

Potential for Continental Scientific Drilling to Inform Fault Mechanics and Earthquake Science

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Abstract Our understanding of fault mechanics and earthquake processes remains limited, largely due to minimal direct observations near active faults at seismogenic depths. This lack of data restricts our ability to accurately assess and mitigate both natural and human-induced seismic hazards. However, recent advancements in drilling capabilities and downhole sensing technologies offer an opportunity to observe and quantify the physical conditions within and adjacent to active fault zones. In this contribution, we highlight how scientific drilling can provide access to the near-fault environment, enabling measurements of stress, strain, temperature, fluid pressure, and rock properties at depths where both aseismic and seismic fault slip occur. These observations are essential to refine models of earthquake nucleation and dynamic rupture, bridging gaps between laboratory experiments, numerical simulations, and surface observations. These insights can advance fundamental understanding in earthquake science while also supporting the development of more effective seismic hazard assessments and risk mitigation strategies.

Non-technical summary We do not yet know all the details about how and why earthquakes happen because they occur deep underground where it is hard to collect information. Without this information, it is difficult to say whether an earthquake might occur and how large it might be. However, new tools and better drilling techniques can get us closer to fault zones – and sometimes inside them. We can place sensors underground to look at what is happening along faults to learn more about how earthquakes start and why they stop. In this article, we discuss how drilling deep into the Earth close to faults can provide important new information about how faults slip.

1 Background and Motivation

In the United States and around the world, a growing number of people live in areas at risk of damaging ground shaking from earthquakes (Petersen et al., 2024; Silva et al., 2019). Increasing demands for subsurface energy sources (oil and gas, enhanced geothermal systems) and geologic sequestration of carbon dioxide will increase the potential for anthropogenically induced earthquakes (Ellsworth, 2013; Majer et al., 2007; Foulger et al., 2018; White and Foxall, 2016). However, the conditions controlling the initiation, propagation,

and arrest of earthquake ruptures remain poorly understood. Seismologists typically observe earthquakes and infer fault properties from surface instruments located tens of kilometers from the causative fault. These seismic data are complemented with other surface and subsurface observations, remote sensing data, laboratory-scale measurements, and computer simulations to attempt to build a picture of fault mechanics and earthquake processes. Our ability to model such geologic systems, forecast their future evolution, and derive effective physics-based hazard mitigation strategies is hampered by the lack of observations of the state and evolution of fault zones at seismogenic depths.

Previous scientific drilling projects near active faults

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have yielded novel and surprising observations, resulting in complex images of near-fault properties and fault behavior. In 1988, the Cajon Pass Scientific Drillhole located approximately 4 km from the San Andreas Fault (SAF) near San Bernardino, California, provided insights into fault and fracture distributions (Barton and Zoback, 1994) and confirmed the low heat flow indicative of a weak San Andreas Fault (Lachenbruch and Sass, 1992), with high differential stresses in the adjacent crust (as expected for a weak SAF/strong crust model) but locally anomalous stress orientations (Zoback and Healy, 1992). The creeping section of the SAF near Parkfield, California, was the target of the SAF Observatory at Depth project (SAFOD; Zoback et al., 2011), which highlighted the role of fault rock properties (e.g., weak mineral phases such as Mg-smectite clay, saponite) in controlling fault strength and slip behavior (Lockner et al., 2011; Carpenter et al., 2011; Moore and Rymer, 2012).

Brodsky et al. (2010) convincingly argued the value of rapid response drilling projects to collect transient data at seismogenic depths after a large earthquake. In the years following the 1999 M7.7 Chi-Chi, Taiwan earthquake, a series of boreholes were drilled into the causative Chelungpu Fault, sampling the principal slip zone of the event and providing a complex picture of the fault damage zone with multiple slip sections within a broader deformation zone (Ma et al., 2006). In 2012, the Japan Trench Fast Drilling Project (JFAST) monitored temperature, fluid flow, and other fault properties across the fault that ruptured in the 2011 M9.1 Tohoku, Japan earthquake. Transient temperature changes were observed coincident with nearby aftershocks that were interpreted to reflect fluid pressure pulses due to fault slip (Fulton and Brodsky, 2016).

