore transform fault that stretches from British Columbia to southern Alaska. While the fault system is a active boundary with 6 M7+ earthquakes over the past century, major questions remain about how relative motion is accommodated across the region. Land-based geodetic data and offshore geomorphic data derived from high-resolution bathymetry suggest different rates of fault motion, which leads to different estimates of how much of the total estimated Pacific-North America motion is taken up by the fault system. Using Euler pole analyses and a combined geomorphic and geodetic dataset, I will develop an improved regional tectonic model that allows a more complete examination of the fault system and how motion is distributed through the plate boundary zone.

The plate configuration surrounding the Fairweather-Queen Charlotte system is complex. The Yakutat block, an oceanic plateau that moves to the northwest, sits to the west of the Fairweather and the northernmost Queen Charlotte fault. The Pacific plate is assumed to lie to the west of the central and southern Queen Charlotte fault. Based on geodetic data and Euler pole analyses, the Yakutat block and the Pacific move distinctly from each other. Geodetic data show that the coastal margin inboard of the fault system moves north relative to North America, implying that the fault system does not take up all relative motion. Adding geomorphic slip rate estimates to the geodetic data results in predicted motion rates along the Queen Charlotte fault with significantly lower degrees of convergence than previous geodetic models. These new rates require a Northeast Pacific block, which moves to the northwest at a rate different from either Yakutat or Pacific, to lie to the west of the central and southern Queen Charlotte fault. The predicted motion of the Northeast Pacific block is not compatible with right-lateral slip along the Gulf of Alaska shear zone, implying that additional blocks or internal deformation of the northeast Pacific may be required.

The Making of a Future Accreted Terrane: Plate Tectonics of the Queen Charlotte Fault System and the Development of the Queen Charlotte Terrace Adjacent to Haida Gwaii

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The NE-section of the Pacific (PAC) and North America (NAM) plate boundary is generally envisioned as a large-scale transform fault (akin to the San Andreas) extending from north of Vancouver Island to eastern Alaska. However its history and present nature along the translational Queen Charlotte-Fairweather Fault system is less clear - particularly along the Haida Gwaii margin. There the extent of underthrusting of the Pacific plate beneath Haida Gwaii, the role of the Queen Charlotte Terrace (QCT) in the plate kinematics, and the way in which the slight obliquity of relative plate motions (~15°) is accommodated all remain unclear and/or contested. As the PAC - NAM plate motions have changed over the past 20 Ma, the Haida Gwaii section of the Queen Charlotte fault (QCF) has become progressively more transpressive. The result is underthrusting of the Pacific plate beneath western Haida Gwaii, and deformation along the continental margin. Earthquakes along the plate boundary, uplift of the western margin of Haida Gwaii, patterns of plate-interface coupling, and detailed analyses of seismic imagery along the margin allow us to propose an evolving, multi-component 3-D structure to the plate boundary in the vicinity of Haida Gwaii.

This plate boundary evolution has led to the QCT adjacent to Haida Gwaii. Although often linked to the Pacific plate (e.g. it lies outboard of the QCF), the QCT is integral to the partitioning of oblique motion between the PAC and NAM plates. This results in the QCT acting as a terrane that is an independent crustal block with sedimentary structures that differ from the adjacent Pacific plate along an abrupt deformation zone. The QCT shows evidence (through seismicity) of being at most partially coupled along its base to the Pacific plate, and is also kinematically independent (across the QCF) of the adjacent Haida Gwaii. We describe the evolution of this present day plate boundary structure from a simple translational plate boundary (pre-12 Ma), to its current configuration and assess the amounts and timing of underthrusting, uplift, and internal deformation of the QCT terrane.

Slope Evolution and the Accommodation of Oblique Convergence From the Central to the Northern Queen Charlotte Fault

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The Queen Charlotte Fault (QCF), the transform boundary between the Pacific and North American tectonic plates offshore Vancouver and southeastern Alaska, experiences rapid deformation at approximately 55 mm/year. This makes it one of the fastest-slipping continental-oceanic transform systems globally. Transpressional deformation, which occurs along the fault, is controlled by variations in fault strike with respect to plate motion leading to increasing degrees of convergence along strike from north to south. The Transform Obliquity on the Queen Charlotte Fault and Earthquake Study (TOQUES) gathered new multichannel seismic reflection data along a ~450 km fault section in 2021. This work focuses on the northern segment, near the site of the 2013 Mw 7.5 Craig, Alaska earthquake. Aftershock sequences suggest that the main QCF dips eastwards or active fault strands exist within the North American plate. We present seismic profiles crossing the 2013 epicentral region, examining fault zone architecture, crustal deformation mechanisms, and deep structural relationships. The profiles reveal a series of normal faults within the Pacific crust, a slightly eastward dipping Pacific basement, and sediments containing multiple vertical faults at the base of the continental slope. The main QCF trace is located on the continental slope. Mid-slope basins record several deformation stages and host multiple vertical faults. On the North American continental shelf, we see glacially truncated, east-dipping strata and minor seafloor sediment deformation. Our observations suggest that strike-slip deformation may be distributed across multiple structures.

A Spectral Perspective on Fault Geometry and Strike-Slip Rupture at Plate-Boundary Scales Along the Queen Charlotte Fault

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We compare scalograms of fault geometry and yield stress to M~7+ ruptures along the Queen Charlotte Fault (QCF). Fault geometry controls stress accumulation and release during earthquakes, implying that sizes, locations, and magnitude distributions of earthquakes should mirror the sizes, locations, and scaling of geometric irregularities on faults. Along the QCF, O(100)-km-scale irregularities in the scalograms mark the extents of all recorded M~7+ ruptures, suggesting that large-scale irregularities act as barriers to rupture. Converting the geometry scalograms to yield stress shows that ruptures nucleate where yield stress equals average values and terminate in high yield stress regions (i.e., barriers). At scales shorter than total rupture length, co-seismic slip is, conversely, highest where yield stress is highest, indicating that longer ruptures release stress accumulated at smaller-scale irregularities. This barrier-asperity model is consistent with other spectral measurements. The O(100)-km scale marks a break in scaling of irregularity height H to length L ratios: At ~35 to 55 km scales, QCF geometry follows a self-affine $H \propto L^\zeta$ scaling with $\zeta \approx 0.6$. At scales >90 km, $\zeta \approx 0.9$. The fractal break separates QCF rupture sizes: Mw 7.5 to 7.9 events are >90 km long, where $\zeta \approx 0.9$; Mw 6.8 to 7.0 events are ~35 to 55 km long, where $\zeta \approx 0.6$. No ~55 to 90-km-long ruptures have been recorded on the QCF. Consistently, the ~55 to 90 km transitional band marks an abrupt increase in irregularity amplitude and high yield stress variation, features that impede rupture. A scaling break at O(100) km is also apparent in the magnitude-frequency distribution (MFD) of QCF earthquakes. Many more great (M > 7.5, L > 100 km) earthquakes have occurred than predicted by Gutenberg-Richter scaling, meaning stress is more readily accommodated by large rather than small ruptures, consistent with predictions from the scalograms. The similar characteristic scaling in fault geometry and rupture distributions may arise from fundamental scale of strike-slip faulting, such as seismogenic zone depth.

Tectonics and Seismicity of Stable Continental Interiors

Oral Session • Friday 3 May • 8:00 AM Pacific

Conveners: Oliver Boyd, U.S. Geological Survey, olboyd@usgs.gov; Jessica Thompson Jobe, U.S. Geological Survey, jjobe@usgs.gov; William Levandowski, TetraTech, will.levandowski@tetratech.com; Zhigang Peng, Georgia Institute of Technology, zpeng@gatech.edu; Anjana K. Shah, U.S. Geological Survey, ashah@usgs.gov

Seismicity and Seismotectonics of the Basque-Cantabrian Zone and Adjacent Areas of the Pyrenean-Cantabrian Mountain Belt: New Data From the Siscan and Misterios Seismic Networks (2014-2020)

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The Basque-Cantabrian Zone is located in the Pyrenean-Cantabrian Mountain belt, in the north of the Iberian Peninsula. Specifically, it comprises the eastern termination of the Cantabrian Mountain Range and its transition to the Western Pyrenees. The region to the west of the Pyrenees has traditionally been considered to have low seismic activity, and has therefore attracted less attention from the seismological community than other areas of the Iberian Peninsula. For this reason, the coverage of permanent seismic stations is sparse, and the present-day seismicity of the Basque-Cantabrian Zone remains relatively understudied.

To fill this gap in the knowledge of the seismicity in northern Spain, we deployed two temporary seismic networks covering the Basque-Cantabrian region and neighboring areas, including the northernmost part of the Iberian Chain and the Western Pyrenees, from 2014 to 2020. In total we deployed more than 50 stations, with an average interstation distance of 30 km. During the 6 years of the study, we built an earthquake bulletin containing more than 1000 located earthquakes with a completeness magnitude of 1.1 Ml, and computed 42 focal mechanisms in a region where this type of data was very scarce. We used the most accurately located events to improve the understading of the seismotectonics of the Basque-Cantabrian Zone, identifying the main active faults in the area, and offering additional data on the local stress field. We also employed the large dataset of amplitude picks to compute a new magnitude scale suitable for the Basque-Cantabrian Zone.

The Earthquake Swarms of Eastern Maine and Nearby New Brunswick Since 2006

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In the past couple decades, several swarms of small earthquakes have been detected in eastern Maine and nearby New Brunswick. The swarms were near Bar Harbor, Maine in 2006-2007, at Searport, Maine in 2011, at McAdam, New Brunswick in 2018, near Jonesboro, Maine in August 2022, near Brewer Maine in December 2022 and January 2023, and near Millinocket, Maine in December 2022 and January 2023. Each swarm has consisted of several to a few dozen events, with the largest event in any of the swarms being an M_{Lg} 4.2 earthquake near Bar Harbor in 2006. Relative locations of the events in the swarms suggest that they are only one or a couple kilometers in spatial extent and that they tend to follow known or inferred local geologic structures. The focal mechanisms of the largest events of the swarms indicate that the earthquakes in these swarms are responding to the regional approximate E-W maximum compressive field seen throughout this region, and the events tend to have thrust focal mechanisms. The swarms all have focal depths of a few kilometers or less. The swarms do not associate with any single structure or structural trend, although most have occurred just east of or on the Norumbega Fault, an ancient, major strike-slip fault that runs from eastern New Brunswick southwest to near the southern tip of Maine. The causes of these swarms are unclear, as is their significance for elucidating the earthquake hazard of the region. However, the swarms do indicate which faults in Maine and New Brunswick might be seismically active in the modern stress field.

Seismotectonic Studies of the Nubia Fault System, Southwest Aswan Area, Egypt

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Numerous active shear systems can easily be detected in the Egyptian Eastern- and Western-Deserts (ED & WD). Among these systems is the Nubia Fault System (NFS) which is an eye-catching structural feature in the extreme southern part of the WD. The NFS is typified by two main trends; E-W (Kalabsha- and Seiyal- Faults; KFZ and SFZ) and N-S (El-Barqa-, Kurkur-, Khor El-Ramla-, Ghazala-, and Abdu Dirwa- Faults). Propagation of shearing along both trends resulted in the formation of different styles of shear zone-related folding reflecting transtensional regime. The present work is an integrated field/structural and seismological approach aiming to decipher the recent activity and seismic hazard potentiality of the NFS. Several lines of evidence indicate recent activity including topographic expression and intensive degree of shearing, and severe fragmentation and pulverization. Detailed investigation of the KFZ and the SFZ proves that both structural elements are transtensional and frequently segmented. The geometry and kinematic history of the KFZ and the SFZ reveal seismogenic events with a strong movement as deduced from surface rupturing, and remarkable fault breccia and gouge which are good signs for ongoing and recent seismic activity. Notable activity along the NFS led to low (to moderate) earthquakes with magnitude up to 5.6 ML. The full moment tensor inversion, which was decomposed it into three parts Isotropic (ISO), Double Couple (DC) and Compensated Linear Vector Dipole (CLVD), offers further information about the NFS. The obtained complete MT for the whole district is characterized by non-DC components which have been represented by ISO and CLVD with average values of 22.2 % and 34.4 %, respectively, and DC components with average value of 39.1%. The average value of the non-DC components of the majority of the selected earthquakes is larger than the DC component. Such results indicate that the seismicity is probably triggered rather than being a pure tectogenic.

Focal Mechanism Analysis of the 2019 Mw 4.9 Wang Nuea Earthquake and Its Implication for Seismotectonics

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On February 20th, 2019, an Mw 4.9 earthquake occurred in Wang Nuea, Lampang Province, northern Thailand. The epicenter was located in a tectonically active region with the potential for strike-slip and normal faulting earthquake sources. However, the responsible fault is not well understood because there are no focal mechanism solutions from available international or local seismological agencies, such as USGS, GCMT, and TMD for this event, either the high-resolution seismicity. The objective of the research was to provide a better understanding of the earthquake mechanism and seismotectonics using a combination of accurate seismicity, focal mechanisms, and geomorphic structures. We applied the generalized Cut-and-Paste (CAP) focal mechanism inversion method to obtain the earthquake focal mechanism and centroid depth at relatively high-frequency ranges (0.02–0.2 Hz for Pnl and 0.03–0.2 Hz for surface waves). The CAP inversion results show a robust strike-slip solution for the mainshock, suggesting the NNW-SSE-oriented fault with a vertical dip and a depth of 7 km, which is consistent with the near N-S distributed aftershocks. This result is also roughly consistent with the geologically mapped strike of the Wang Nuea Fault and reveals seismic activity along the fault. The seismicity and focal mechanisms of the earthquakes, as well as the geomorphic lineament, explain the characteristics of the fault in the N–S direction. We suggest that similar waveform inversion could be generalized for focal mechanism inversion in Thailand routinely.

Middle Crustal Earthquakes and Neotectonics in the Western East Sea (Sea of Japan)

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The East Sea (Sea of Japan) is located in the eastern margin of the Eurasian plate of stable intraplate plate regime. The western East Sea is seismically active. The seismicity in the western East Sea occur around the paleo rifting structures where seismic and geophysical properties apparently change. The nature of seismicity in the western East Sea is important information for mitigation of seismic hazards. Both reverse faulting and strike slip earthquakes occur in the region. The maximum focal depth generally increases with distance from the coast, reaching the peak maximum focal depths of ~32 km in the continental slope of the western East Sea. Middle crustal earthquakes continue around the paleo-rifting structures that may extend to the lower crust and Moho. Clustered episodic earthquakes occur in four local offshore areas including the stress-induced areas by the 2016 ML 5.8 Gyeongju earthquake and 2017 ML 5.4 Pohang earthquake. The spatiotemporal clustering of earthquakes suggests episodic stress release at localized structures. The seismicity properties suggest progressive thrust motions across the crust around the paleo-rifting structure in the western East Sea.

Seismicity and Structure of SW Australia via the SWAN and Western Australia Seismic Networks

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The South-West region of Australia is the country's most seismically active zone and has experienced ~20 M5+ events in the last 50 years, including the most damaging event in Australian history (1968 M6.8 Meckering). It is also privy to numerous seismic swarms, including a year-long event which began in early 2022, captured by the new SWAN network (2P, 2020-2023). As SW Australia is far from any plate boundary, there is no obvious explanation for the frequent shallow intra-continental earthquakes here which mostly occur within the Archean-aged Yilgarn Craton. This area has recently been examined by the 27 broadband stations (SWAN) as well as 130 stations across the ambitious new WA-Array rolling network (XO, 2022-2032) which has a linear array geometry with 40 km station spacing. Between 2020-2023 over 10,000 earthquakes have been located using a Machine Learning phase picker (e.g. EQTransformer, Mousavi et al. 2020), event associator (e.g. REAL, Zhang et al. 2019) and locator (e.g. NonLinLoc, Lomax et al. 2000). These events have been used to derive regional body wave velocity models, centroid moment tensors, and estimated Greens Functions between each station pair have also been used to create an ambient noise velocity model. Both models outline the Yilgarn Craton as well as the thick sedimentary deposits of the Perth Basin, west of the Darling Fault. We also imaged a distinct high-velocity fragment in the lower crust along the western margin of Yilgarn Craton, east of the Darling Fault, which may reflect the terrane accretion tectonics. At the time of writing, our results are being integrated with other geophysical and geological information, with the ultimate goal of unveiling the history of Yilgarn and the unusual intra-plate seismicity that has been observed across the oldest craton on Earth.

Recurrent Large Intraplate Earthquakes on the Jindabyne Thrust, Southeast Highlands, Australia

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The recurrence characteristics of large intraplate earthquakes are poorly understood, leading to large uncertainties in seismic hazard assessments, particularly at the low annual probabilities of exceedance important to the design and maintenance of critical infrastructure. The southeast highlands of Australia have the greatest elevation and topographic relief of anywhere in the continent, relatively high seismicity rates, and a number of faults showing geomorphic evidence for neotectonic activity. The region also hosts major dam and hydroelectric infrastructure critical to Australia's water and energy security. Despite this, no paleoseismic studies have previously been undertaken to characterise the earthquake potential of faults in the region.