The Deep Fault Drilling Project targeted the shallow portion of the Alpine Fault in New Zealand to understand fault properties late in the seismic cycle (Townend et al., 2009), using various geophysical logs to detail the densities and orientations of fractures (Massiot et al., 2018) and monitor fluid flow (Janku-Capova et al., 2018). A fault zone observatory at 5–7 km depth explored conditions near reservoir-triggered earthquakes in Koyna, India (Gupta et al., 2015), providing strong constraints on the in situ stress field (Goswami et al., 2020). The Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) is a long-term drilling project from 2007–2018 that targeted the megathrust fault at the plate interface offshore of Honshu, Japan and, while ultimately falling short of that goal, made extensive technological advancements for drilling through complex near-fault regions, returned core from a fault zone, and established long-term fluid pressure monitoring at multiple boreholes (Tobin et al., 2019). Araki et al. (2017) showed that even outside the primary fault zone, formation pore pressures could be used to estimate volumetric strain and infer slip on the near-trench segment of the megathrust. These prior drilling projects highlight the value of measurements and observations in the near-field of faults at seismogenic depths.

New subsurface drilling efforts can build on the technological advancements made by past drilling projects

and leverage the latest drilling and sensor technologies that allow the direct measurement and ongoing monitoring of the evolution of stress, strain, and rock properties in the near-fault volume. Fault drilling projects targeting active seismicity, such as repeating earthquakes as was the target of SAFOD (Zoback et al., 2011) or near vigorous induced seismicity sequences as proposed by the Scientific Exploration of Induced Seismicity and Stress (SEISMS) effort (Savage et al., 2017), provide a unique opportunity to densely sample the near-field of an earthquake. Except in the case of infrequent, large magnitude earthquakes, it is generally not possible to collect near-field recordings of earthquakes (i.e., within a fraction of the rupture length of an earthquake) at the surface or even with shallow boreholes. Fault drilling could enable such near-field observations in areas of active seismicity with high rates of moderate and smaller earthquakes. However, it remains a steep challenge, as the target earthquakes are small ($M < 4$) and sensors must thus observe the event within 100 m or less. Here, we highlight the value of scientific drilling projects that target the fault volume near active faults and leverage new advances in drilling and sensor technologies to answer fundamental questions in earthquake science.

2 Opportunities for Earthquake Science from Scientific Drilling Projects

Despite the knowledge provided by prior scientific drilling projects, there is still much to learn through the collection of dense time-lapse datasets at seismogenic depths near faults (Reches and Ito, 2007; Anselmetti et al., 2020; Ben-Zion et al., 2022). Most scientific drilling projects focused on earthquake processes were initiated over a decade ago, prior to the refinement of drilling techniques and the development of new sensor technologies. Figure 1 shows a sketch of the conventional and advanced borehole technologies that are available for dense time-lapse data collection at seismogenic depths near faults. Significant technological advances in drilling, completion, and instrumentation of highly deviated and/or multilateral boreholes will enable laterally extensive sampling of the near-fault volume, rather than point sampling of the fault zones (Ma et al., 2016; Lindsey and Martin, 2021; Teodoriu and Bello, 2021). For example, the NanTroSEIZE project made significant drilling advancements that improved borehole stability in the geologically complex near-fault regions and enabled better sampling and logging using measurement-while drilling techniques (Yamada et al., 2019). Recent advancements in sensor technologies enable 4D monitoring of subsurface conditions under the challenging pressures and temperatures encountered at seismogenic depths. Distributed sensing technologies for absolute static and dynamic strains (Jin and Roy, 2017), pore pressures, permeability fields, seismic signals, and temperature (Karrenbach et al., 2018) have been shown to be reliable for borehole monitoring. Distributed sensors, such as distributed acoustic sensing (DAS), distributed strain sensing (DSS), and distributed temperature sensing (DTS), could be installed in cross-