We excavated four trenches on the more than 100 km long Jindabyne Thrust fault, and one trench on the 24 km long Hill Top Fault, which occurs in the hanging wall of the Jindabyne Thrust and is truncated by the thrust at its southern extent. Evidence for multiple large earthquakes was found on both faults, showing reverse displacement on the Jindabyne Thrust and strike-slip displacement on the Hill Top Fault. Trenches on the Jindabyne Thrust exposed a thick clay gouge zone within bedrock underlying the faulted alluvial sediments, and single-event displacements are on the order of 1.5–2.0 m. Optically stimulated luminescence dating of displaced alluvial and colluvial sediments is being used to constrain the timing of these earthquakes. The results demonstrate persistent recurrence of large surface-rupturing earthquakes on the Jindabyne Thrust over the Late Quaternary, implying a neotectonic component to range uplift in the south-eastern highlands, and an extant seismic hazard.

Seismic Evidence of Crustal Modifications Below the North American Midcontinent

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Despite being relatively stable, the interiors of global cratons preserve clear evidence of modification on geologic timescales. The North American craton is the locality of a series of rifts, basins, arches, and domes, varying in size and orientation. Geologic evidence suggests that these features formed throughout the Paleozoic or earlier with limited subsequent deformation. However, the mechanism(s) that drove the uplift and subsidence of these intracratonic features is poorly understood. Linking these upper crustal features with deep crustal and upper mantle processes is an important step in understanding the evolution of "stable" cratons including the timing, rate, and style of cratonic modification. Here we present new results using a 3-D shear-wave velocity model from full-wave ambient noise tomography to identify compositional and structural modifications in the crust across the North American midcontinent. Our results show a heterogeneous crustal structure below major surface tectonic features, suggesting strong crustal modifications related to the formation and evolution of these surface deformations. For example, the late Mesoproterozoic Midcontinent Rift is underlain by a confined low-velocity zone along strike in the upper crust, broadening at greater depths. There is a crustal low-velocity layer across most of the study area. This low-velocity layer is shallower below basins than other regions, varying from 15-20 km deep below the Illinois and Michigan Basins (Neoproterozoic - Paleozoic) to 25-30 km in other regions. The doming of this crustal low-velocity layer below the basins may be the consequence of crustal uplift before the basin subsidence. We will discuss the implications of the velocity structure for the origin and evolution of intracratonic deformation, combining other geological and geophysical constraints.

Crustal Thickness and Radial Anisotropy Below the North American Midcontinent

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The relative stability and longevity of cratons preserve the imprints of major tectonic events on geologic timescales. Seismic observations provide information on compositional and structural variations of the cratonic lithosphere, shedding light on the dynamic evolution of craton interiors. The North American craton is an amalgamation of tectonic structures (rifts, basins, domes, and arches) formed in the Paleozoic and earlier. Here we present results from averaging eight crustal thickness models covering the North American midcontinent (the number of models at each grid is variable) and compare them with other geophysical observations, such as lithosphere thickness and shear-wave velocity model. Our crustal thickness results reveal heterogeneous crustal thickness across tectonic units, with relatively deep (about 45-55 km) Moho beneath the Williston, Illinois, and Appalachian Foreland Basins and shallower (about 35-42 km) Moho below the Forest City Basin

and the central and northwestern Michigan Basin. In addition, we will build a radial anisotropy model using ambient noise cross-correlation to investigate the crustal modification associated with different structural features. We will examine the relationship among the variation of crustal, lithospheric thickness, seismic isotropic, and anisotropic velocity structures to understand the tectonic evolution of the North American midcontinent. Our study, joining with geological and geochronological constraints, will contribute to understanding the connection between regional tectonic events (relative timing and scales) and local heterogeneities and, in general, the style and scale of the tectonic evolution of cratonic interiors.

Lithospheric Layering and Seismic Activity of the British Isles

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Recent progress in imaging of the upper mantle made it possible to show a close correlation of seismic activity of the British Isles with the properties of their lithosphere. Specifically, sparse seismicity of Ireland appears to be well explained by the relatively thicker and colder, hence stronger, lithosphere beneath it, while a region of relatively thinner and warmer lithosphere spanning Great Britain hosts vast majority of all recorded earthquakes.

The upper mantle imaging study linking seismicity and lithospheric properties of the British Isles relies on surface wave data that tend to smooth abrupt lateral changes in properties. Methods based on mode-converted body waves (aka receiver functions) offer excellent lateral resolution and can detect fine vertical layering in the upper mantle, however their use is hampered by an overprint of the intra-crustal multiply-reflected waves.

Long-duration continuous broad-band seismological observations provide data necessary to resolve directional and incidence-angle variations in converted waves, facilitating discrimination of multiple and direct P-S waves and detection of conversions from vertical gradients in seismic anisotropy.

We recently showed that constraints on the upper mantle layering from P-S receiver functions agree with thermal constraints on the vertical extent of the lithosphere in northeastern North America, a region that shares geological history with the Caledonides of the British Isles. Notably, we resolved lateral changes in lithospheric layering over distances <50 km, a significant improvement over laterally smooth global models developed using surface waves in the same region.

We are undertaking a systematic survey of the upper mantle layering beneath the British Isles using advanced receiver function techniques and recently collected data. We will present their inference for the vertical extent, layering, and their lateral variation in the lithosphere, with an emphasis on the anticipated differences between the relatively seismically active Great Britain and seismically inert Ireland.

Complex and Contrasting Temporal Patterns of Large Intraplate and Interplate Earthquakes

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Large (or the so-called characteristic) earthquakes are expected to be periodic or quasi-periodic, but such regular earthquake recurrences are not common in nature. Instead, most sequences of large earthquake are complex and variable, often showing clusters of events separated by long and irregular intervals of quiescence. We compiled and analyzed dozens of catalogs of large interplate and intraplate earthquakes and found a clear difference: most sequences of large interplate earthquakes are quasi-periodic (COV<1), but most intraplate earthquakes are clustered (COV>1). The cause of earthquake clustering is likely complicated, but we can show that stress transfers from earthquake-induced viscoelastic relaxation and fault interaction are among the major factors. Both real and synthetic catalogs show that the periodicity correlates with the loading rates, which may explain the difference between intraplate and interplate earthquakes. In intraplate settings where tectonic loading is slow, stress from viscoelastic relaxation and other processes, including non-tectonic loading, becomes relatively significant and contributes to irregular earthquake occurrences. In contrast, fast and steady tectonic loading in interplate fault zones tends to suppress the effects of these irregular loadings and lead to more regular occurrence of earthquakes. All sequences of large earthquakes, either interplate or intraplate, exhibit the statistical signature of the Devil's Staircase, a fractal property of nonlinear complex systems. In such a system, change of any part (e.g., rupture of one fault or segment) could impact the whole system. Thus, earthquake studies need to go beyond the analysis of stress accumulation and release on individual faults. While predicting the short-term fault behavior is challenging, useful insights may be gained by studying the system behavior of faults in a region.

Use of Seismometers in Studies of Precariously Balanced Rocks (PBRs) in the Eastern U.S.

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Although seismometers have been placed on natural arches and pillars, and on bedrock to examine site amplifications at precariously balanced rock (PBR) sites, we are unaware of seismometers being used on PBRs to discern parameters directly relevant to toppling the rocks. To help use PBRs to constrain eastern U.S. ground motions over tens of thousands of years, we have been placing 3-component, 5-Hz seismometers on PBRs and on nearby bedrock surfaces to record both environmental noise and gentle pushes of the PBRs. Spectral ratios between the rock and bedrock recordings show one or more prominent peaks that define the dominant frequencies of rocking during weak, ambient ground motions. Because the frequency of rocking decreases with increasing amplitude of rocking, the dominant frequencies during weak motions likely reveal the highest frequencies relevant to toppling the rocks during strong ground motions. After giving gentle pushes to perpendicular sides of the rocks, particle motion diagrams from the seismometers on the rocks show the dominant directions of rocking. Increases in frequency with decreasing amplitude after the pushes confirm that rocking is occurring, which also is confirmed by visible motions of some rocks. The directions of rocking are useful for interpreting the orientations of alpha angles most important for estimating fragility by established methods. The decay in the amplitude of rocking per cycle allows for determination of the coefficients of restitution, which previous workers show can be directly related to the alpha angles and, if the heights of the centers of mass are known, the widths of the contact surfaces with the underlying rocks. We have also been measuring the locations and strengths of the input pushes in preparation for calibrating future 3D modeling of the rock responses. These measurements have been made with extremely small angles of perturbation, and stronger rocking may change the direction and frequency of rocking due to uneven bases to the rocks, but the weak motion responses help characterize the responses of the PBRs during initiation of rocking.

Identifying Probable Fault Planes in Stable Continental Regions of Canada for Use in Hazard Assessment

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Seismic hazard assessment has advanced beyond relying solely on magnitude recurrence rates to incorporating additional parameters, such as seismogenic fault characteristics and deformation rates. In the stable craton of Canada, active faults have been very difficult to identify. Only the 1989 Ungava, northern Quebec, earthquake is clearly associated with a surface rupture. Additional sources of information, such as Globa Navigation Satellite Systtems and Interferomic Synthetic Aperture Radar which have been invaluable in active tectonic regions have thus far been of limited value for hazard assessment in cratonic Canada because of poor spatial coverage, the relatively modest sizes of recent earthquakes and the slow deformation rate. The region, however, comprises several active seismic zones. Large earthquakes have occurred historically and the current seismograph network provides accurate locations of the many small to moderate earthquakes throughout the region. Building on an initial study focused on the Western Quebec Seismic Zone, statistical analyses of focal mechanisms in all seismically active regions of southeastern Canada and the eastern Canadian Arctic are applied to determine probable fault planes. Although some earthquakes occur outside the seismic zones, there are insufficient focal mechanisms to extend the study to these less active areas. In the Canadian craton, this method has been successful in determining strike direction and dip angles but the results for dip direction have been largely equivocal, at least in part because thrust faulting dominates and many depths are poorly constrained. The results, however, are useful for developing weighting schemes for incorporating fault place information into the hazard assessment. Relocations of active aftershock sequences for a small number of earthquakes provide additional information about fault orientations. Although the impetus of this study is to provide input to future Canadian seismic hazard models, the results will also provide input to other research topics, such as associating earthquakes with actual faults.

A Machine Learning Re-Analysis of Seismic Archives in the Northeastern U.S.: Implications for the Nature of Active Faults and Faulting

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The Northeastern United States, a stable continental region of low strain and seismicity rates, faces unique challenges in understanding the behavior of active faults that are capable of failing in large events, and the hazard such large events pose to nearby metropolitan areas. Harnessing recent advances in machine learning (ML) techniques, we re-analyze two decades (2000-2020) of continuous seismic waveform data recorded by the Lamont Cooperative Seismic Network (LCSN) and neighboring networks. Our approach integrates supervised machine learning (ML) and cross-correlation template matching for (sub-noise) event detection and phase arrival and delay time measurement (PhaseNet, BPMF), unsupervised ML for source characterization and discrimination (SpecUFEx), inversion and grid search methods for accurate absolute hypocenter location (HINV, NLL) and double-difference methods for precise relative location (HypoDD). In our preliminary analysis we find close to 100,000 new events, many of them identified as quarry blasts. However, even with conservative detection parameters, we find more than twice as many locatable events compared to the existing catalog of about 1,000 earthquakes detected during the 20-year period of routine LCSN operation. Initial results from a 50 km long segment of the Ramapo fault only 50 km west of the New York City metropolitan, which at the surface indicates a broad zone of deformation, show a clearly defined, near vertical active fault down to 10 km. These newly detected and relocated earthquakes demonstrate the potential such new catalogs have to gain new insights into active faults and faulting processes in the northeastern U.S. and in other stable continental regions. Such large, compute intensive re-analysis studies will benefit from ongoing efforts within the NSF funded SCOPED project that focuses on implementing such modules on a hybrid HPC-cloud computational platform for use by the broader scientific community.

Active Seismicity Around a Cretaceous Magmatic Intrusion in Monchique, SW Iberia

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Monchique is a prominent topographic high in SW Iberia (Europe) that reaches a maximum altitude of 902 m, standing out from the surrounding plane of southern Portugal. It is located to the north of the Eurasia-Africa plate boundary, which locally accommodates a low rate oblique convergence (~5 mm/yr). At the surface Monchique shows alkaline magmas that intruded during the Late Cretaceous, following the break-up of Pangea. Monchique is a well-known region of hydrothermal activity, with several natural springs and an active natural water bottling industry and spa services. Monchique also hosts the most active seismic cluster in mainland Portugal when considering the number of earthquakes. However, most earthquakes in Monchique are of low magnitude (<M4) and no active seismic faults are mapped in Monchique.

In this work, we present the results of geophysical modelling of the Monchique magmatic intrusion. In particular, we present the results of magmatic and gravity modelling based on locally collected data. The magnetic data was collected using a drone, which allowed for an improved coverage of the region. The seismicity was relocated using NonLinLoc, which implements a non-linear probabilistic inversion methodology, and an appropriate 3D regional tomographic model. We find that earthquakes align along 4 main lineations that radiate outwards from the intrusion. We also find that the intrusion is limited to the topmost 8 km below the surface and that most earthquakes occur below this depth. We discuss the relationship between the seismicity and the magmatic intrusion, as well as the roles of hydrothermal fluids and the nearby plate boundary in facilitating and driving the seismicity of Monchique.

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Amplification and Attenuation: Putting the Puzzle Together for Ground Motions in the Atlantic and Gulf Coastal Plains

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The Atlantic and Gulf coastal plains (CPs) host the areas of largest seismic hazard to the Central and Eastern United States. Unique geologic structures consisting of nearly-flat, soft, unconsolidated sediments and sedimentary rock that overlay bedrock and extend laterally hundreds of kilometers in the Atlantic and Gulf coastal plains exert a significant influence on earthquake ground motions. Thicknesses of the sedimentary columns can reach 10 km and they overlay high-velocity bedrock, which results in a strong seismic impedance contrast. There have been multiple relevant efforts to account for the effects of geology and sediment thickness in seismic hazard estimations for the region. In this work, we use the most recent sediment thickness map of the CPs, surface geology, and a curated compilation of measured shear wave velocity data to create a seismic velocity model that can inform future efforts of ground motion characterization in the region.

In addition to capturing impedance effects within regional seismic velocity models, the characterization of attenuation constitutes an important piece of the seismic hazard puzzle. Local site attenuation influences ground motion characteristics in the high-frequency range and can affect the scaling from soft to hard rock. Only a few studies have focused on characterizing attenuation properties of shallow and deeper portions of the CPs. We aim to develop a new regional seismic attenuation model by integrating information from multiple attenuation parameters measured and estimated in the region (e.g., Q and kappa) and examining their relationship with geology. Findings from this work can improve our understanding of site contributions to ground motion characteristics unique to the CPs, and they can also support future physics-based ground motion simulations and regional models of ground motion site amplification.

The 1886 Charleston, South Carolina, Earthquake: Source Properties and Ground Motions

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The 1886 Charleston, South Carolina, earthquake was felt over much of the eastern United States, with magnitude 6.8-7.3 previously estimated from felt reports. In spite of extensive contemporaneous documentation, the earthquake and Charleston Seismic Zone have remained enigmatic. Bilham and Hough (TSR, 2023) recently developed an elastic deformation model for the 1886 earthquake using identified geodetic constraints, including a ~4.5-m dextral offset in a railroad line southeast of Summerville where the track crosses the previously mapped Summerville fault. The offset was described in contemporary accounts but never considered by subsequent studies. Unlike other railroad disturbances in the epicentral region it cannot be explained by site response. The preferred deformation model yields moment magnitude 7.3, but in contrast to conclusions of previous studies, we found no support for significant slip south of the Ashley River. We also revisited the near- and far-field intensity distribution using extensive archival accounts. We compare the intensity distribution, constrained at nearly 1300 locations, with predictions from modern ground motion models (GMMs) and ground motion-intensity conversion equations. Although GMMs are characterized by significant epistemic uncertainty for large earthquakes, we show that the intensity distribution is consistent with average model predictions, assuming Mw 7.3. Given the complex influence of site response on saturated Atlantic Coastal Plain (ACP) sediments throughout the epicentral region, the fit to near-field intensities is insensitive to the rupture length or other detailed rupture properties. Macroseismic intensities can be used together with model predictions to improve a ShakeMap for the earthquake, but cannot improve the independently determined rupture model or Mw. An apparent concentration of high intensities near Rantowles, west of Charleston, was defined by a multiplicity of environment effects that are readily explained by dynamic stress effects and site response on saturated ACP sediments prevalent throughout the low-lying marshy regions surrounding Charleston.