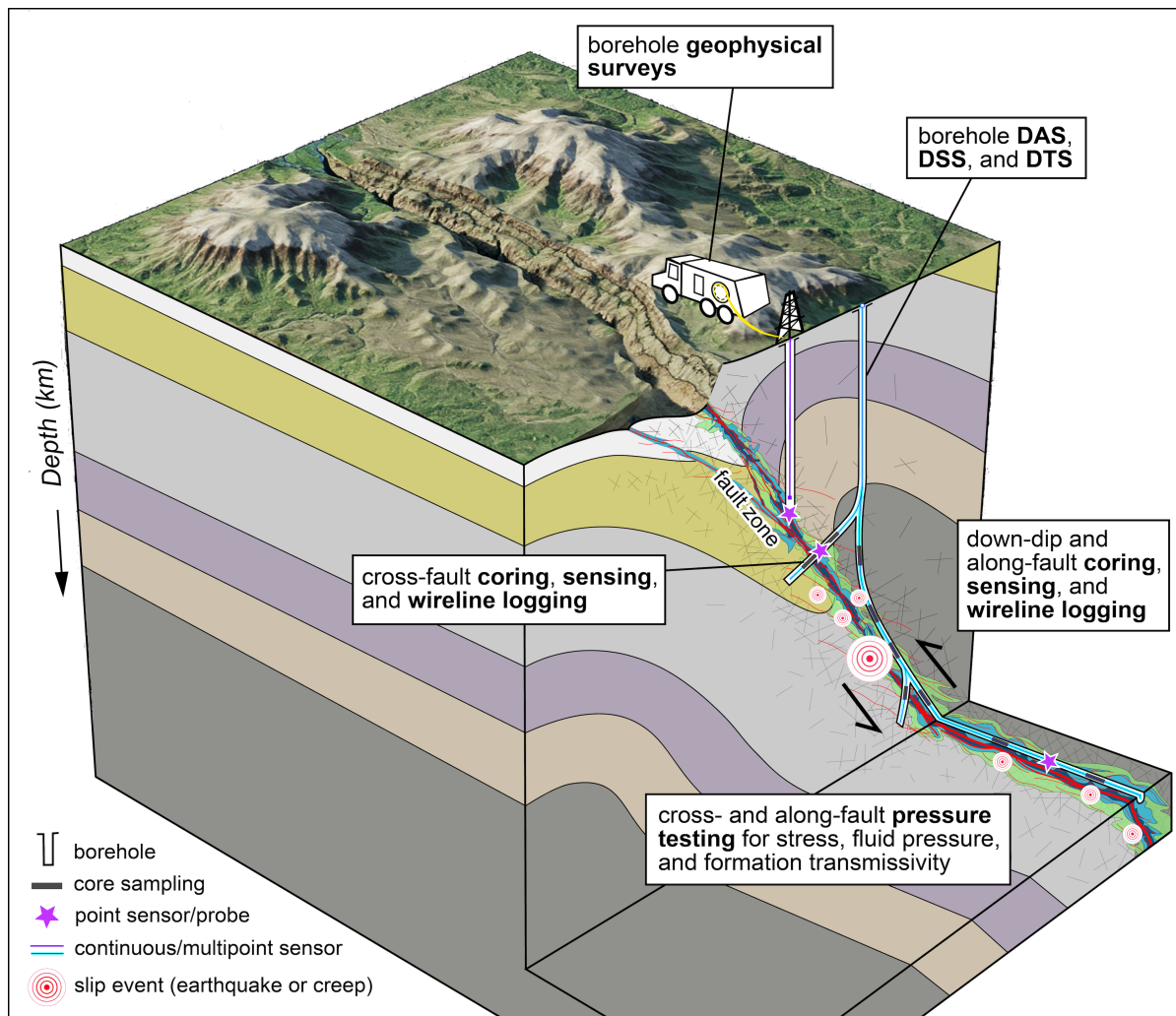


Figure 1 3-dimensional sketch of an active fault zone showing the conventional and advanced borehole technologies that are currently available for dense time-lapse data collection at seismogenic depths near faults. DAS - distributed acoustic sensing, DSS - distributed strain sensing, DTS - distributed temperature sensing. Vertical and deviated boreholes would allow for cross-fault and along fault coring, sensing, and wireline logging. Wireline logging can provide relevant formation property measurements including (but are not limited to) resistivity and conductivity, fluid pressures, porosity, geochemical sampling, and borehole imaging. Cross- and along-fault pressure testing could provide information about stress, fluid pressure, and formation transmissivity. Borehole monitoring is typically complemented by a wide range of surface instrumentation (not illustrated here).

and along-fault laterals providing data from a volume within and near the fault (Figure 1). These new technologies could complement more traditional, higher fidelity point measurements both in boreholes and at the surface (Mellors et al., 2021; Ma et al., 2024). Longer-term monitoring to capture evolution of a fault zone through a portion of the seismic cycle remains challenging as it requires instrumentation that can withstand elevated depths and temperatures for extended durations. Scientific drilling projects aimed at establishing well-instrumented underground observatories in the 3D volume around an active fault are likely to play a critical role in advancing our understanding of the earthquake triggering and propagation mechanisms.