Reactivated Paleozoic and Mesozoic Basement Faults in the Charleston, South Carolina, Seismic Zone

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The Charleston, SC, seismic zone is the site of a M~7.0 earthquake in 1886 that devastated much of the city. To better understand seismic hazard within this region, we used 2019-2020 high-resolution airborne magnetic data, previous seismic reflection data, and ground penetrating radar (GPR) data to image basement structures at seismogenic depths that may have had more recent reactivation. Comparisons between the aeromagnetic data and seismic reflection profiles show NE- and ESE-trending magnetic lineaments associated with faults visible within pre-Cretaceous strata. Of these, a subset of faults show disturbances within overlying Cenozoic sediments. This includes the >60-km-long NE-striking Gants fault, extending from Pinopolis in the NE to an area between Jacksonboro and Walterboro in the SW and interpreted as a reactivated Paleozoic structure, and the >20-km-long ESE-trending Summerville lineament, which has a western termination at Gants fault and extends along part of the Ashley River towards North Charleston and possibly farther east, and is interpreted as part of a Mesozoic rift structure. Other NE-striking faults parallel or sub-parallel to Gants fault also show Cenozoic disturbances, and some evidence of possible Quaternary motion. The Summerville lineament is well-aligned with a plan-view offset in seismicity and a topographic slope previously observed in lidar data, further supporting associated fault reactivation over the last < 1 m.yr. Gants fault, which is coincident with and parallel to the series of paleoshorelines that define the Penholoway Formation but lies several km west of the eastern edge of these shorelines, expresses only small vertical displacements at the shallow (<15 m) erosional unconformity at the base of Quaternary imaged using GPR. Previous focal mechanisms have shown both ESE- and NE-trending motion, further supporting slip along similarly oriented faults. We find, in fact, that numerous faults within the region show evidence of recent slip, making it very challenging to determine a unique causative fault for the 1886 earthquake.

Evidence of Quaternary Deformation in the Ste. Genevieve Fault Zone, Southeastern Missouri: Preliminary Results

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The Ste. Genevieve fault zone (SGFZ) is a 190 km long, northwest-southeast trending zone of complex deformation in southeastern Missouri and southern Illinois that separates the Ozark Dome from the Illinois Basin. The SGFZ has variable deformation along strike, including variations in fault occurrence and spacing, block rotations, changes in the direction of stratigraphic offset between faults, and deformed noncylindrical and monoclinal folding. Structural mapping done over many decades shows normal, reverse, strike-slip, and oblique-slip faulting due to more than one phase of fault reactivation. Structural relief on the Precambrian surface across the SGFZ varies from less than 1 km at its northwestern end to nearly 4 km at its southeastern end. There is a zone of active seismicity associated with the SGFZ, but there are no known examples of neotectonic deformation linked to the fault zone.

One possible example of tectonically deformed Quaternary alluvium lies in a cut bank exposure on Clines Branch in Perry County, Missouri. This exposure contains a prominent vertical fault that cuts very dense, highly fractured silt deposits. There are several, less obvious silt blocks displaced east of the fault, and west of the fault is a ~1 m wide zone of fault breccia containing a 0.5 m wide block of Glen Dean limestone that appears uplifted. A coarse lag deposit is folded into a small anticline above the fault, and east of the anticline a laminated clayey silt also appears to be folded. The age of the faulted silt is inferred to be either Roxanna Silt or the B horizon of the Sangamon Geosol, indicating deformation is Late Pleistocene. Luminescence and ^{14}C samples from the deformed units are currently being processed for geochronology. Paleoliquefaction features that formed ~11.4 ka to 4.7 years cal BP on the lower Big Muddy River, 17 km east of Clines Branch in southwest Jackson County, IL, and other small liquefaction features on the lower Apple Creek, ~16 km to the south in Cape Girardeau County, could be coeval with deformation at Clines Branch, but additional work is needed to confirm the deformation is tectonic.

Microgal-Precision Gravity Imaging Within an Active Intraplate Fault: The 2020 m5.1 Sparta, Nc Epicentral Zone

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The 2020 M_w5.1 Sparta, NC mainshock resulted from remarkably shallow (hypocenter < 1.5 km) sinistral-reverse slip on the ESE-striking Little River Fault (LRF). Moreover, the earthquake caused the first observed surface rupture in the eastern U.S., thus providing the first definitive exposure of an active intraplate fault in the region and an unprecedented opportunity: A microgravity (microGal-precision relative gravity) survey collected 558 readings at 492 unique locations over 7 days in September 2023 to illuminate structures in the epicentral region and surface trace at scales ranging from ~2 km to a few meters. Empirical precision is ±0.006 mGal. The residual gravity anomaly field features ENE-trending alternating +/- 1 mGal gravity anomalies across the LRF footwall. The most prominent high coincides with an erosion-resistant topographic high that may delineate a garnet/magnetite schist zone within the Alligator Back metamorphic suite. This anomaly intersects the LRF along the surface rupture, up-dip from the hypocenter, and its muted signature can be traced beneath the hanging wall to the epicenter. This anomaly is interpreted to delineate a relatively competent—both with respect to erosion and to brittle deformation—lithology that resists underthrusting and acts as a macro-asperity along the LRF. The reverse component of the mainshock was greatest up-dip of the hypocenter, grading eastward (away from the asperity) to nearly pure strike-slip (Pollitz, 2023). In old, cold, strong continental interiors, along-strike variations in footwall structure may thus control rupture nucleation and create complex ruptures.

Tectonics and Seismicity of Stable Continental Interiors [Poster Session]

Poster Session • Friday 3 May

Conveners: Oliver Boyd, U.S. Geological Survey (olboyd@usgs.go); Jessica Thompson Jobe, U.S. Geological Survey (jjobe@usgs.gov); William Levandowski, TetraTech (will.levandowski@tetratech.com); Zhigang Peng, Georgia Institute of Technology (zpeng@gatech.edu); Anjana K. Shah, U.S. Geological Survey (ashah@usgs.gov)

POSTER 35

Inferring Crustal Stress Distribution Within the Middleton Place/summerville Seismic Zone, South Carolina

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The 1886 ~M7 Summerville earthquake in South Carolina remains enigmatic with no surface faulting evidence. Several studies (Mckinley, 1887; Chapman et al., 2016; Bilham and Hough, 2023) offer varying source fault interpretations in the Charleston-Summerville region, but the exact fault structure that ruptured during the 1886 mainshock remains unknown. Ongoing microseismicity near the Middleton Place/Summerville Seismic Zone (MPSSZ), possibly aftershocks of the 1886 mainshock, could shed light on the source fault and improve our understanding of seismic hazards in the area. Preliminary analysis of microseismicity in Summerville using a network of 19 temporary short-period stations from May 2021-May 2023 (Jaume et al., 2021) identified a south-striking, west-dipping zone in the southern seismicity cluster and a north-south striking near-vertical plane further north (Chen et al., 2023). From February to May 2023, we deployed two linear arrays with 22 stations in the study area. Currently, we reoccupied 14 of the 19 stations by 5-Hz Smartsolo nodes and added 6 new stations near the MPSSZ and in the under-monitored northern region towards Pinopolis. In this study, we plan to further develop our current results based on our analysis of 181 events detected from the first half of the temporary network continuous data presented at the 2023 SSA Annual Meeting (Adeboboye et al., 2023). Our objective is to gain insights into the local crustal stresses and orientations of fault slips at depth. This begins with applying a modified workflow for building earthquake catalogs (Neves et al., 2023) to additional data from our recent experiment. Following this, we obtain focal mechanisms of the area, and constrain their solutions using relative S/P amplitude ratios (Skoumal et al., 2023). Subsequently, we will use the focal mechanism solutions, combined with ear-

lier results (e.g., Chapman et al. 2016, Adeboboye et al. 2023), to invert for the local stress inversion (Hardebeck & Michael, 2006). We expect that these efforts will provide insights into the source fault of the 1886 earthquake and its connection to present seismicity.

POSTER 36

Developing Ground Motion Model Using Nonparametric Machine Learning Techniques for Induced Earthquakes in Central and Eastern North America (Cena)

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Ground motion models (GMMs) play a crucial role in the probabilistic assessment of seismic hazards and their uncertainties. In this research, we develop new GMMs using nonparametric machine learning, including artificial neural networks, kernel ridge, random forest, and gradient boosting regression techniques. GMM is specifically developed for small-to-moderate magnitude, potentially induced seismic events in Central and Eastern North America (CENA). The study assesses the efficacy of various machine learning algorithms in predicting peak ground acceleration (PGA) and 17 different spectral accelerations, considering features like moment magnitude (M_W), hypocentral distance (R_{hypo}), and the timed-average shear-wave velocity of the upper 30 m of soil (V_{s30}). The training process is conducted using a database of about 31,000 ground motion records from CENA, with small and moderate moment magnitudes ranging between 3.0 and 5.8 and recorded at hypocentral distances up to 200 km. Traditional GMMs typically rely on linear regression models with predefined functional forms, which may restrict the use of complicated and nonlinear equations. While traditional regression models are more interpretable, machine learning models have the potential of superior outcomes given sufficient training data. Error metric analysis indicates that gradient-boosting regression shows enhanced performance. Additionally, we have applied a machine learning ensemble approach to merge the regression results from four different machine learning algorithms. This ensemble technique leads to smoother outcomes.

POSTER 37

Seismic Networks Important in Lower Seismic Hazard Environments like Australia

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Australia is a region of low seismicity compared to the rest of the world and so every earthquake counts. Irrespective of the absolute level of seismic hazard, understanding the level of hazard is important to infrastructure and communities. Earthquake magnitude recurrence (EMR) plots are used to evaluate the activity rates of a seismotectonic zone based on the Gutenberg-Richter seismicity recurrence equation. Quantification of the seismicity of a zone requires an estimate of the detection levels of the seismic network in the area and the completeness level of the earthquake catalogue. The magnitude of completeness level of the earthquake catalogue varies with time and is estimated from the recorded seismicity as well as from knowledge of the history of the seismic network in the area. Seismic networks provide the raw data to EMR plots and so are vital in assessing the seismic hazard of a site. Not having a seismic network in place or decommissioning seismic networks will impact on the accuracy and completeness of future earthquake locations. Without this recorded seismicity the EMR plots can have a large amount of uncertainty associated with them and may not appropriately show the hazard in that area. We have compared EMR plots for a series of seismotectonic zones to investigate the outcome when local scale seismic networks are decommissioned or such local scale networks were never in place.

POSTER 38

Neotectonic Mapping of the Charleston Seismic Zone, South Carolina

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The Charleston, South Carolina, region experienced an ~M7 earthquake in 1886, with widely felt ground shaking and corresponding damage. However, the locations and kinematics of the fault(s) that ruptured in the 1886 earthquake, or faults that may have ruptured during pre-1886 earthquakes, remain unknown. There have been multiple previous efforts to map potentially active faults from seismicity, 3-m lidar-derived topography, and aeromagnetic, seismic reflection, ground-penetrating radar (GPR) surveys. Here, we present preliminary neotectonic mapping on new <1-m lidar-derived topography of the 1886 epicentral region. We integrate our observations with existing surface and subsurface datasets and interpretations, including geologic maps, previous lineament and fault mapping, seismic reflection data, GPR surveys, and new high-resolution aeromagnetic data. We map east-southeast–west-northwest-trending and east–west-trending scarps between the Cooper, Goose, and Ashley Rivers that vertically offset late Quaternary geomorphic surfaces with a primarily down-to-the-north sense of motion. Sets of scarps extend for 4 to 6 km, with individual scarps that are 200 m to 1.5 km long. Some paired scarps suggest the presence of a graben. At least one prominent east-west scarp that offsets mapped Quaternary deposits aligns with an aeromagnetic lineament that extends towards Summerville. Seismic reflection and GPR data are not available at the scarp site but are available to the northwest on the same magnetic lineament. There, the seismic reflection data support deformation of Cenozoic units. In addition to mapping fault-related scarps, we also map slumping associated with ground-shaking near a well-known apparently offset railroad track, suggesting the track was deformed by secondary shaking effects and does not record primary surface rupture. These new observations may help better constrain the locations of faults that ruptured in the 1886 or previous earthquakes and lead to an improved understanding of seismic hazard in the region.

POSTER 39

Determination of Focal Depth of Offshore Earthquakes Around the Korean Peninsula Using Depth Phase

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The focal depth of earthquakes is one of the fundamental parameters for describing the tectonic process in a region. Especially in an intraplate region with low seismicity, the accurate determination of the focal depth of earthquakes is crucial, as it can enhance our understanding of subsurface faults and local stresses, which can be very difficult to observe with other approaches. However, estimating the focal depth is more challenging than determining the epicentral location. Owing to dense seismic network, the focal depth of earthquakes within the southern Korean Peninsula can be accurately estimated using the traditional location method, which utilizes the arrival times of various seismic phases. However, offshore earthquakes occurring around the peninsula inherently lack direct seismic arrivals, which are critical for improving the accuracy of focal depth estimates. This led to discrepancies in focal depths of offshore events in seismic bulletins cataloged by local and global agencies. Alternatively, regional moment tensor inversions could provide reliable focal depth estimates of moderate-sized offshore events around the peninsula (Song et al., 2022). However, focal depths of some offshore events were determined to too shallow (less than several kilometers). In this study, therefore, we determined the focal depths of offshore events with magnitudes larger than 3.5 occurred around the southern Korean Peninsula from 2005 and 2023 using depth phases. To validate our approach, the focal depths of inland earthquakes, reliably obtained by the previous studies, were determined with a limited number of depth phases. Since the focal depths depend on the velocity model, we also tested the dependency using five local crustal models and three global models.

POSTER 40

Africa's Lithospheric Architecture With Multi-Mode Body Wave Imaging

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Africa's lithosphere hosts the longest-lived cratons on our planet and records a rich and diverse tectonic history: plate subduction to the North, a long rift system in the East, the super swell in the South, and a record of continental breakup to the West. However, gaps remain in our current efforts to study its lithospheric layering due to sparse coverage and noisy short-term seismic deployments. Here, we present a body-wave dataset and model assessment products for investigating Africa's lithosphere (ADAMA). We address the challenge of lithospheric imaging on the continent using sparse and noisy teleseismic body wavefields, i.e., receiver functions and SS precursors. The latter extends lithospheric illumination in regions without station coverage. In both cases, we explore novel denoising approaches: (1) CRISP-RF (Clean Receiver Function Imaging with Sparse Radon Filters), which uses sparse Radon transforms to interpolate the sparse receiver function data and eliminate incoherent noise, and (2) FADER (Fast Automated Detection and Elimination of Echoes and Reverberations), which deconvolves thin-layer reflections buried in long-period SS precursors. We improve constraints on bulk crustal structure and lithospheric layering, e.g., from H-k stacking, following CRISP-RF denoising. We extend spatial sampling and detections of lithospheric layering by jointly interpreting receiver functions and SS precursors following cepstral deconvolution of long-period SS precursor waveforms. Our final model, ACE-ADAMA-BW (Africa's Continental Layering Evaluated with ADAMA's Body Waves), will improve 3-D resolution of lithospheric layering spanning the cratons (West Africa, Tanzania, Congo, Kaapvaal, Zimbabwe), rifts (Gourma, East African Rift System) and basins (Taoudeni, Goo, Congo) of Africa.

POSTER 41

Crustal Structure and Mantle Deformation Across the Central African Plateau, Zambia: Evidence from Receiver Functions and Shear-Wave Splitting Analysis

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The Central African Plateau comprises numerous Archean cratons sutured in Proterozoic to early Cambrian times — the Congo, Bangweulu and Kalahari cratons. In the heart of this region lies the copper-rich Neoproterozoic Katangan basin. Major deformation zones and complex craton margin fault zones reflect the region's tectonic history, which is further complicated by the Permo-Triassic and Pliocene development of the Southwestern Rift in southern Zambia. The extent to which surface deformation is mirrored to deeper crustal, and mantle lithospheric depths is uncertain but may also be key to ultimately understanding the Cu, Co and Ni mineralisation of the Katangan Basin. To investigate the tectonics and geodynamics that shaped the region, we utilise data from the Copper Basin Exploration Science (CuBES) seismic experiment — a NW-SE-trending, 750km-long profile of 35 broadband seismograph stations deployed across Zambia. Lithospheric deformation fabrics associated with past and present tectonic deformation are explored via an SKS splitting study of mantle seismic anisotropy. Crustal and lithospheric mantle seismic structure are also elucidated via receiver function and surface-wave analysis, the results of which are compared to bulk-crustal constraints derived from the modified H-K stacking method of Ogden et al., (2019). Results thus far reveal variable bulk crustal Vp/Vs ratios along the entire CuBES line, with crustal thickness contrasts across major tectonic boundaries, and clear evidence for short length-scale variations in upper-mantle seismic anisotropy.

POSTER 42

Stochastic Inversions of Source, Path, and Site Parameters for West Texas Earthquakes

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The increase in seismicity in West Texas since 2020 coupled with the enhanced seismic network coverage by the Texas Seismological Network has generated significant earthquake data that allows for the study of source, path, and site characteristics in the region. In this research, we utilize a Bayesian parametric inversion technique for broadband spectral decomposition of ground motion records from seismic events in the Delaware Basin of West Texas. Ground motion records from earthquakes with reported M_L >= 3.0 (largest M_L = 5.4) and hypocentral distances up to 300 km are used to evaluate source, path, and site terms. The dataset consists of 6,477 ground motion records from 354 events recorded at 49 stations. We implement a geometric spreading function with a gradual transition from a near-field geometric spreading rate (γ) to a fixed far-field spreading rate of 0.5, incorporating a variable transition distance. Preliminary analyses show a quality factor (Q_0) value of 781, frequency dependent anelastic attenuation parameter (η) of 0.70, γ of 1.15, and a transition distance of 76 km. Inverted M_W values tend to be smaller than the reported M_L values. Inverted stress drop values range from ~3 to 120 bars and these values increase with increasing magnitude. This finding aligns with the available literature for West Texas and other regions. The inversions provide frequency-dependent site amplification and the high frequency decay parameter (κ_0) for each station. The site amplification varies considerably in amplitude and shape across the stations, and κ_0 also varies considerably from 0.008 to 0.057 s. In summary, our study leverages an efficient inversion technique, offering a robust framework for characterizing a seismically active region. Integrated into the regional context, these findings advance our understanding of seismicity in the Delaware Basin of West Texas from an engineering and seismic hazard perspective such that the results can be used to develop robust ground motion models for larger events (M_W > 5.0) that are of engineering significance.

POSTER 43

The 2020 Sparta, North Carolina, Earthquake: Insights From Double-Difference Earthquake Relocations, Regional Moment Tensor Inversion and Coulomb Static Stress Transfer

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The study examined the spatial and temporal distribution of the 2020 Mw 5.1 Sparta, North Carolina foreshock-mainshock-aftershock sequence, recorded by 13 permanent stations of the US national seismic network. The double-difference (HypoDD) earthquake relocation algorithm was applied to the foreshocks, mainshocks, and aftershocks to characterize the fault responsible for the earthquake. 105 earthquakes that occurred between August 2020 and June 2023 were relocated using a total of 922 P and 942 S differential travel times. The relocations resulted in five individual clusters, with the primary cluster involving 57 aftershocks located to the south-west of the mainshock. The relocation indicates a south-west dipping reverse fault with aftershock hypocenters at depths from 0.2 km down to 12 km. We also computed the mainshock focal mechanism using the regional waveforms recorded with the US permanent seismic array. This inversion used waveforms bandpassed between frequencies 0.05 and 0.11 Hz and demonstrates a reverse fault mechanism at a centroid depth of 3 km for the mainshock. The strike, dip, and rake computed for the nodal plane are 114, 60, and 64, respectively. We are now examining the Coulomb static stress transfer relationship between mainshock and the aftershock sequence.

POSTER 44

Neotectonic Controls on the Meadow Bank Scarp, Wabash Valley Seismic Zone USA

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Scarps typically have much steeper slopes than those of the surrounding topography and are driven by abrupt spatial changes in geologic materials and/or temporal processes like active faulting. The Meadow Bank scarp (MBS) in southeastern Illinois is widely accepted as satisfying the former but has historically lacked consensus as a tectonically driven scarp. Debate has focused on the process controlling the pronounced ~10-km-long and 4-to-7-meter-high down-to-the-east linear feature. Regional seismic reflection and well-log data suggest the northeast-trending MBS parallels the underlying structural fabric of the Wabash Valley fault zone and lies within a region of active seismicity. The scarp also acts as a flood plain boundary of the Wabash River and is located near the terminus of the Pleistocene glacial advances which produced frequent "outburst" flood events. To better constrain scarp genesis, we acquired a 917-m-long, 9-fold, SH-wave seismic-reflection survey across the feature using an 18.24 m landstreamer with twenty-four grouped pairs of polarity compatible 4.5 Hz horizontal geophones spaced at 0.76 meters, along with a rolling steel wheel and hammer acting as a horizontal impact energy source. The resultant reflection image indicates a 400-m-wide set of faults that lie immediately west (inboard) of the scarp face. These faults antiformally fold and displace the top of Paleozoic bedrock by approximately 8 m at depths of 30 to 50 m. Fault and/or fault-bend-fold deformation appears to extend into the shallowest Quaternary strata: within the upper 10 meters. Consequently, we interpret the MBS as formed by the Quaternary-active Wabash fault zone.

POSTER 45

Source Characterization of the 2020 Mw 5.1 Sparta, North Carolina, Earthquake Sequence

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On August 9, 2020, a Mw 5.1 earthquake shook the Blue Ridge Mountains near Sparta, North Carolina, causing damage to roads, utility lines, and masonry structures. This earthquake is the strongest recorded in North Carolina since the 1916 M 5.2 earthquake near Asheville. Despite its moderate size, the Sparta mainshock generated the first documented surface rupture due to faulting in the eastern United States (EUS). The co-seismic surface rupture was identified along a ~2-km-long ESE-striking, SSW-dipping reverse fault. The mainshock was preceded by 8 foreshocks with duration magnitude (Md) ranging between 1.8 and 2.6 within the 25 hours before the mainshock and followed by hundreds of locatable aftershocks. The focal mechanism of the mainshock that we determined using moment tensor inversion reveals a very shallow (1 km depth) oblique reverse fault striking SE (N118°E) and dipping 52° to SW. This mechanism matches well with the observed surface deformation. Spectral analysis of the mainshock data indicates a corner frequency of 0.77 Hz, corresponding to a Brune stress drop of only 5.7 MPa, unusually small for an EUS mainshock, and the calculated source radius of 1.5 km and average slip of 20 cm both agree well with field observations. Preliminary relocations of ~300 events in the sequence using the double-difference algorithm greatly improved the spatial alignment of the seismicity compared to the original catalog. Notably, in addition to the NW-SE-striking fault associated with the mainshock fault plane and the surface rupture, the relocated events also delineate a conjugate fault trending NE, which intersects the mainshock fault near the northwest edge of the surface rupture. Ongoing work involves the construction of a rupture model for the mainshock, the detection and location of more events to construct a more complete catalog of the sequence, focal mechanism determination and stress drop estimation for smaller events in the sequence. Our results will help shed light on the source processes and seismic hazard assessment in this very low strain rate intraplate setting.

Towards Advancing Earthquake Forecasting and Nowcasting: Recent Progress Using AI-Enhanced Methods

Oral Session • Wednesday 1 May • 2:00 PM Pacific

Conveners: Yangkang Chen, University of Texas at Austin (yangkang.chen@beg.utexas.edu); Katsumi Hattori, Chiba University (khattori@faculty.chiba-u.jp); Lisa G. Ludwig, University of California, Irvine (lgrant@uci.edu); Dimitar Ouzounov, Chapman University (ouzounov@chapman.edu); John Rundle, University of California, Davis (john.b.rundle@gmail.com)

Towards Deep-Learned Picking at the USGS National Earthquake Information Center

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Phase picking by deep neural networks often outperforms traditional methods at local-regional scales, but the implementation of deep earning in real-time global earthquake detection has received relatively less attention. Deep learning methods can improve the accuracy, precision, and recall of phase picks and once trained, can handle large data streams more quickly and with less computational overhead compared to traditional approaches. Deep learning models also are advantageous as they can be designed and trained specifically to meet the requirements of a particular monitoring system. We discuss our design considerations and requirements for a National Earthquake Information Center (NEIC) machine-learning seismic phase picker, including the selection of most appropriate training dataset to meet the NEIC's needs. We also include how we approach the detection and usage of secondary teleseismic phases. The NEIC heavily relies on first-arriving P and local S picks, and therefore we train a model specifically to target these features. Finally, we compare the performance of our new picker to the existing NEIC automatic multi-band filter phase picker, test its performance in conjunction with NEIC's GLASS3 associator, which requires reliable and non-spurious picks for optimal performance, and discuss the integration of the picker into NEIC's operational systems.

Evaluating the Application of Machine Learning in Seismic Site Classification: A Case Study of Vs30 Development in Po Plain, Italy

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The continuous application of VS30, representing the time-averaged shear-wave velocity in the upper 30m, as a proxy for site characteristics, has consistently driven the necessity to enhance methodologies and strive for an approach that can improve accuracy of the estimation of seismic site classifications. Widely adopted methodologies, including terrain-based, geological, and hybrid regression-based models, have formed the backbone of research and applications in VS30 mapping. Recent advancements have witnessed the expansion of open-source datasets, advancements in satellite and remote sensing data as well as integration of more sophisticated approaches, particularly those based on Machine Learning (ML) algorithms. Our investigation centers on VS30 mapping in the Po Plain region in Italy, utilizing field data from over 3000 sites along with other geospatial parameters such as surficial geology, Digital Elevation Models (DEM) based derivatives, and physiographic divisions. In this study, our objective is to employ ML-based algorithms for comparing VS30 estimations with conventional geostatistical methods to highlight the strengths and limitations inherent in these methodologies. The findings demonstrate the capability of ML predictive algorithms to improve spatial interdependence across geological, geophysical, and geotechnical data. The insights derived from this study can be employed to formulate a well-informed assessment of seismic risk at the local level.

An AI-Assisted Real-Time Earthquake Forecasting Case Study in China

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Earthquake forecasting aims to save human lives and reduce economic loss by providing early alerts before the occurrence of large destructive earthquakes. It was long considered challenging due to the various uncertain factors, including data processing artifacts, unknown physical mechanisms, geological complexity, anthropogenic interventions, etc. With the advent of artificial intelligence (AI) and gigantic datasets from multiple sources, earthquake forecasting has become more hopeful. In this study, we trained an earthquake forecasting model using a classic random forest algorithm and a large-scale dataset from West China, where earthquake activities are prevalent. We obtained encouraging real-time testing results on an independent dataset from the same area. The training data comprises the geo-acoustic (GA) and electromagnetic (EM) data of more than 120 M>3.5 earthquake events recorded by 150 stations from 10/01/2016 to 12/31/2020. Instead of using the continuous waveforms directly, we extract physically meaningful features to lower the freedom and uncertainty involved in the training process. The real-time forecasting performance reaches above 70% accuracy with a distance error close to 200 miles and a magnitude error below 0.5 Ml. This research sheds light on more widely tackling the enigmatic earthquake forecasting problems using AI-assisted data-harnessing technologies.

Now-Casting With Real-Time Strong-Motion Response Spectra

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Now-casting serves as a crucial and complementary component of Earthquake Early Warning Systems (EEWS). While EEWS are essential for providing advanced warning in seismic events, they inherently have blind zones where the strong shaking arrives before the early warning alert. In these instances, now-casting steps in to bridge the gap. This approach offers the advantage

of delivering actionable information within mere seconds after the onset of significant shaking, ensuring that individuals and organizations have immediate guidance for response to the event. Moreover, now-casting is particularly valuable in situations where implementing preventive measures via EEWS could be cost-prohibitive. Furthermore, now-casting's utility extends beyond areas covered by comprehensive EEWS networks. It remains effective in seismic regions with sparse station coverage, ensuring that earthquake monitoring and response capabilities are not restricted solely to regions with fully established EEWS infrastructure.

We employ strong-motion response spectra calculated in real time from accelerometers to create exceedance alerts for one or more engineering demand spectra, e.g., Design Response Spectrum (DRS), Operational Basis Earthquake (OBE), and Safe Shutdown Earthquake (SSE). This approach measures true ground motion and doesn't require an earthquake location and magnitude, thus these alerts can be calculated within milliseconds and then disseminated. In addition, the warning carries qualitative information on possible damage to structures and buildings in the vicinity of a given strong-motion station. We will show data and examples gathered during an experiment in the ANZA network to demonstrate strong-motion response spectra as a now-casting tool.

Abnormal Low-Magnitude Seismicity Preceding the M6.4-M7.1 2019 Ridgecrest (California) Sequence and the M7.1 2018 Anchorage (Alaska) Earthquake

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Empirical analysis indicates that large, locked fault zones concentrate stresses both within their internal configurations and in their host rock, leading to possible variations in low-magnitude seismic patterns on a regional scale. However, the intricate spatiotemporal distribution of low-magnitude seismicity, coupled with gaps in previous earthquake catalogs, obstructs the conclusive determination of whether major seismic events are consistently preceded by identifiable seismic or tectonic unrest. The advent of novel machine learning-based methodologies provides the oppportunity to decipher subtle and nonlinear patterns from historical seismic events. In this study, we employ a novel multivariate, supervised, machine learning-based algorithm to investigate whether low-magnitude seismicity conceals robust, nonlinear precursory patterns that could reliably signal forthcoming large-magnitude earthquakes. Our algorithm integrates a random forest machine learning approach and statistical features derived from openly available earthquake catalog data. The analysis reveals that the M6.4-M7.1 2019 Ridgecrest (California) sequence and the M7.1 2018 Anchorage (Alaska) earthquake were preceded by approximately three months of tectonic unrest on regional scales. This unrest manifested as anomalous low-magnitude seismic activity spanning roughly 15-25% of the total area of Southern California and Southcentral Alaska. Further support for our findings comes from finite element solid mechanics models, demonstrating that the presence of large, locked faults can induce uneven variations in the regional stress field when the pore fluid pressure within these fault segments significantly increases, and thus their internal structure becomes softer (lower Young's modulus). These discoveries offer latent avenues for monitoring agencies to potentially detect regions approaching a significant earthquake (fault rupture) weeks to months before its occurrence.

Towards Advancing Earthquake Forecasting and Nowcasting: Recent Progress Using AI-Enhanced Methods [Poster Session]

Poster Session • Wednesday 1 May

Conveners: Yangkang Chen, University of Texas at Austin (yangkang.chen@beg.utexas.edu); Katsumi Hattori, Chiba University (khattori@faculty.chiba-u.jp); Lisa G. Ludwig, University of California, Irvine (lgrant@uci.edu); Dimitar Ouzounov, Chapman University (ouzounov@chapman.edu); John Rundle, University of California, Davis (john.b.rundle@gmail.com)

POSTER 149

Short-Term Earthquake Forecast Using Precursor Phenomena

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The year 2023 marks exactly 100 years since the 1923 Taisho Kanto Earthquake, which was a massive trench earthquake that occurred in the Sagami Trough. It is known that large-scale trench earthquakes, so-called Kanto earthquakes, have occurred repeatedly in the Sagami Trough, and that the 1703 Genroku Kanto Earthquake occurred, causing great damage. On the other hand, there is also concern about an earthquake directly below the Tokyo metropolitan area. According to the Cabinet Office, there is a 70% probability of an earthquake directly below the Tokyo metropolitan area occurring within the next 30 years. Earthquake disaster prevention measures are more focused on post-event response. The main pre-earthquake countermeasures are to strengthen buildings and structures against earthquakes, and there is no system for active evacuation based on prior information before a disaster occurs, as in the case of heavy rainfall disasters in the weather, even though the occurrence of an event is uncertain. In the case of the torrential rain disaster, the decision makers were appropriately informed of crisis avoidance actions and were able to manage the risks. This is due to the experience of the decision makers and the accuracy of the advance information. In the case of torrential rain disasters in Japan, typhoons and torrential rains occur somewhere every year, accumulating knowledge and insight into the spatiotemporal events before and after the event. Observation technology has also advanced, and it is now possible to grasp the current situation through radar images and other means. What about earthquakes, on the other hand? The government's view on prior information, except for long-term forecasts, has not been established. The time scale of large earthquakes that cause damage does not match the time scale of human life, and knowledge has not been accumulated efficiently. The preparation for the earthquake directly under the Tokyo metropolitan area and the direction of future earthquake disaster mitigation research (short-term forecasting research) will be discussed using the ULF geomagnetic field variation.

POSTER 150

Deep Learning for Higher-Order Aftershock Forecasting in Near-Real-Time

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The use of machine learning (ML) methods for earthquake forecasting has recently emerged as a promising avenue, with several recent publications exploring the application of neural point processes. Such models, in contrast to those currently applied in practice, offer the flexibility to incorporate additional datasets alongside earthquake catalogs, indicating potential for enhanced earthquake forecasting capabilities in the future.

However, with a forecasting performance that currently remains similar to that of the agreed-upon benchmark, the Epidemic-Type Aftershock Sequence (ETAS) model, the black-box nature of ML models poses a challenge in communicating forecasts to lay audiences.

The ETAS model has stood the test of time and is relatively simple and comprehensively understood, with few empirically derived laws describing aftershock triggering behavior.

A main drawback of ETAS is its reliance on large numbers of simulations of possible evolutions of ongoing earthquake sequences, which is typically associated with long computation times or resources required for parallelization.

In this study, we propose a deep learning approach to emulate the output of the well-established ETAS model, bridging the gap between traditional methodologies and the potential advantages offered by machine learning. By focusing on modeling the temporal behavior of higher-order aftershocks, our approach aims to combine the interpretability of the ETAS model with the computational efficiency intrinsic to deep learning.

Evaluated using commonly applied metrics of both the ML and earthquake forecasting communities, our approach and the traditional, simulation-based approach are shown to perform very similarly in describing synthetic datasets generated with the simulation-based approach.

Our method has two major benefits over the traditional approach. It is faster by several orders of magnitude, and it is not susceptible to being influ-

enced by the presence (or absence) of individual `extreme' realizations of the process, and thus enables accurate earthquake forecasting in near-real-time.