Understanding when and where an earthquake will start and how large it will grow remains enigmatic. Even for induced earthquake sequences that show strong correlations with local fluid injection, the mechanisms governing when and how large an earthquake

may occur, or even whether an earthquake sequence will occur at all, remain largely unknown (Ellsworth, 2013; Kivi et al., 2023). Seismological observations, laboratory studies of natural and simulated fault rocks and surfaces, and numerical simulations demonstrate a complex interplay between fault geometry, fluid flow, friction, fault and host rock composition, in-situ stress, and possible induced or triggered (poro-)elastic stress changes in controlling fault slip initiation, propagation, and arrest (Ampuero et al., 2006; Cochran et al., 2023; Goebel et al., 2017; Allam et al., 2019; Fan et al., 2019; Heimisson, 2020; Kroll and Cochran, 2021; Haddad and Eichhubl, 2023). Yet, we lack observational constraints on many of these properties, including their interactions, heterogeneity, and influence on earthquake occurrence at seismogenic depths. To make progress, we need to know what the fault properties (e.g., stress distribution, fluid conditions, fault material) are at seismogenic depths and have detailed images of the near-fault

structure, damage zones (Zhang and Schmitt, 2025), and slip planes (Lay et al., 2021). Such information could only be collected using arrays of borehole sensors within or in the near-field of active faults.

Direct observations of the in-situ conditions of the near-fault volume at seismogenic depths are critical, including their evolution through time. As discussed in Hickman et al., (1995, and associated papers) it has long been recognized that fluids can exert mechanical and chemical effects on a variety of faulting processes, including the structural and mineralogical evolution of fault zones, fault strength, and the nucleation, propagation, arrest and recurrence of earthquake ruptures. Fluids are likely a key controller of earthquake occurrence and triggering (Ross et al., 2020; Takano et al., 2024; Gabrielli et al., 2022; Haddad and Eichhubl, 2023). While fluid transport regimes, fluid pressures, fluid chemistries, and fluid-rock interactions in and near faults have been studied extensively for exposed faults (Bense et al., 2013; Callahan et al., 2020; Williams and Fagereng, 2022), we only have limited knowledge of these processes at seismogenic depths of active faults beyond the fault-zone drilling projects described above (SAFOD, NanTroSEIZE, Chelungpu Fault project, and JFAST). Similarly, the temperatures encountered near and within fault zones at seismogenic depths are closely tied to fluid flow and provide critical information on fault strength and mineral stability, (Rowe and Griffith, 2015; Harris, 2017; Fulton et al., 2013). Quantifying a range of near-fault properties before, during, and after slip supports theoretical and modeling efforts within the broader research community (Sone and Uchide, 2016; Ben-Zion et al., 2022; Dal Zilio et al., 2023). Scientific drilling combined with long-term downhole observations within and adjacent to fault zones may be required to make progress on these topics.

Strain and displacement measurements within and near the fault can capture seismic or aseismic fracturing or faulting along the fault and within a volume around the primary slip zone. Optical fibers can measure distributed strains and are often cemented between the casing and rock along extended sections of the borehole (Lellouch et al., 2021). And new sensor technology, deployed inside sections of the casing of boreholes, can measure three-dimensional displacements (Guglielmi et al., 2021). With such observations close to the seismic sources, the full stress tensor and its variability across active faults can be estimated. Moreover, such new borehole instruments can help provide in situ estimates of the frictional and hydromechanical properties of faults. A significant fraction of the relative fault motion may also be accommodated by deformation in a zone around the primary fault structure that may vary over the seismic cycle (Oskin et al., 2007; Johnson, 2013). In-situ borehole observations provide opportunities to validate the magnitudes of such distributed deformation and its time-dependence.

Precursory phenomena, specifically earthquake nucleation processes (Dieterich, 1992; Lapusta and Rice, 2003), have not been reliably observed for natural earthquakes. Recent earthquakes like the 2011 M_w 9.1 Tohoku, the 2014 M_w 8.1 Iquique, and the 2024 M_w 7.6 Noto

earthquakes were preceded by slow slip and/or swarms of earthquakes (Kato et al., 2012; Ruiz et al., 2014; Kumazawa and Ogata, 2024). Near-field observatories in areas of ongoing seismicity would allow subtle features associated with earthquake initiation, if present, to be observed and characterized. For example, measurements of initial fault acceleration and the evolution of moment release are only possible very close to the nucleating slip surface, requiring instrumentation to be installed at depth in the near-field of the rupture (McLaskey, 2019). Additionally, the role of aseismic slip in earthquake occurrence and the triggering of crustal faults remains unclear. Scientific fault drilling would allow us to get close enough to the fault to image minor aseismic transients.

Furthermore, how stresses change along a fault both during rupture and over the seismic cycle remains poorly resolved. Borehole observations provide rare opportunities to infer the absolute magnitude of stress and its variation near active faults (Lin et al., 2013; Talukdar et al., 2022; Talukdar and Sone, 2024). Seismologists can infer stress drops during rupture, based on a corner frequency and low-frequency amplitude measured from the spectrum of an earthquake (Brune, 1970). However, these measures are highly scattered and likely too simplistic (Shearer et al., 2006; Prieto et al., 2007; Abercrombie, 2014; Baltay et al., 2024) because seismologists are using observations tens of kilometers away from an earthquake to measure the high-frequency behavior of an earthquake rupture (Kemna et al., 2020; Parolai and Oth, 2022; Abercrombie, 2015). The interpretation of stress drops, their variability with depth (Abercrombie et al., 2021), through time (Ruhl et al., 2016; Kemna et al., 2021), and relation to aftershock productivity (Wetzler et al., 2016) are still active areas of research. Instrumentation installed at depth and in the near-field of small to moderate earthquakes could provide the necessary resolution to reliably estimate stresses released during earthquakes. Only by combining these with absolute stress magnitude estimates from borehole observations can we learn if an earthquake's stress drop fully or partially releases the shear stress on a fault.

3 Summary

Advances in our understanding of earthquake physics and triggering mechanisms have important implications far beyond seismic risk assessment in tectonically active regions. A better knowledge of the temporal evolution of stress, fluid flow, and mechanical properties of fault zones could assist in mitigating anthropogenically induced seismicity related to energy exploration and development. Subsurface technologies such as geologic carbon sequestration, enhanced geothermal systems, and wastewater disposal play a critical role in energy security, but significant advancement in their risk reduction and public acceptance may be limited without further gains in understanding the controls on fault slip initiation, propagation, and arrest.

Continental scientific drilling projects that target active faults represent perhaps the best chance to advance

both natural and induced seismic risk assessment and mitigation. Near-field observations and monitoring in the fault zones could provide better constraints on factors controlling earthquake size, recurrence and stress interactions, spatial heterogeneity of the subsurface properties and their evolution throughout the seismic cycle. Filling knowledge gaps in these areas has the potential to advance complementary theoretical and modeling efforts in earthquake science and fault mechanics.

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Data and code availability

No data were collected, or codes developed, as part of this work.

Competing interests

The authors have no competing interests.