POSTER 151

Study of the b-Value Change Preceding the 2024 Noto Peninsula Earthquake M7.6, Japan

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On January 1, 2024, an earthquake of magnitude 7.6 occurred in the Noto Peninsula of Ishikawa Prefecture, Japan. The Noto Peninsula lies on the southeastern margin of the Japan Sea, and the northeastern tip of the Noto Peninsula has been subject to a swarm seismic activity for the last three years, with the largest earthquake being a Mw 6.3 event that took place in May 2023. The Noto earthquake swarm mainly include four regions: northern, northeastern, western, and southern, and the depths are mainly distributed at 10-15km. This study aims to investigate the statistical characteristics of seismicity of Gutenberg-Richter Law, with a focus on the b-value, an important parameter used in earthquake prediction. And we also introduce the parameter P to examine the significance level of b-value changes in the temporal variation by bootstrap approach with Akaike's Information Criterion (AIC). As the selection of magnitude of completeness (Mc) in the catalog has significant impact on the results of b-value, in this study, the maximum curvature (MAXC) technique and the bootstrap approach is applied to calculate Mc value. Then the b-value is estimated by the Aki-Utsu maximum likelihood estimation. The anomalous increase in b-values preceding a main seismic event indicates heightened and intensified seismic activity, reflecting the accumulation and subsequent release of stress in the crust. This phenomenon signifies a region where seismic occurrences become more frequent, signaling the imminent occurrence of substantial earthquakes.

POSTER 152

The January 1, 2024, Noto Hanto, Japan, Mw 7.6 Earthquake as a Plausible 'Dragon King' Event

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We query whether the January 1, 2024, Noto Hanto, Japan, M_W7.6 earthquake, which punctuated the intense and long-lasting swarm, can be regarded as a 'Dragon King event' in the perspective of 'Dragon King' theory. We analyzed the earthquake catalogue from JMA since 2004 which uses M_V to quantify an earthquake and M_W to quantify those events with moment tensor solutions. We inspected the frequency-magnitude distribution and generated the rank-ordering plots, within a fixed spatial range around the Noto Peninsula, to determine whether the M_W 7.6 event is an outlier which significantly deviates from the power law scaling. We obtained that for the period from 2004 to 2024 the earthquake cannot be regarded as a significant 'Dragon King' event, while for the period from 2021 to 2024 the earthquake can be regarded significantly as a 'Dragon King' event. This observation seems consistent with the report that complex precursory behavior has occurred since December 2020, implying the predictability of the 'Dragon King' event. We suggest that detailed study of this earthquake, based on the previous results of investigation, may contribute to the theory of the mechanism and prediction of a 'seismic Dragon King'.

POSTER 153

Building an Enhanced Earthquake Catalogue for Aotearoa New Zealand: Applying an Automated Workflow With Cutting-Edge Machine Learning Methods to Mine New Zealand's Seismic Data

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The New Zealand nationwide seismic catalogue produced by GeoNet is primarily focused on ensuring fast hazard communication and response. The focus on hazard response, combined with the inconsistent nature of the New Zealand seismograph network, can mean events are mislocated or not located at all. We propose and develop a cutting-edge automated workflow to generate research-grade earthquake catalogues for Aotearoa New Zealand and have begun to apply this to New Zealand's seismic data. This workflow expands and improves the current catalogue, enabling further research into New Zealand's tectonic setting and a better understanding of present-day seismic hazard. We apply uniform identification, classification and location methods to the entire catalogue, reducing errors and uncertainties introduced by inconsistencies in the current catalogue.

We use the now well-tested EQTransformer AI seismic picker to efficiently and accurately detect and pick events in a uniform manor. We locate all events using the NZWide 2.3 3D Velocity Model (Eberhart-Phillips et al., 2022), producing accurate locations and robust uncertainties. We present the results of initial testing on five distinct regions around Aotearoa as well as the first years of the enhanced catalogue we have produced. We find differences in manual and automatic picking to be negligible in determination of final location for most events and that the improved velocity model with the removal of depth fixing has a much larger influence on final location. In all test regions, most events locate deeper than initially estimated by GeoNet, though smaller changes in location are observed in more densely monitored regions with less complex velocity structures. Future work will extend this cataloguing through time to develop a self-consistent high-quality earthquake catalogue that will have enhanced capabilities for capturing precursor signals important for earthquake forecasting across New Zealand.

Translating Seismic Imaging into Geodynamic Understanding

Oral Session • Wednesday 1 May • 4:30 PM Pacific

Conveners: Ebru Bozdag, Colorado School of Mines (bozdag@mines.edu); Rebecca Fildes, University of California, Davis (rfildes@ucdavis.edu); Menno Fraters, University of Florida (menno.fraters@ufl.edu); Lorraine J. Hwang, University of California, Davis (ljhwang@ucdavis.edu); Andrew Lloyd, Lamont-Doherty Earth Observatory, Columbia University, (andrewl@ldeo.columbia.edu); Brandon VanderBeek, Università di Padova (brandonpaul.vanderbeek@unipd.it)

Integration of Geophysical Constraints in Global Mantle Flow Models for Insights Into Plate Tectonics

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Integrating seismic imaging into geodynamic models is key to our understanding of the structure and dynamics of Earth's interior. However, modeling the physical processes governing mantle flow across a range of length and time scales while integrating different data sets and models still remains a challenging problem.

We here address this challenge using the example of global instantaneous 3-D mantle convection models. Our models combine (1) a heterogeneous density and viscosity distribution inferred from the LLNL-G3D-JPS tomography model, (2) subducted slab geometries defined using the Slab2 model (Hayes et al., 2018), (3) weak plate boundaries from the Global Earthquake Model (GEM, Pagani et al., 2018), (4) crustal thickness from the CRUST1.0 model (Laske et al., 2012) and lithospheric thickness from Priestley et al. (2018), and (5) a recent model of the thermal structure of the lithosphere (Osei Tutu et al., 2018). We build these models in the geodynamic modeling software ASPECT in a modular fashion to allow any combination of the individual features and associated datasets. This modular design is further supported by an interface to the Geodynamic World Builder software, which is used to define the thousands of complex fault geometries in our models.

We vary our model parameters to optimize the fit to observed plate velocities and to quantify the relative importance of forces and individual datasets. We find that a low-viscosity mid-mantle layer (660–1000 km depth) is required for slabs to effectively transfer slab pull forces to the surface plates. Our best-fit models have plate boundaries that are 3 to 4 orders of magnitude weaker than the surrounding lithosphere and low asthenospheric and mid-mantle viscosities (~1e20 Pa s). They achieve a 94% directional fit and a speed residual of 0.7 cm/yr relative to the observed plate motion. In these models, more than three quarters of the average plate velocity is generated by slab pull alone.

These results advance our understanding of mantle flow and can be used as global constraints for regional studies of plate boundary dynamics and surface processes.

Immersive Insights: Visualization of Earth's Interior in VR and Dome Theaters

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This project aimed to integrate three-dimensional global seismic models of the mantle into Virtual Reality (VR) and planetarium environments. The primary focus of 3D visualization is to allow a more engaging medium in educational and public outreach activities, while promoting deep-Earth sciences. To demonstrate the use of immersive environments in different branches and scales, we built an interactive user experience for the recent global adjoint mantle models, i.e., GLAD-M25 (Lei et al. 2020), GLAD-M50-AZI (Bozdag et al. in prep.), constructed based on full 3D spectral element modeling of synthetic seismograms and data sensitivity kernels where crust and mantle were inverted simultaneously down to the core-mantle boundary. Focusing on mantle plumes, we have demonstrated these models so far:

1) in the VR environments with the Colorado School of Mines Math Club graduate and undergraduate students

2) at the Gates Planetarium of the Denver Museum of Nature & Science and the Morrison Planetarium of the California Academy of Sciences.

Our primary challenge involved the incompatibility of Paraview-formatted models with the software used for VR and many planetariums. Taking advantage of multi-format import and export options within these software, we used a three-step pipeline. This pipeline involved transitioning the models from Paraview as a .gltf, commonly used for scientific analysis, to Blender, serving as an intermediary software to make corrections caused by data loss during the export process. After corrections have been made, the model is then exported from Blender as an .fbx to be opened in Unity, the software used to build VR environments, or as a .glb file for OpenSpace, a visualization software used in planetariums. The success of these demonstrations shows the versatility of our approach, making scientific data accessible across multiple platforms, ultimately fostering interest and understanding among diverse audiences. In coming demonstrations, in addition to plumes, we will also highlight slabs, seismicity, anisotropy, and other potential geophysical data.

Investigating the Seismic Signature of Galápagos Mantle Flow Models

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The Galápagos Archipelago, which lies less than 200 km south of the Galápagos Spreading Center (GSC), provides a novel setting to study how mantle plumes, spreading centers, and the lithosphere interact. Numerous geophysical, geochemical, and petrologic studies have defined variations in mantle temperature and composition, as well as magma flux of the ridge-plume system. What these characteristics imply about upper-mantle rheology and plume-to-ridge mass and heat transfer is not well understood. To address this issue, Ito and Bianco (2014) provide two models of plume flow at the Galápagos Archipelago that account for realistic ridge geometry of the GSC and varying mantle structure. The first model represents a plume with low viscosity due to temperature-dependent mantle rheology. Fed by a narrow plume stem, plume mantle ponds below the thermal lithosphere and is channeled up to and along the ridge by the sloping lithosphere. The second model represents a plume with high viscosity in the upper mantle due to added dependence on water content, simulating extraction of water by partial melting. A wide plume stem creates a thick plume pond that accumulates under a deeper, dehydrated compositional lithosphere. To determine the sensitivity of teleseismic data to different patterns of mantle flow, this study will generate a synthetic anisotropic seismic dataset of P and S arrivals from these two models and compare the absolute traveltime differences. Anisotropy will account for lattice-preferred orientation (LPO) of olivine crystals, which are highly anisotropic in seismic velocity and tend to align in the direction of plastic flow. Due to LPO, mantle flow creates a strong anisotropic pattern that needs to be accounted for in seismic imaging problems. The geometry of the Marine IGUANA (2024) experiment, consisting of 53 broadband ocean bottom seismometers deployed for 15 months, will be used as the synthetic teleseismic array. This study will demonstrate how the two models of plume flow can be distinguished through their seismic signature to inform the interpretation of the observed Marine IGUANA seismic data.

First Steps Towards Imaging the Antarctic's 3D Viscosity Structure Using GPS Observations

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A critical challenge of Glacial Isostatic Adjustment (GIA) modeling is seeking a combination of mantle viscosity and ice history that satisfies existing GIA observations. Current approaches vary in their complexity, but all fundamentally rely on solving the forward problem many hundreds of times. This is practical if Earth's viscosity varies with only depth, but quickly becomes unfeasible if lateral variations in viscosity are considered. In order to limit the parameter space and ensure a reasonable mantle structure, researchers are inferring 3D mantle viscosity from other geophysical models, such as seismic tomography. However, the resulting 3D viscosity inferences may not improve the GIA model's fit to the data because of shortcomings associated with the geophysical models, the mapping to viscosity, the rheological model, and the ice history.

We take a different approach, inspired by seismic tomography, and use gradient-based optimization along with the adjoint method to invert solid Earth deformation measured by Antarctic GPS stations to directly image 3D mantle viscosity. This iterative inversion ensures that the final GIA model is consistent with the observations. Here we focus on the setup and methodology of the inversion. First, for our starting viscosity model we adopt a 3D viscosity inference based on the shear wave speeds of the continental and global tomography models ANT-20 and GLAD-M25, respectively. These inferences are obtained using the inverse calibration scheme of Richards et al. (2020), but for ANT-20 we explore the use of additional calibration constraints to further refine the anelastic calibration parameters and also obtain a 3D inference of Q^{-1}. Next, we examine the viscosity sensitivity kernels for solid Earth deformation and demonstrate how differential measurements can be used to restrict the spatial extent of the kernel, allowing us to update only the Antarctic mantle and minimize the influence of errors. Finally, results from a synthetic inversion using the potential Antarctic GPS dataset will be shown.

Instantaneous 3D Tomography-Based Convection and Melt Generation Beneath the Rungwe Volcanic Province, East Africa

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Within the Western Branch of the East African Rift (EAR), volcanism is highly localized, which is distinct from the voluminous magmatism seen throughout the Eastern Branch of the EAR. We hypothesize that the interaction of plume material with the base of the continental lithosphere enables the localization of melt beneath the Western Branch to regions where there are sharp variations in lithospheric thickness. To test our hypothesis, we investigate sub-lithospheric mantle flow and melt generation beneath the Rungwe Volcanic Province (RVP), which is the southernmost volcanic center in the Western Branch. We use seismically constrained lithospheric thickness and sublithospheric mantle structure to develop an instantaneous 3D thermomechanical model of tomography- based convection (TBC) with the physics for melt generation beneath the RVP using ASPECT. Shear wave velocity anomalies suggest excess temperatures reach ~250 K beneath the RVP. We use the excess temperatures to constrain parameters for melt generation beneath the RVP and find that partial melt develops at a maximum depth of ~140 km. Our TBC model suggests that upwellings from a thermally heterogeneous asthenosphere distributes and localizes deep melt sources beneath the Western Branch in locations where there are sharp variations in lithospheric thickness. Even in the presence of a uniform lithospheric thickness in our TBC models, we still find a characteristic upwelling and melt localization beneath the RVP, which suggests that sublithospheric heterogeneities exert a dominant control on upper mantle flow and melt localization in this region. Our TBC models demonstrate the need to incorporate upper mantle constraints in mantle convection models.

Translating Seismic Imaging into Geodynamic Understanding [Poster Session]

Poster Session • Wednesday 1 May

Conveners: Ebru Bozdag, Colorado School of Mines (bozdag@mines.edu); Rebecca Fildes, University of California, Davis (rfildes@ucdavis.edu); Menno Fraters, University of Florida (menno.fraters@ufl.edu); Lorraine J. Hwang, University of California, Davis (ljhwang@ucdavis.edu); Andrew Lloyd, Lamont-Doherty Earth Observatory, Columbia University, (andrewl@ldeo.columbia.edu); Brandon VanderBeek, Università di Padova (brandonpaul.vanderbeek@unipd.it)

POSTER 161

Guiding Deep Earthquake Investigation with Subduction Modeling: Is Thermal Shear Instability Viable in the Deep Slab?

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The processes that lead to deep (>70 km) earthquake failure in subducting lithosphere are an ongoing investigation. The high pressures and temperatures in sinking slabs at these depths inhibit the brittle failure mechanism understood for shallow earthquake failure. It is currently proposed that deep earthquakes occur through dehydration embrittlement, transformational faulting, and/or thermal shear instability (TSI). It was proposed recently that strain-rate variations, in addition to temperature, control where deep earthquakes can occur: high strain-rate regions in cold portions of the slab. However, this high strain-rate constraint hypothesis was not tested using location-specific subduction modeling, nor did it differentiate between proposed failure mechanisms. Here we present a new methodology that links location-specific geodynamic subduction modeling with TSI modeling and earthquake observations to investigate the viability of TSI initiating at deep slab conditions. Subduction model slab geometries are constructed for a specific location based on seismic tomography and observed seismicity. These 2D location-specific dynamic visco-elastic-plastic subduction models are used to determine deep slab physical conditions (strain-rate, stress, temperature, and pressure). These location-specific models allow for a more direct comparison to observations as the results are compared with the deep earthquake observations for the same profile the model was based on. The physical conditions found in regions overlapping with observed seismogenic regions of the slab are extracted from the subduction model and used as the initial conditions in a separate TSI model to test whether TSI can initiate or not at these conditions. This methodology of using the subduction modeling as a lens to guide the investigation of TSI viability extends the depth range of conditions that TSI has been investigated under before. The location-specific subduction modeling is a step forward in constraining the conditions required for deep earthquake rupture and could be similarly used to investigate other proposed deep earthquake failure mechanisms.

POSTER 162

Seismic Imaging of the Mendocino Triple Junction: Unraveling the Geodynamics of a Fundamental Plate Boundary Transition

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The Mendocino Triple Junction (MTJ) demarcates the fundamental change along the North American plate boundary from subduction (Cascadia) to translation (San Andreas). This plate boundary transition initiates the lithospheric shear zone that develops into the San Andreas plate boundary system. It is one of the most seismogenic regions of North America and a location of abrupt changes in topography and relief. Over the past several decades our understanding of the tectonics intrinsic to this transition has advanced, but key questions about the structure and deformational processes at the MTJ remain. Our new regional tomography of the MTJ region allows us to better constrain the crust-upper mantle structure and its relationship to the abundant seismicity, and therefore interpret the main controls on San Andreas plate boundary formation. The high-resolution of the tomography (3 km x 3 km x 0.5 km) allows us to clearly differentiate among the 3 primary components of the plate boundary system - the subducting Gorda Slab, the North American crust (composed of the Franciscan, Klamath, and Great Valley terranes), and the Pacific plate (including a fragment that extends inland under the North American crust). We also image the upwelled mantle within the slab window. Additionally, we observe significant variations in crustal thickness within the overlying North American crust, associated with the migration of the MTJ and slab window. Using this new image of the crust-upper mantle structure in northern California we can interpret that much of the on-shore and near-shore seismic activity in the region (including most of the larger events) occurs within the overlying North American crust near or above the slab interface, rather than within the subducting slab. Additionally, this imagery indicates significant variations in crustal thickness of the overlying North American crust, associated with the migration of the MTJ and slab window.