References

- Abercrombie, R. E. Stress drops of repeating earthquakes on the San Andreas Fault at Parkfield. *Geophysical Research Letters*, 41(24):8784–8791, 2014. doi: <https://doi.org/10.1002/2014GL062079>.
- Abercrombie, R. E. Investigating uncertainties in empirical Green's function analysis of earthquake source parameters. *Journal of Geophysical Research: Solid Earth*, 120(6):4263–4277, 2015. doi: <https://doi.org/10.1002/2015JB011984>.
- Abercrombie, R. E., Trugman, D. T., Shearer, P. M., Chen, X., Zhang, J., Pennington, C. N., Hardebeck, J. L., Goebel, T. H. W., and Ruhl, C. J. Does Earthquake Stress Drop Increase With Depth in the Crust? *Journal of Geophysical Research: Solid Earth*, 126(10):e2021JB022314, 2021. doi: <https://doi.org/10.1029/2021JB022314>.
- Allam, A. A., Kroll, K. A., Milliner, C. W. D., and Richards-Dinger, K. B. Effects of Fault Roughness on Coseismic Slip and Earthquake Locations. *Journal of Geophysical Research: Solid Earth*, 124(11):11336–11349, 2019. doi: <https://doi.org/10.1029/2018JB016216>.
- Ampuero, J.-P., Ripperger, J., and Mai, P. M. Properties of Dynamic Earthquake Ruptures with Heterogeneous Stress Drop. In Abercrombie, R., McGarr, A., Toro, G. D., and Kanamori, H., editors, *Earthquakes: Radiated Energy and the Physics of Faulting*, pages 255–261. American Geophysical Union (AGU), 2006. doi: <https://doi.org/10.1029/170GM25>.
- Anselmetti, F., Ashwal, L., Ariztegui, D., Bohnhoff, M., Bomberg, M., Claeys, P., Eichelberger, J., Ellsworth, W. L., Goodenough, K., Heubeck, C., et al. ICDP Science Plan: 2020–2030. 2020. doi: [10.2312/icdp.2020.001](https://doi.org/10.2312/icdp.2020.001).
- Araki, E., Saffer, D. M., Kopf, A. J., Wallace, L. M., Kimura, T., Machida, Y., Ide, S., Davis, E., and IODP Expedition 365 shipboard scientists. Recurring and triggered slow-slip events near the trench at the Nankai Trough subduction megathrust. *Science*, 356(6343):1157–1160, 2017. doi: [10.1126/science.aan3120](https://doi.org/10.1126/science.aan3120).
- Baltay, A., Abercrombie, R., Chu, S., and Taira, T. The SCEC/USGS Community Stress Drop Validation Study Using the 2019 Ridgecrest Earthquake Sequence. *Seismica*, 3(1), May 2024. doi: [10.26443/seismica.v3i1.1009](https://doi.org/10.26443/seismica.v3i1.1009).
- Barton, C. A. and Zoback, M. D. Stress perturbations associated with active faults penetrated by boreholes: Possible evidence for near-complete stress drop and a new technique for stress magnitude measurement. *Journal of Geophysical Research: Solid Earth*, 99(B5):9373–9390, 1994. doi: <https://doi.org/10.1029/93JB03359>.
- Bense, V., Gleeson, T., Loveless, S., Bour, O., and Scibek, J. Fault zone hydrogeology. *Earth-Science Reviews*, 127:171–192, 2013. doi: <https://doi.org/10.1016/j.earscirev.2013.09.008>.
- Ben-Zion, Y., Beroza, G. C., Bohnhoff, M., Gabriel, A., and Mai, P. M. A Grand Challenge International Infrastructure for Earthquake Science. *Seismological Research Letters*, 93(6):2967–2968, September 2022. doi: [10.1785/0220220266](https://doi.org/10.1785/0220220266).
- Brodsky, E. E., Mori, J., and Fulton, P. M. Drilling Into Faults Quickly After Earthquakes. *Eos, Transactions American Geophysical Union*, 91(27):237–238, 2010. doi: <https://doi.org/10.1029/2010EO270001>.
- Brune, J. N. Tectonic stress and the spectra of seismic shear waves from earthquakes. *Journal of Geophysical Research (1896-1977)*, 75(26):4997–5009, 1970. doi: <https://doi.org/10.1029/JB075i026p04997>.
- Callahan, O. A., Eichhubl, P., and Davatzes, N. C. Mineral precipitation as a mechanism of fault core growth. *Journal of Structural Geology*, 140:104156, 2020. doi: <https://doi.org/10.1016/j.jsg.2020.104156>.
- Carpenter, B. M., Marone, C., and Saffer, D. M. Weakness of the San Andreas Fault Revealed by Samples from the Active Fault Zone. *Nature Geoscience*, 4(4):251–254, April 2011. doi: [10.1038/ngeo1089](https://doi.org/10.1038/ngeo1089).
- Cochran, E. S., Page, M. T., van der Elst, N. J., Ross, Z. E., and Trugman, D. T. Fault Roughness at Seismogenic Depths and Links to Earthquake Behavior. *The Seismic Record*, 3(1):37–47, March 2023. doi: [10.1785/0320220043](https://doi.org/10.1785/0320220043).
- Dal Zilio, L., Giardini, D., Carbonell, R., and Wiemer, S. Harnessing the potential of digital twins in seismology. *Nature Reviews Earth & Environment*, 4(8):510–512, August 2023. doi: [10.1038/s43017-023-00469-y](https://doi.org/10.1038/s43017-023-00469-y).
- Dieterich, J. H. Earthquake nucleation on faults with rate- and state-dependent strength. *Tectonophysics*, 211(1):115–134, 1992. doi: [https://doi.org/10.1016/0040-1951\(92\)90055-B](https://doi.org/10.1016/0040-1951(92)90055-B).
- Ellsworth, W. L. Injection-Induced Earthquakes. *Science*, 341(6142):1225942, 2013. doi: [10.1126/science.1225942](https://doi.org/10.1126/science.1225942).
- Fan, Z., Eichhubl, P., and Newell, P. Basement Fault Reactivation by Fluid Injection Into Sedimentary Reservoirs: Poroelastic Effects. *Journal of Geophysical Research: Solid Earth*, 124(7):7354–7369, 2019. doi: <https://doi.org/10.1029/2018JB017062>.
- Foulger, G. R., Wilson, M. P., Gluyas, J. G., Julian, B. R., and Davies, R. J. Global review of human-induced earthquakes. *Earth-Science Reviews*, 178:438–514, 2018. doi: <https://doi.org/10.1016/j.earscirev.2017.07.008>.
- Fulton, P. M. and Brodsky, E. E. In situ observations of earthquake-driven fluid pulses within the Japan Trench plate boundary fault zone. *Geology*, 44(10):851–854, October 2016. doi: [10.1130/G38034.1](https://doi.org/10.1130/G38034.1).
- Fulton, P. M., Brodsky, E. E., Kano, Y., Mori, J., Chester, F., Ishikawa,

- T., Harris, R. N., Lin, W., Eguchi, N., Toczko, S., Expedition 343, T., and Scientists, K.-. Low Coseismic Friction on the Tohoku-Oki Fault Determined from Temperature Measurements. *Science*, 342(6163):1214–1217, 2013. doi: 10.1126/science.1243641.
- Gabrielli, S., Akinci, A., Ventura, G., Napolitano, F., Del Pezzo, E., and De Siena, L. Fast changes in seismic attenuation of the upper crust due to fracturing and fluid migration: The 2016–2017 central Italy seismic sequence. *Frontiers in Earth Science*, 10: 909698, 2022. doi: 10.3389/feart.2022.909698.
- Goebel, T. H., Kwiitek, G., Becker, T. W., Brodsky, E. E., and Dresen, G. What allows seismic events to grow big?: Insights from b-value and fault roughness analysis in laboratory stick-slip experiments. *Geology*, 45(9):815–818, July 2017. doi: 10.1130/G39147.1.
- Goswami, D., Hazarika, P., and Roy, S. In Situ Stress Orientation From 3 km Borehole Image Logs in the Koyna Seismogenic Zone, Western India: Implications for Transitional Faulting Environment. *Tectonics*, 39(1):e2019TC005647, 2020. doi: <https://doi.org/10.1029/2019TC005647>.
- Guglielmi, Y., Cook, P., Soom, F., Schoenball, M., Dobson, P., and Kneafsey, T. In Situ Continuous Monitoring of Borehole Displacements Induced by Stimulated Hydrofracture Growth. *Geophysical Research Letters*, 48(4):e2020GL090782, 2021. doi: <https://doi.org/10.1029/2020GL090782>.
- Gupta, H., Purnachandra Rao, N., Roy, S., Arora, K., Tiwari, V. M., Patro, P. K., Satyanarayana, H. V. S., Shashidhar, D., Mallika, K., Akkiraju, V. V., Goswami, D., Vyas, D., Ravi, G., Srinivas, K. N. S. S. S., Srihari, M., Mishra, S., Dubey, C. P., Raju, D. C. V., Borah, U., Chinna Reddy, K., Babu, N., Rohilla, S., Dhar, U., Sen, M., Bhaskar Rao, Y. J., Bansal, B. K., and Nayak, S. Investigations related to scientific deep drilling to study reservoir-triggered earthquakes at Koyna, India. *International Journal of Earth Sciences*, 104(6):1511–1522, September 2015. doi: 10.1007/s00531-014-1128-0.
- Haddad, M. and Eichhubl, P. Fault Reactivation in Response to Salt-water Disposal and Hydrocarbon Production for the Venus, TX, Mw 4.0 Earthquake Sequence. *Rock Mechanics and Rock Engineering*, 56(3):2103–2135, March 2023. doi: 10.1007/s00603-022-03083-4.
- Harris, R. A. Large earthquakes and creeping faults. *Reviews of Geophysics*, 55(1):169–198, 2017. doi: <https://doi.org/10.1002/2016RG000539>.
- Heimisson, E. R. Crack to pulse transition and magnitude statistics during earthquake cycles on a self-similar rough fault. *Earth and Planetary Science Letters*, 537:116202, 2020. doi: <https://doi.org/10.1016/j.epsl.2020.116202>.
- Hickman, S., Sibson, R., and Bruhn, R. Introduction to Special Section: Mechanical Involvement of Fluids in Faulting. *Journal of Geophysical Research: Solid Earth*, 100(B7):12831–12840, 1995. doi: <https://doi.org/10.1029/95JB01121>.
- Janku-Capova, L., Sutherland, R., Townend, J., Doan, M.-L., Massiot, C., Coussens, J., and Célériér, B. Fluid Flux in Fractured Rock of the Alpine Fault Hanging-Wall Determined from Temperature Logs in the DFDP-2B Borehole, New Zealand. *Geochemistry, Geophysics, Geosystems*, 19(8):2631–2646, 2018. doi: <https://doi.org/10.1029/2017GC007317>.
- Jin, G. and Roy, B. Hydraulic-fracture geometry characterization using low-frequency DAS signal. *The Leading Edge*, 36(12): 975–980, 2017. doi: 10.1190/tle36120975.1.