POSTER 163

Image of Crust and Upper Mantle of Ne India Based on Surface Wave Tomography

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The Indian Plate (IP) present below the Shillong Plateau (SP) and Mikir Hills (MH) is buckled up. It is because it is in a vice-like grip between the Eastern Himalayas (EH) to its North, below which it is underthrusting, and the Indo-Burma Ranges (IBR) to its East, below which it is subducting. A thick layer of sedimentary rock is present in the Bengal Basin (BB). Its thickness varies from ~10 km to ~20 km from West to East. The E-W trending Dauki fault separates it from the high-velocity Precambrian rocks present at shallow depths of the SP. The Dauki Fault and the Eastern Hinge Zone (EHZ) demarcate the northern and western boundaries of the oceanic crust present below the BB from the continental crust to its North and West. Sediments are getting underthrusted in the southern part of the IBR. The Moho depth varies both along and across the trend of the EH. We opine that the along-trend variation is caused by the anticlockwise rotation of the continental part of the IP after it first collided with the Eurasian Plate (EP) on the western side. Such rotation has caused crumpling of the crust of the Himalayas along its entire length. Average Moho depth increases from entire length. Average Moho depth increases ~40 km in the south to ~70 km in the northern part of the study area smoothly in most places but abruptly at other places. The underthrusting process of the IP below the EP varies from place to place. Below the Nepal Himalayas repeated underthrusting and overthrusting are observed. In some parts of NE India, it appears that the IP has broken and a new front of underthrusting is developing. In the Brahmaputra River Valley, 5–6 km thick sedimentary layers are present. However, the north of the SP and the MH sedimentary layer is very thin. The Moho depth decreases from ~70 km west of the Yadong-Gulu rift to ~60 km toward the east which may be the effect of collision geometry to control the underplating of the IP in this section of LB. Several low-velocity bodies are observed in the mid-to-lower crust of the LB, mostly below the N-S trending rift zones indicating the presence of partial melts or fluid-filled fracture zones.

POSTER 164

Transdimensional Mt. Etna Volcano P-Wave Anisotropic Seismic Imaging

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Transdimensional inference identifies a class of methods for inverse problems where the number of free parameters is not fixed. In seismic imaging these methods are applied to let the data decide the complexity of the models and how the inferred fields partition the inversion domains. Monte Carlo transdimensional inference is performed implementing the reversible-jump Markov chain Monte Carlo (rjMcMC) algorithm; the nature of Monte Carlo exploration allows the algorithm to be completely non-linear, to explore multiple models with different dimensions and meshes and to investigate the under-determined nature of the tomographic problems. Implementations of this method overcome the main limitations of traditional linearized solvers: the arbitrariness in the selection of the regularization parameters, the linearized iterative approach and in general the collapse of the information behind the solution into a unique inferred model. We present applications of the rjMcMC algorithm to anisotropic seismic imaging of Mt. Etna using P-waves. Mt. Etna is one of the most active and monitored volcanoes in the world, typically investigated under the assumption of isotropic seismic speeds. However, since body waves manifest strong sensitivity to seismic anisotropy, we parametrize a multi-fields inversion to account for the directional dependence in the seismic velocities. Anisotropy increases the ill-condition of the tomographic problems and the consequences of the under-determination are more relevant. When multiple seismic fields - such as speed anomalies and anisotropy - are investigated, the data-sets used may not be able to independently resolve them, resulting in non-independent estimates and corresponding trade-offs. Monte Carlo exploration allows for the evaluation of the robustness of seismic anomalies and anisotropic patterns, as well as the trade-offs between isotropic and anisotropic perturbations, key features for the interpretation of the tomographic models. The approach is completely non-linear, free of any explicit regularization and it keeps the computational time feasible, even for large data-sets.

POSTER 165

Ecoman 2.0: An Open-Source Software for Exploring the Consequences of Mechanical Anisotropy in the Mantle.

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In this contribution we introduce ECOMAN 2.0, an open-source software package for (1) modelling the strain-/stress-induced rock fabrics and related mechanical anisotropy, and (2) performing isotropic and anisotropic inversions using real/synthetic P- and S-wave travel-times and S-wave splitting parameters.

The strain-induced intrinsic mantle fabrics are modelled inputting the velocity, pressure, temperature and dominant creep mechanism fields from large-scale mantle flow simulations into D-Rex (*Kaminski et al., 2004*). This open-source software has been parallelized using a hybrid MPI and OpenMP scheme and modified to account for combined diffusion-dislocation creep mechanisms, LPO of transition zone and lower mantle polycrystalline aggregates (Wadsleyite, Bridgmanite, post-Perovskite), P-T dependence of single crystal elastic tensors, advection and non-steady-state deformation of crystal aggregates in 2D/3D cartesian/spherical grids (*Faccenda, 2014; Faccenda and Capitanio, 2013*).

Extrinsic elastic anisotropy due to grain- or rock-scale fabrics or fluid-filled cracks can also be estimated with the Differential Effective Medium (DEM) (*Faccenda et al., 2019*). Similarly, extrinsic viscous anisotropy can be modelled yielding viscous tensors to be used in large-scale mantle flow simulations (*de Montserrat et al., 2021*).

The elastic tensors can then be interpolated in a tomographic grid for (i) visual inspection of the mantle elastic properties (such as Vp and Vs isotropic anomalies; radial, azimuthal, Vp and Vs anisotropies), (ii) generating input files for large-scale synthetic waveform modelling (e.g., SPECFEM3D format), or (iii) P- and S-wave isotropic and anisotropic inversions (e.g., *Faccenda and VanderBeek, 2023*). The latter can be performed with the new PSI (Platform for Seismic Imaging) module, which includes recently developed techniques for seismic anisotropic inversions of body waves (*VanderBeek and Faccenda, 2021; VanderBeek et al., 2023*).

Understanding and Quantifying the Variability in Earthquake Source Parameter Measurements

Oral Session • Friday 3 May • 8:00 AM Pacific

Conveners: Rachel E. Abercrombie, Boston University (rea@bu.edu); Shanna Chu, U.S. Geological Survey (schu@usgs.gov); Sydney Gable, University of Michigan (gablesyd@umich.edu); Gene Ichinose, Lawrence Livermore National Laboratory (ichinose1@llnl.gov); Colin N. Pennington, Lawrence Livermore National Laboratory (pennington6@llnl.gov)

Estimating Seismic Attenuation, Site Corrections and Geometrical Spreading From Large Seismic Catalogues Using Linearized Spectral Ratios and Regression Regularization Paths

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Estimating source parameters from earthquake signals requires discriminating source properties (e.g. corner frequency and radiation pattern) from path, site and geometrical spreading effects. Commonly used seismic source models incorporate nonlinear combinations of these terms, making it challenging to estimate and isolate these effects from individual event spectra. Here, I present a linearized spectral ratio approach for simultaneously estimating all non-source-dependent terms (i.e. quality factor Q, geometrical spreading, and site-specific κ / average corrections) from large catalogues of low-magnitude ($M<3$) seismicity. Inter-station spectral ratios are used to cancel the corner frequency term from source model equations, leaving only the contribution of path, site and spreading effects to estimate. Large systems of linearized spectral ratio equations are then constructed for subsequent regression, each incorporating many events (e.g. 50–100 events) and all available pairwise station combinations. An iterative regularized regression procedure is then used, where the strength of the parameter regularization is gradually annealed to zero, encouraging the regression algorithm to first estimate 'global' site and spreading terms before estimating the more variable Q attenuation terms for each source-receiver pair. Lastly, distributions are generated for maximum likelihood estimates of each term by repeatedly applying this approach to subsets of large seismic catalogues, providing more robust final estimates and uncertainty quantification.

I demonstrate this approach on a machine-learning-derived catalogue of seismicity from Nabro volcano in Eritrea, comprising nearly 34,000 events. The resulting estimates are compared against some commonly assumed values (e.g. for average radiation pattern and geometrical spreading) and other inferred geophysical properties at Nabro, providing interesting insights into the subsurface properties beneath this volcano. The results also highlight important considerations regarding the use of 'textbook' values and assumptions of frequency (in)dependence for some source model parameters.

Extraction of Source Parameters for French Seismicity Based on a Radiative Transfer Approach: Importance for Attenuation and Site Corrections

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An accurate magnitude estimation is necessary to evaluate properly the seismic hazard. Unfortunately, magnitudes of small earthquakes are subject to large uncertainties due to high-frequency propagation effects, which are generally not accurately considered. To address this issue, we developed a method to separate source, attenuation and site parameters from the elastic radiative transfer modeling of the full energy envelopes of seismograms. Our separation method is based on a 2-step inversion procedure. First, for each source-station pair, we retrieve optimal frequency-dependent attenuation parameters fitting the observed energy envelopes in the 0.375-24Hz band. In a second step, we separate the source spectra and the site amplification relative to (1) the network of stations and (2) a selection of stations showing small amplification (characterized by approximatively flat H/V ratios). From the source spectra, we estimate the moment magnitude Mw, the corner frequency fc and the stress-drop Δσ. We applied the inversion procedure to more than 16000 waveforms recorded by EPOS-FR stations from 662 earthquakes of magnitudes Mw ranging from 2.0 to 5.0. We show that the choice of the reference in site amplification affects in a critical manner source parameters (Mw, fc and Δσ), highlighting the necessity of a careful selection of the source-site separation criteria minimizing site amplification bias on the estimated seismic source. More specifically, we observe an increase of Δσ with Mw if the site amplification is determined relatively to the whole network of stations. However, if the site amplification is relative to selected stations with approximatively flat H/V ratios, Δσ does not scale with Mw. The resulting magnitudes are compared to existing Mw catalogues in France (Si-Hex, FMHEX-22, Buscetti et al. SSA meeting). The role of attenuation maps is explored according to the stabilization of the site and source terms separation. In the future, we intend to automate our method and apply it routinely to smaller earthquakes for which traditional methods are not readily applicable due to the complexity of waveforms.

A Joint Inversion Method for Computing Earthquake Stress Drop With Spectra and Spectral Ratios

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Earthquake stress drop is fundamentally important for understanding the earthquake rupture process, fault strength, and assessing seismic hazard. It is commonly calculated with corner frequency, measured from earthquake spectra, assuming a simple circular rupture model. One significant source of error in determining stress drop in this way is the trade-off between source and path attenuation parameters. To address this issue, we have developed a new method that uses earthquake spectra and spectral ratios to jointly invert source and path attenuation parameters. Our synthetic tests show that this method can effectively mitigate the trade-off between corner frequency and the attenuation parameter. We have been applying this method to analyze earthquakes in the San Francisco Bay Area. In the Bay Area, depth dependence of stress drop was observed in a previous study, but may be due to depth-varying attenuation. Our method accounts for attenuation variations and our preliminary analysis of a set of earthquakes along the northern Hayward Fault shows no depth dependence. We will further assess the data bandwidth requirement for avoiding bias in corner frequency and stress drop.

Earthquake Source Parameter Analysis Using Peak Narrow Band Displacement Amplitudes

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We present a source parameter analysis of nearly 13,000 earthquakes in the 2019 Ridgecrest sequence as part of the SCEC Stress Drop Validation Study. We measure an apparent spectrum defined as the maximum amplitude of the S-wave displacement seismogram after it is passed through a series of band-pass filters. From each seismogram we extract 17 peak amplitude measurements in half-octave bands between 0.125 and 46 Hz. The apparent spectrum is defined by the half-octave peak amplitudes. Given an S-wave arrival for each event, this workflow is fully automated and reproducible. We compare two different methods which use these spectra to measure stress drops.

In the first method, we obtain the source spectrum by applying corrections for site and path effects using a frequency-dependent distance correction based on Richter's local magnitude relation (-log(A0)). Our frequency-dependent attenuation relations account for geometric spreading, attenuation, and local site amplification. We fit an omega-squared Brune model to the median spectrum from all observing stations to obtain the moment and corner frequency for each event. In the second method, we take spectral ratios for close pairs of events to isolate the source effects. We employ the asymptotic spectral ratio method to measure relative stress drops using the high and low frequency levels. This has the benefit that we don't need to resolve corner frequency, which also means we can compare earthquakes of similar magnitude. Using an inversion with all possible earthquake pairs, we compare relative stress drops to our first method. We find that moment magnitude can be reliably measured using both methods for earthquakes at least as small as Mw 1.0. We find an average stress drop of 3.3 MPa and a clear increase in average stress drop with magnitude.

Three Years of the International SCEC/USGS Community Stress Drop Validation Study: What Have We Achieved and Where Next

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The SCEC/USGS Community Stress Drop Validation study has engaged a wide international community since its launch in 2021. The broad aim of the collaboration is to improve the quality of estimates of stress drop and related fundamental earthquake source parameters (corner frequency, source duration, etc.) and their uncertainties, to enable more reliable ground motion forecasting, and to obtain a better understanding of earthquake source physics. Seismological estimates of stress drop from earthquake spectral measurements have become standard practice over the last 50 years, but their wide variability, model dependence and inconsistency between studies have led to controversy and concerns about how to assess and interpret these measurements.

We present the findings of the community comparative analysis of a common data set of earthquakes in the 2019 Ridgecrest, California, sequence, focusing on what we have learnt about assessing the accuracy and stability of different estimates. We also discuss the development of plans for the next stage of this community endeavor in which we aim to work towards providing the optimal characterization of earthquake source parameters for the various user communities. This will likely include a community experiment involving model-generated synthetic data. We welcome new members to the study, wishing to observe, learn or more actively participate; more information can be found at https://www.scec.org/research/stress-drop-validation.

Understanding the Contribution of Site Effects to Variability in Microearthquake Source Parameter Measurements Using a Large, Dense Array in Oklahoma

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Untangling whether the wide variability of estimated source parameters indicates real source property variation, or relates to measurement uncertainty and bias, is a challenging yet important task. When predicting ground motions and modeling earthquake source spectra, the effects of the shallowest, highly attenuating and low velocity layers play an outsize role. Simplifying, or neglecting, the near-surface attenuation and velocity structure in modeling may lead to bias or uncertainties due to parameter tradeoff. We investigate the source parameter variability for microearthquakes recorded beneath the dense 1820 station, Large-N Seismic Survey in Oklahoma to understand the relative influences of sediment depth and surficial deposits on earthquake source parameters and ground motions. We observe large variations in source parameters (a factor of 2 for corner frequency) and ground motions (over a factor of 3 of site-amplification) at different stations, despite the low-relief and relatively flat basin basement depth. We take advantage of the dense station coverage to obtain the velocity and attenuation structure in the top 0.5 km and compare them with the corner frequency and ground motion measurements. Despite the smooth lateral structural changes at depth, the near-surface site attenuation varies significantly across the array with the range of variation exceeding the travel-time-dependent attenuation. Known local Quaternary alluvium and glacial-related shallow deposits play a significant role in absorbing the high frequency energy despite the waves spending a relatively small portion of travel time in these formations. We show that not recognizing the site-attenuation can (1) cause site-dependent source parameter measurements, (2) produce tradeoff between the corner frequency, the quality factor Q, and the spectral falloff parameter n, which result in significant variation between estimates at nearby stations. Our work shows the importance of considering laterally varying site effects when measuring source parameters even within a region with seemingly simple structure with little topographic change.

Demystifying Earthquake Stress Drop Discrepancies Using Synthetic Source Time Functions

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We evaluate how well simple, commonly used stress drop estimation methods recover known stress drops of synthetic, complex ruptures, constructed by combining multiple simple kinematic source models. Earthquake stress drop is a commonly estimated parameter that can provide insight into both earthquake source physics and the resulting ground motion. Stress drop methods usually assume that earthquakes are a symmetric circular crack which release their energy in a single pulse with a simple source time function (STF). Real earthquakes, however, often have complex STFs with multiple pulses of seismic moment release, and studies have shown that stress drop estimates contain significant uncertainties. We also have limited knowledge of the subsurface structure of the earth and its impact on the observed waveforms, so recovering the original earthquake signal requires additional assumptions of material properties and path attenuation.

Therefore, in this study, we seek to investigate how the complexity of earthquakes and different signal deconvolution assumptions can bias two common stress drop estimates—the time-domain method (i.e., estimating rupture duration) and the spectral, frequency-domain method (i.e., estimating corner frequency). We create a synthetic catalog of complex rupture earthquakes (combining multiple simple, circular-crack models with known static stress drops), quantify their complexity, and estimate their stress drop. We first assess how accurate the estimation methods are for complex earthquakes when the rupture process is perfectly known. We then convolve the synthetic earthquakes with a known Earth model to simulate propagation effects and apply different deconvolution techniques (assuming no knowledge of the true model) to recover the source signal and estimate stress drop. This analysis will allow researchers to better assess the potential bias and uncertainty of stress drop estimates for real earthquakes due to both rupture complexity and the effects of deconvolution techniques meant to remove propagation effects.

Variable High Frequency Radiation From Complex Laboratory Ruptures Due to a Normal Stress Bump

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Fault heterogeneities such as roughness, stepovers, and other irregularities are known to affect the spectra of radiated waves during an earthquake, and may therefore affect earthquake source parameters such as stress drop. To investigate the effect of normal stress heterogeneity on the earthquake spectra, we produced a series of ruptures on a 0.74 m PMMA laboratory fault with a single, localized bump of increased normal stress. By varying the bump prominence (defined here as the increase in the normal stress on the bump divided by the average normal stress across the entire fault), we produced earthquake-like ruptures that ranged from smooth, continuous, sample-spanning ruptures to complex ruptures with variable rupture propagation velocity, slip distribution, and stress drop. Vertical ground motions were measured using an array of eight piezoelectric sensors calibrated using a ball drop technique. Radiated seismic waves were strongly affected by the bump prominence. High prominence bumps produced complex events that radiated more high frequency energy, relative to low frequency energy, than continuous events without a bump. In complex ruptures, the high frequency energy showed significant spatial variation in amplitude and timing while continuous ruptures emitted spatially uniform bursts of high frequency energy. Near field peak ground acceleration (PGA) measurements of complex ruptures show nearly an order of magnitude higher PGA near the bump than on the rest of the fault. We expect a similar phenomenon to occur in the earth. We propose that for natural faults, fault geometric heterogeneities, such as roughness or stepovers, may act as earthquake gates and can be a spatially heterogeneous source of enhanced high frequency radiation. This may be a plausible explanation for commonly observed order of magnitude variations in near-fault PGA such as during the 2023 Turkey M_w 7.8 and 7.6 earthquakes.

Source Parameter Scaling Relations for Shallow Crustal Earthquake with a Simple Heterogeneous Source Model

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In this study, the source parameters of shallow crustal earthquakes (M_w 3.2–6.0) were estimated in Japan by the spectral ratio method developed by Shimmoto (2022). This spectral ratio method estimates the finite source properties of a homogeneous rectangular source model. Since the rupture area estimated from this spectral ratio method corresponds to the localized rupture area with large slip, the stress drop was calculated using a simple heterogeneous source model with a single localized area with a concentrated stress drop. We usually estimate the stress drop of small-to-moderate earthquakes with the corner frequency method. In this method, we need to determine a constant (the *k* value) to relate the corner frequency to the source radius by assuming a source model. However, the stress drop values can differ significantly depending on the source model selection. This study addressed this issue by calibrating an appropriate average *k* value by comparing the stress drop estimated from the S-wave corner frequency to the stress drop estimated from the method proposed by Shimmoto (2022). This study also found that the *k* value can vary considerably for different events. The *k* value variability contributes to the potential stress drop uncertainty.

The scaling relations of stress drop, apparent stress, radiation efficiency, and fracture energy were compiled over a broad magnitude range by combining the source parameter results of this and previous studies. The calibrated *k* value was applied to re-calculate the stress drops of small earthquakes analyzed in previous studies. The stress drop and apparent stress increase with increasing magnitude up to M_w ~5 and become constant for larger magnitudes. The radiation efficiency is independent of magnitude and typically ranges from 0.1 to 1.0. The slip dependencies of the source parameters compiled in this study can be explained consistently by the ones predicted from the slip-weakening model incorporating the thermal pressurization effect by Rice (2006).

Reducing the Uncertainty of Stress-Drops

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Stress-drop defines the overall reduction of average stress due to the release of stresses due to an earthquake, and should reflect geometrical, rheological and dynamic properties of the seismic source. Its variability up to four-orders made it an enigmatic parameter, and a reason for extensive research. There have been many efforts to reduce the stress-drop uncertainty, and to perceive better understanding of the factors controlling its variability. These efforts focused mainly on observational aspects, in which source properties such as, corner-frequency and seismic moment, were measured, considering site, path and additional source properties. Another aspect, that has hardly been pursued, is to challenge the formulation applied for stress-drop calculation. One of the basic assumptions is a constant *K* coefficient, relating corner-frequency with geometrical dimensions of the source. We suggest an alternative formulation, based on the results of dynamic modelling, in which the *K* coefficient is not constant and increases with strain-drop (ratio between slip and source length), resulting in a new equation relating stress-drop with seismic moment and corner-frequency. While for a constant *K* coefficient, stress-drop is proportional to a cubed corner-frequency, for the strain-drop dependent *K*, stress-drop is proportional to the corner-frequency in a power of *4/3*, reducing the impact of corner-frequency uncertainty on the stress-drop. Therefore, our stress-drop formulation, significantly lowers the stress-drop uncertainty, and shows better fit to field observations. Using the new formulation, we show that the stress-drop values range between 5-25 MPa, for dynamic rupture events with a wide range of seismic moments, and corner-frequencies.

Constraining Source Parameters of Seismic Events Generated by Circular Gouge Patches on 4-meter-long Laboratory Fault

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The mechanics of the dynamic earthquake ruptures are investigated with the friction law applied to the fault. The source size, the stress drop, and the energy budget of the ruptures help us to configure it. The source size is usually estimated with the corner frequency of the radiation via source models such as Brune (1970) or Madariaga (1976). However, the models assume the rupture propagation on the circular patch with a given rupture velocity and a shear wave velocity, which causes a bias in the estimation of the source parameters. In this study, therefore, we control the size and shape of the source by artificially setting thin circular gouge patches on the laboratory fault such that we constrain the energy budget and the friction law without using predefined source models.

We used the 4-meter-long biaxial rock friction apparatus to conduct the stick-slip experiments with the macroscopic normal stress of 2.0MPa. We set seven gouge patches with a diameter of 8mm on the fault. We preliminarily measured the enhanced normal stress on the gouge patch, showing 4.5MPa on average with the background stress of 2.0MPa. The seismic events are observed during the propagation of the preslip towards the mainshock, most of which correspond to the location of the gouge patches. We first fit the numerically computed waveforms to one of the seismic events and obtained its seismic moment as 0.31Nm (Mw=-6.4). Given the ruptured size is equivalent to the gouge patch, we obtained the average slip of 0.16μm, the stress drop of 2.1MPa, and the seismic efficiency of 0.17, which are in reasonable ranges concerning the amount of preslip on the simulated fault and the normal stress on the patch. However, the observed seismic efficiency was significantly smaller than the estimation from Brune's source model even though the model provides a better fit on the source size with the best-fit source duration to the gouge patch size. This study aims to contribute to clarifying such discrepancies by investigating the possible stress and frictional conditions on the controlled patch to cause the ruptures reproducing the observed AE waveforms.

Constraining the Rupture Extent of Mw 6--7 Intraslab Earthquakes Using Geodetic Data: The 110 Km Deep 2020 Calama Earthquake, Northern Chile

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The driving factors behind large intraslab earthquakes ($M_w > 6.5$, 40 -- 300 km depth), along with their potential seismic hazards, are poorly understood due to limited observational information about the rupture process and extent of such events. This study presents a case study of a 110 km deep M_w 6.8 earthquake from 3rd June 2020 under Northern Chile (the Calama earthquake), for which we attempt to place the best-possible constraints on the location and extent of the rupture plane. As we show, with careful signal processing of Sentinel-1 Interferometric Synthetic Aperture Radar (InSAR) data we can detect the low-amplitude coseismic surface displacement field from this earthquake (with peak surface displacements ~6 mm), in spite of its depth. Using these geodetic data (both our InSAR data and limited near-field GNSS data) to supplement seismological data allows us to determine the finite extent of the source fault. For the 2020 Calama earthquake, we obtain a well-constrained fault plane (with a long, narrow aspect ratio of ~2.5) and relatively high static stress drop (~40 MPa). Whilst only applied to a single case-study here, this demonstrates the capacity for careful analysis of satellite remote sensing data to provide important additional constraints on intraslab earthquake ruptures, supplementing what can be learn from seismological-only studies.

Uncertainty Estimates for Moment Tensors and Quantities Derived From Them From Comparison of Global Catalogs

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Analysis of moment tensor catalogs gives insight into general properties of many earthquakes beyond what can be obtained by studies of individual earthquakes and allows estimating uncertainties in the determination of seismic source processes. Traditionally, uncertainties in moment tensors are derived from the misfit between observed and synthetic waveforms. However, the differences between moment tensors in the USGS and the Global CMT Project catalogs are typically an order of magnitude larger than the reported errors, suggesting that the reported errors substantially underestimate the uncertainty due to different inversion procedures. Differences between double-couple (DC) components decrease with magnitude, and correlation between non-double-couple (NDC) components increases, suggesting that seismic sources of large earthquakes are determined more reliably. A dataset compiled from three global and four regional catalogs shows that NDC components are essentially independent of magnitude for earthquakes over a large magnitude range, with a mean deviation from a DC source of about 20%. Additionally, there is essentially no difference in NDC components between earthquakes with different fault mechanisms and in different geologic environments. This consistency indicates that most NDC components, especially for smaller earthquakes, do not reflect real source processes and are likely to be artifacts, presumably due to not accounting for laterally varying Earth structure during the inversion. Numerical experiments confirm this result. Generating synthetic seismograms for a perturbed Earth model and inverting them using the unperturbed Earth model yields NDC components whose size is similar to the ones reported in global moment tensor catalogs. Comparison of NDC components in three global catalogs allows quantifying the noise contained in them and shows that the GCMT catalog provides the most precise NDC components. Furthermore, this comparison reveals that NDC components of large earthquakes are more reliably determined and that the largest NDC components are more likely to represent real source processes.

Regional Moment Tensor Estimation With 3D Velocity Models—Application and Assessment to the 2017 Hojedk, Iran Sequence

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The Arabia-Eurasia plate convergence, accommodated in a wide deforming zone, generates a host of moderate-to-large earthquakes in Iran. Using in-country broadband data from the Iranian Seismological Center and the Iranian National Seismic Network, we built a moment tensor (MT) database with over 2,000 solutions for Mw 3.4 to 7.8 earthquakes from 2004 to 2023 using a single, regional 1D velocity model. We selected a subset of events in the Hojedk region of central Iran to assess result stability and parameter resolution employing 1D and 3D velocity models. We used the Moment Tensor Uncertainty Quantification (MTUQ) software, which performs a grid search over source parameters, for moment tensor estimation and uncertainty analysis. For a 3D model, we used the detailed, adjoint-tomography-derived Middle East model of Örsvuran et al. (in prep.), which is based on fitting 30-s surface waves at far-regional distances, and calculated 3D Green's Functions (GFs) at various crustal depths for selected Hojedk events using high-performance computing (HPC) facilities. We found that the 3D GFs reduce waveform misfits, time shifts, and non-double couple contributions compared to results from 1D-based synthetics for periods as short as ~15-20 s. For 1D synthetics, we found a good agreement between the MT database results and double couple and deviatoric MTUQ results. Larger differences are restricted to small events with low S/N waveforms observed only at a few close-by stations. Grid searches over the full MT suggest a wide range of moment tensor solutions are permitted by relatively long-period data even for events with seemingly well-constrained double couple sources. We suspect inclusion of shorter-period data (5-10 s) and explicit use of P waves or their polarities will provide tighter constraints and reduce parameter uncertainty. For Iran, 3D-model refinements, required to use shorter-period data, can be achieved with available in-country data and a subset of well-constrained solutions from our regional MT database.

Quantifying the Effect of 3D Wavespeed Models on Moment Tensors Using Synthetic Data in the Middle East

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Moment tensors provide information on seismic source properties including general fault orientations for tectonic events, non-double-couple components, and seismic moments. To invert for moment tensors, a seismic wavespeed model is typically used to calculate Green's functions. One-dimensional (1D) wavespeed models are often used to calculate Green's functions since it is computationally inexpensive and works well for many applications. However, using three-dimensional (3D) wavespeed models has been demonstrated to reduce the misfit in moment tensor inversions, particularly in tectonically complex regions (e.g., Chiang et al., 2022; Covellone and Savage, 2012). To quantify the impacts of using 3D wavespeed models on moment tensor accuracy, we developed a synthetic experiment using earthquake data in the Middle East region. We computed synthetic waveform data for 25 events using a 3D model of the Middle East and Central Asia (MESWA, Rodgers, 2023) assuming source parameters from the Global Centroid Moment Tensor (GCMT) catalogue (Ekström et al., 2012). These synthetic data and source parameters served as the ground truth in the synthetic experiment. To test the impact of various models, we computed Green's functions for a set of 1D and 3D models. For the 1D models, we considered PREM (Dziewonski & Anderson, 1983) and a regional 1D model (Rodgers et al., 1999; Pasyanos et al., 2004). For the 3D models, we considered the SPiRaL (Simmons et al., 2021) and CSEM (Fichtner et al., 2018) models. Moment tensors were inverted using a time-domain full waveform moment tensor inversion software (MTTime, Chiang, 2020) and compared to the GCMT parameters which serve as the control (i.e., target moment tensors). We will quantify the differences in the moment tensors using each of the models including uncertainties in the moment tensor space (e.g., Tape & Tape, 2015) and highlight the significance/importance of the 3D structure on the resulting tensor solutions.

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Understanding and Quantifying the Variability in Earthquake Source Parameter Measurements [Poster Session]

Poster Session • Friday 3 May

Conveners: Rachel E. Abercrombie, Boston University (rea@bu.edu); Shanna Chu, U.S. Geological Survey (schu@usgs.gov); Sydney Gable, University of Michigan (gablesyd@umich.edu); Gene Ichinose, Lawrence Livermore National Laboratory (ichinose1@llnl.gov); Colin N. Pennington, Lawrence Livermore National Laboratory (pennington6@llnl.gov)

POSTER 54

Using a 1-D Radially Symmetric Coda Envelope Model for Robust Source Scaling in Iraq's Tectonically Diverse Zones

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Estimation of moment magnitude can be challenging for Iraq due to the strong lateral heterogeneity of the diverse tectonic zones. In this study, we investigate the reliability of using 1D coda envelope model for the entire country despite the lateral effects and the differences in the tectonic zones' geophysical characteristics. Iraq comprises two main tectonic zones: 1-The Outer Platform which consist of the northwestern Zagros Fold-Thrust Belt and the Mesopotamian Foredeep; 2-The Inner Platform that is covering the Iraqi western desert. Due to the fact that coda waves have a low sensitivity to the source and the path heterogeneity, a simple 1-D coda envelope model was used. Three separate coda calibrations were conducted in order to investigate the reliability of using one calibration for the country, Iraq calibration, Zagros calibration, and Mesopotamia calibration. 51 events (Mw>4.5) recorded by ten stations were used for Iraq calibration while for Zagros calibration, 42 events from three stations located within Zagros zone were used. The last calibration is for Mesopotamian Foredeep, where there are 7 stations in this zone. 40 events with Mw>5 were enough to calibrate the zone. Ground truth (GT) reference spectra derived from the coda spectral ratio method were used to constrain high-frequency site terms. There were no drastic differences when comparing the moment magnitudes that were calculated from the three calibrations. However, Zagros calibration showed a better estimation of the apparent stress because the apparent stress that we used as references for the calibrations were located in Zagros zone. We could not find good candidate events in Mesopotamia to calculate the apparent stress due to the low seismicity. As a result of this study, we recommend using Iraq calibration since 10 stations were used in this calibration giving it the best path correction, and there were slight differences in the estimated magnitudes of the three calibrations. The proposed calibration serves as a fundamental step to update the comprehensive earthquake catalog for Iraq and probabilistic seismic hazard assessments.

POSTER 55

A Comparison of the Stress Drop Estimates Derived From Different Techniques in Pollino, Italy

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Seismic spectral estimates of earthquake stress drop remain controversial, subject to large uncertainties, despite the fundamental role the source parameter plays in assessing the seismic forecasting in a given area and in improving ground motion predictions for seismic hazard mitigation. Comparing different measurement techniques to understand how analysis processes affect the resulting estimates of stress drops is a necessary first step to improve resolution. It can also be useful to perform the same procedures using different data sets. In this study we focus on the Pollino area, southern Apennines, where structural complexities are thought to control seismic activity. We compare estimates of the Brune-style stress drop for 100 earthquakes (M2.2-5.2) derived from two techniques: spectral fitting for attenuation, site effects and source), and spectral ratio fitting in which an empirical Green's function event is assumed to remove the path and site effects. In all cases, the Brune (1970) source is assumed. In the spectral fitting we first assume a regional attenuation model, and second estimate path attenuation from the high-frequency decay of 8 well-recorded earthquakes (M3.6-5.2), to obtain attenuation-corrected spectra. We estimate and remove the site term in both cases by averaging the attenuation-corrected spectra for each event, and then computing the difference from the mean event spectrum for each station (assuming the mean site correction is zero). These differences are averaged over the event ensemble to obtain a mean site term for each station, which is then removed before fitting the resulting estimates of source spectra to obtain the final source parameter estimates. In the EGF approach, we divide the spectra of the target events by those of co-located smaller EGF earthquakes, and fit the resulting spectral ratios, for each event, at each station, assuming all path and site effects are removed. We perform the fitting first with no constraints on the stress drop (and corner frequency) of the EGF event, and then with constraints based on different scaling laws of stress drop to seismic moment.

POSTER 56

Sensitivity Analysis of Seismic Hazard Parameters for the Understanding of Its Uncertainties: A Study Case for Central America

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The parameters involved in seismic hazard calculations introduce both epistemic and random uncertainties that must be controlled to minimize errors and obtain an accurate seismic model representing expected accelerations in a region. In this regard, it is essential to apply a sensitivity analysis of the results provided by seismic hazard calculations to understand the behavior of uncertainties associated with the parameters. Statistical methods (e.g., RMSE, MSE, and CV) are employed for such analysis, relating observed variables to those predicted by the models used, enabling both analytical and spatial examination of interacting parameters in seismic hazard.

Consequently, we conducted a case study for Central America, analyzing the sensitivity of parameters involved in seismic hazard calculations. In this case, we examined the fitting method for the recurrence model (least squares and maximum likelihood), the use of scaling laws, and the application of ground motion models (GMM). Ultimately, we obtained coefficient of variation (CV) maps illustrating the variability of results and highlighting regions in Central America where these trends are evident. This variability and sensitivity analysis helped refine the weights and parameters of the logical tree used to generate new seismic hazard maps for Central America for PGA and Sa(1.0s) at return periods of 475, 975, and 2475 years. Additionally, we compared our results with seismic hazard maps created by other authors in the region to assess the significance of acceleration variability.

POSTER 57

Adjoint Earthquake Source Inversion Method Using P-Wave Spectra and Focal Mechanism Solutions

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Improving characterizations of small earthquake sources advances our understanding of fault structures and seismic mechanics. Traditional methods for determining focal mechanisms, stress drops, and rupture directivities are limited by ambiguities in nodal plane identification and the neglect of rupture directivity, which impedes in-depth analyses and comparisons between earthquakes of varying magnitudes. To address these challenges, we introduce an innovative adjoint source inversion method that integrates focal mechanism solutions with P-wave spectra. Initially, we determine the apparent P-wave corner frequencies for the target event by analyzing the source spectral ratio between the target event and its surrounding Empirical Green's Function (EGF) events. We then synthesize corner frequencies with all potential fault plane orientations derived from the focal mechanism solutions and select the optimal fault plane orientation and 3D rupture directivity that best correspond with the observed azimuthal variations of P-wave corner frequencies.

Validated using a synthetic dataset and 2634 M≥1.5 events around the Parkfield locked patch, our findings indicate significant unilateral rupture directivity in 88% of the earthquakes. Of these, 53% occur along the main fault with various dipping angles, and 47% exhibit high angle to the main fault with near-vertical dips. Events above the locked patch predominantly show NE dipping planes with SE directivity, while those below exhibit SW dipping with NW directivity, suggesting consistent earthquake rupture direction with the hanging wall's slip direction. Incorporating directivity effects, 84% of events exhibit larger corner frequency, indicating higher stress drops than those previously estimated without directivity corrections. The proposed method can help to solve unprecedented detailed spatiotemporal variation of small earthquake properties, including fault orientation, 3D rupture directivity, and stress drop, which offers new perspectives on fault geometry, kinematics, and dynamics.

POSTER 58

Bayesian Inference for the Seismic Moment Tensor Using Regional Waveforms and a Data-Derived Distribution of Velocity Models

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The largest source of uncertainty in any source inversion is the velocity model used to construct the transfer function employed in the forward model that relates observed ground motion to the seismic moment tensor. However, standard inverse procedures often does not quantify uncertainty in the seismic moment tensor due to error in the Green's functions from uncertain event location and Earth structure. We attempt to incorporate this uncertainty into an estimation of the seismic moment tensor using a distribution of velocity models calculated in a prior effort based on different and complementary data sets. The posterior distribution of velocity models is then used to construct Green's functions for use in Bayesian inference of an unknown seismic moment tensor using regional waveform data. The combined likelihood is estimated using data-specific error models and the posterior of the seismic moment tensor is estimated and can be interpreted in terms of most-probable source-type.

POSTER 59

Characterizing Directivity in Small (M3-5) Aftershocks of the Ridgecrest Sequence

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A longstanding issue in source seismology is whether or not the variation in measured "stress drop" is due to methodological differences or physical assumptions, which leads to confounding results about predicted ground motion in regional earthquake hazards and source physics. The spectrum of seismic radiation is commonly used to derive the stress drop for earthquakes, which relates an earthquake's source dimension to its ground motion. The first step in using the spectrum to estimate the stress parameter is to separate out source contributions in the raw data from site- and path- effects, which may be performed in various ways. In this study, we compare two common methods of deconvolving source spectra from waveform records: using a non-parametric matrix inversion (spectral decomposition) and using an empirical Green's function (eGf) method. Using the example case of the 2019 Ridgecrest sequence, we classify source spectra into types based on observed spectral complexity, noting that complex spectral shapes (at both the event and station level) are more likely to yield variable estimates of the stress parameter when the deconvolution method differs. We show that source directivity can account for some amount of discrepancy in source parameter estimates between the two methods. Typically, azimuthal heterogeneity in path is not accounted for in a spectral decomposition, while eGf methods specifically account for specific paths. We present an approach to understand the variation in corner frequency due to azimuthal variability.

POSTER 60

DAS Derived Source Characterization of Ridgecrest Aftershocks Using Coda Spectral Ratios

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Distributed acoustic sensing technology provides a new capability to densely sample the seismic wavefield in difficult or previously inaccessible areas. However, measurements made on existing telecommunications cables are limited to uniaxial measurements of strain along the buried optical fiber, and the ground coupling of the cable is often unknown, hindering determination of seismic source properties. To overcome these limitations, we use coda spectral ratios to obtain estimates of the seismic source parameters using relative source spectra. Waveform envelope measurements of coda waves provide azimuthally insensitive information about their source spectra and ratios of envelopes from two sources measured by the same sensor can remove path, and crucially for DAS measurements, the sensor site effects. We demonstrate the effectiveness of this method using both DAS and traditional seismic measurements of the well-studied aftershocks of the 2019 Ridgecrest earthquake. We show that the relative source functions obtained using the DAS data are like those obtained using the traditional seismic data, confirming that the coda spectral ratio method can overcome the azimuthal and unknown ground coupling limitations of using DAS data for the study of seismic source properties. Further, we show that the derived stress drops and magnitudes are commensurate with those of other studies which employ more traditional seismic analysis methods.

POSTER 61

Understanding Sources of Variability and Uncertainty in the Relative Magnitude Method

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A precise understanding of earthquake magnitudes is vital for accurate calculations of magnitude exceedance probabilities and seismic hazard assessment. However, characterization of earthquake magnitude, particularly for small events, is complicated by differences in network capabilities and procedures. Furthermore, the use of differing magnitude scales for events of various sizes introduces additional challenges and produces disparate magnitude estimates for the same events. To address the need for a consistent magnitude estimation procedure that can accurately estimate magnitude across a wide magnitude range and in diverse tectonic environments, we investigate the use of the relative magnitude method. This approach utilizes amplitude ratios of highly correlated waveforms among numerous interlinked event pairs to compute magnitudes for a group of events. While the relative magnitude method is advantageous because it can be applied uniformly in various regions and does not require distance or attenuation corrections, there are several parameters that currently require human decision which may introduce bias. These include acceptable thresholds for signal-to-noise ratios and cross-correlation, filtering procedures, sampling windows, and station selection. Our research focuses on computing new relative magnitudes for events in southern California, including the 2019 Ridgecrest sequence. We investigate the uncertainty that human decision may impose on the resulting magnitudes and compare our results to other magnitude estimation methods. Finally, we present our recommendations for routine procedures that minimize uncertainty and variability in the relative magnitude method, aiming to enhance the utility of this method for future users.

POSTER 62

Development of Empirical Scaling Relationships Between Spectral Displacement Amplitudes Measured in the Time Domain and Earthquake Magnitudes in South Korea

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In South Korea, a local magnitude scale using the maximum amplitude of S waves has been proposed (Sheen et al., 2018). However, the time when the previous study was conducted, there were very limited number of observations within an epicentral distance of 50 km. For this reason, it is difficult to accurately determine the magnitudes of small earthquakes typically observed only at short distances, using the previous scaling relationship. The recent increase in the number of seismic stations in South Korea enables us to develop an empirical scaling relationship accounting for short distances. In addition, it is shown that the moment magnitude can be measured for earthquakes as small as M 2.0 using peak displacement amplitudes (Al-Ismail et al., 2023). In this study, we collected seismograms of 647 earthquakes occurred in and around South Korea from 2017 to 2022. Spectral displacement amplitudes of S waves were measured from vertical components in the time domain using multiple narrowband filters and in the frequency domain using the multitaper method. Then, we developed empirical relationships between displacement amplitudes and seismic moments, separately for each frequency band, and use them to measure magnitudes. To validate the empirical relationship proposed in this study, we estimated the magnitudes of earthquakes in the 2016 Gyeongju earthquake sequence. Consequently, we demonstrate that spectral amplitude estimation in the time domain is an effective method for determining the magnitude of small earthquakes.

POSTER 63

Moment-Rate Spectra, Source Scaling and Spectral Fall-Off in the Korean Peninsula Using the Coda Calibration Tool (2.0<Mw<5.5): Application to Natural and Man-Made Sources

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We applied the Coda Calibration Tool (CCT) to local and regional broadband data across the Korean peninsula and Yellow Sea region with the goal of obtaining stable moment-rate source spectra. The 2016 Gyeongju and 2017 Pohang sequences allowed us to compute stable coda spectral ratios that were used as reference events, an integral step in the CCT calibration methodology. We are able to measure single-station M_w for events as small as ~2.0, compare earthquake source scaling with other independent methods, and study the spectral characteristics of shallow induced events as well as man-made sources over the past 20 years. Another important focus of this study was the spectral fall-off. While source scaling studies must account for the inherent trade-offs between site, source and path effects, the empirical Green's function (eGf) approaches, and their variants, have been attractive because common path and site terms cancel. Source complexity and *a priori* assumptions can bias eGf results so we plan to address these following challenges in this study, namely: 1) The spectral models used to fit the data must assume a spectral fall-off which are also a topic of active debate; 2) Potential issues with source directivity of either or both events which might bias the results; 3) Source complexity that can create spectral holes and peaks as reported in a number of finite-fault inversions; 4) Finally, the assumption of an eGf stress drop can, in theory, bias both the small magnitude corner frequencies and subsequent interpretation of the overall source scaling.

POSTER 64

Evaluating Scaling Relationships From Insar-Derived Earthquake Source Parameters

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Scaling relationships are key to understanding which earthquake source parameters—quantities that describe the earthquake source (e.g. fault length, fault width, slip, and seismic moment)—are key to producing large earthquakes. Proposed scaling relationships include the presence or absence of scaling breaks and the existence of a power law (or not), in length-moment scaling, or area-length scaling (Scholz, 1982, 1994; Romanowicz, 1982, 1992, Leonard, 2010). Better constraints on scaling relationships of source parameters will allow for improved estimates of potential future earthquake sizes and improved forecasts of earthquake hazards.

In this work, we aim to bring a new perspective to scaling relationships by using an InSAR-derived source parameter dataset. InSAR can provide robust constraints on key parameters such as fault length by direct measurements and on other fault parameters by modeling. To compile our dataset, we simultaneously mine the literature for source parameters for InSAR-based studies and also model recent earthquakes not present in the literature ourselves. For our own models, we estimate the source parameters (e.g. strike, slip, length) using a rectangular elastic dislocation model, fitted to downsampled InSAR data from the Sentinel-1 satellites, whose parameters are estimated using a Powell algorithm with multiple Monte Carlo restarts. To evaluate scaling relationships, we use statistical approaches (e.g. regression analyses) to quantify the relationships between the source parameters (e.g. length, width, seismic moment). Our preliminary results, based on over 200 earthquakes studied with InSAR, are consistent with a length squared-moment scaling ($L2 \propto Mo$), suggesting that slip may be proportional to fault length.

The value of the scaling relationships obtained in this way are only as robust as the earthquake models and the modeled source parameters. To assess the likely impact of uncertainties in these parameters, we examine a few well-studied events, such as the 2015 Gorkha, Nepal and 2019 Ridgecrest, CA earthquakes, to quantify the variability in published models.

POSTER 65

Rupture Directivity of Small Earthquakes in Southern Korean Peninsula

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Good knowledge of rupture directivity is crucial for both earthquake physics and seismic hazard mitigation. Analyzing bulk of small earthquakes may provide insights into the potential mechanism of rupture directivity, but such studies have been rare in stable continental regions. The Southern Korean Peninsula (SKP) hosts a dense network of seismic stations and hence provides opportunities of investigating the characteristics of earthquake rupture in the SCR. We analyze the rupture properties of 28 small (M_L 2.1–4.1) earthquakes in SKP since 2019, employing the empirical Green's function method to calculate the relative source time functions (RSTFs). Adopting the line source model, we use Bayesian inference to invert key finite source properties—rupture direction, length, velocity, and degree of asymmetry. This approach allows us to elucidate the characteristics of earthquake rupture by explaining variations in RSTF durations concerning azimuths and ray takeoff angles, while robustly characterizing parameter uncertainties by considering data errors and trade-offs.

Our analysis reveals that a majority of events display asymmetrical rupture with a dominant direction in accordance with the nodal plane of focal mechanism, while a few events exhibit nearly symmetrical rupture. This implies that the rupture directivity may be relatively common for small earthquakes in SCRs, challenging the simplistic assumption of symmetrical circular rupture. We further revisit the 2020 Haenam earthquake sequence that exhibited unusual swarm-like behavior in the lower crust of southwestern SKP. Five $M \geq 2$ events show diverse spectrum of rupture behaviors, ranging from bilateral to unilateral, with contrasting directions. However, we find that the largest event (M_L 3.1) ruptured away from other earlier events, implying that those earlier events may have influenced the rupture direction and extent of the largest event. This demonstrates that the detailed analysis of small event ruptures could enhance our understanding of earthquake sequences in the SKP.

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On the Variability Discrepancy Between PGA and Spectral Stress Drop: Insight From Double-Corner-Frequency Spectra

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The stress drop estimated from the corner frequency (spectral stress drop) is considered an important parameter in ground motion prediction. Cotton et al. (2013) found that the observed variability of the spectral stress drop is significantly larger than expected from the observed *PGA* variability. In this study, we conducted spectral ratio analysis for 34 crustal earthquakes with

M_w 5.0–7.1 in Japan to resolve this variability paradox. First, we applied the standard spectral ratio method, which assumes the single-corner-frequency (SCF) spectrum model, to estimate the spectral stress drop $\Delta\sigma_{fc}$. Second, we applied the two-stage spectral ratio method developed in this study. This method enables us to obtain the double-corner-frequency (DCF) spectra at broadband frequencies. We determined the corner frequency f_{ch} by fitting the SCF model to the DCF model at low and high frequencies. The spectral stress drop calculated using f_{ch} is called the stress parameter $\Delta\sigma_{fch}$, which characterizes the intensity of the high-frequency radiation.

The standard deviation of $\ln\Delta\sigma_{fc}$ is 1.0, as high as the ones found in previous corner frequency studies. In contrast, the standard deviation of $\ln\Delta\sigma_{fch}$ is 0.55, which predicts the standard deviation of $\ln PGA$ of 0.44, comparable to the between-event variability of *PGA* observed in Japan. The corner frequency obtained from the standard spectral ratio method crudely corresponds to the lower corner frequency of the DCF model, f_{ca}. Thus, the variability discrepancy between $\Delta\sigma_{fc}$ and *PGA* could mainly arise from the difference in the variability of f_{ca} and f_{ch} of the DCF spectrum. The DCF model successfully explains the spectra for all events and has the potential to explain both the observed $\Delta\sigma_{fc}$ and *PGA* variabilities. Finally, we found that the deviation of the observed spectra from the SCF model becomes significant on average as the magnitude increases. Implementing the DCF model can be important for predicting ground motions.

POSTER 67

New Version of the Earthquake Mechanism of Mediterranean Area (EMMA) Database With a Web-Gis Interface

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We present a new version (4.0) of the database of Earthquake Mechanisms of the Mediterranean Area (EMMA) of "checked" first-motion focal solutions available from the literature. The EMMA database, developed on MS-ACCESS and managed by original software, uniforms the different formats of the data available and try to solve misprints, inaccuracies and inconsistencies that make them almost useless for other users (e.g. tests the perpendicularity of nodal planes and/or P and T axes of all solutions and, when both axes and planes are given, even their mutual consistency). The database now collects more than 34,000 focal solutions (~+ 850%, ~560%, ~ +280% with respect to previous three existing database versions). The EMMA database is not a homogeneous catalogue because it includes focal mechanisms computed with different methodologies covering different areas and magnitudes, depending on original papers available. We added the missing parameters (e.g. time, magnitude) and, when possible, we link the data to the earthquakes available in other catalogues (e.g. HOmogenized instRUmental Seismic catalog-HORUS-, International Seismological Centre -ISC-). We merged EMMA with the focal mechanisms (mainly by moment tensor inversion) from different available on-line catalogues ;at global and regional scale (e.g. GCMT, RCMT). An automatic procedure, based on several criteria, permits to choose the most "representative" (preferred) solution when more than one solution is available for a same earthquake comparing quantitatively the alternative solutions (e.g. Kagan angle between solutions, Frohlich ternary diagram representation).

A web-GIS interface based on OpenLayers (an open-source javascript library) allows now to select (e.g. for areas, magnitude range, time period), display and export the data suitable to be handled by graphic software and user written procedures. The EMMA database is a powerful tool for characterising the tectonic regime and for seismotectonic and deformation analyses, extending the data coverage of other catalogues available for the Mediterranean area over time and to a lower magnitude threshold.

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