- Johnson, K. M. Slip rates and off-fault deformation in Southern California inferred from GPS data and models. *Journal of Geophysical Research: Solid Earth*, 118(10):5643–5664, 2013. doi: <https://doi.org/10.1002/jgrb.50365>.
- Karrenbach, M., Cole, S., Ridge, A., Boone, K., Kahn, D., Rich, J., Silver, K., and Langton, D. Fiber-optic distributed acoustic sensing of microseismicity, strain and temperature during hydraulic fracturing. *Geophysics*, 84(1):D11–D23, December 2018. doi: 10.1190/geo2017-0396.1.
- Kato, A., Obara, K., Igarashi, T., Tsuruoka, H., Nakagawa, S., and Hirata, N. Propagation of Slow Slip Leading Up to the 2011 Mw 9.0 Tohoku-Oki Earthquake. *Science*, 335(6069):705–708, 2012. doi: 10.1126/science.1215141.
- Kemna, K. B., Peña Castro, A. F., Harrington, R. M., and Cochran, E. S. Using a Large-n Seismic Array to Explore the Robustness of Spectral Estimations. *Geophysical Research Letters*, 47(21):e2020GL089342, 2020. doi: <https://doi.org/10.1029/2020GL089342>.
- Kemna, K. B., Verdecchia, A., and Harrington, R. M. Spatio-Temporal Evolution of Earthquake Static Stress Drop Values in the 2016–2017 Central Italy Seismic Sequence. *Journal of Geophysical Research: Solid Earth*, 126(11):e2021JB022566, 2021. doi: <https://doi.org/10.1029/2021JB022566>.
- Kivi, I. R., Boyet, A., Wu, H., Walter, L., Hanson-Hedgecock, S., Parisio, F., and Vilarrasa, V. Global physics-based database of injection-induced seismicity. *Earth System Science Data*, 15(7): 3163–3182, 2023. doi: 10.5194/essd-15-3163-2023.
- Kroll, K. A. and Cochran, E. S. Stress Controls Rupture Extent and Maximum Magnitude of Induced Earthquakes. *Geophysical Research Letters*, 48(11):e2020GL092148, 2021. doi: <https://doi.org/10.1029/2020GL092148>.
- Kumazawa, T. and Ogata, Y. Spatial and temporal variations of the 3-year earthquake swarm activities leading up to the M7.6 Noto Peninsula earthquake and interpretations of their activities. *Earth, Planets and Space*, 76(1):164, December 2024. doi: 10.1186/s40623-024-02112-6.
- Lachenbruch, A. H. and Sass, J. H. Heat flow from Cajon Pass, fault strength, and tectonic implications. *Journal of Geophysical Research: Solid Earth*, 97(B4):4995–5015, 1992. doi: <https://doi.org/10.1029/91JB01506>.
- Lapusta, N. and Rice, J. R. Nucleation and early seismic propagation of small and large events in a crustal earthquake model. *Journal of Geophysical Research: Solid Earth*, 108(B4), 2003. doi: <https://doi.org/10.1029/2001JB000793>.
- Lay, V., Buske, S., Townend, J., Kellett, R., Savage, M., Schmitt, D. R., Constantinou, A., Eccles, J. D., Gorman, A. R., Bertram, M., Hall, K., Lawton, D., and Kofman, R. 3D Active Source Seismic Imaging of the Alpine Fault Zone and the Whataroa Glacial Valley in New Zealand. *Journal of Geophysical Research: Solid Earth*, 126(12):e2021JB023013, 2021. doi: <https://doi.org/10.1029/2021JB023013>.
- Lellouch, A., Schultz, R., Lindsey, N., Biondi, B., and Ellsworth, W. Low-Magnitude Seismicity With a Downhole Distributed Acoustic Sensing Array—Examples From the FORGE Geothermal Experiment. *Journal of Geophysical Research: Solid Earth*, 126(1):e2020JB020462, 2021. doi: <https://doi.org/10.1029/2020JB020462>.
- Lin, W., Conin, M., Moore, J. C., Chester, F. M., Nakamura, Y., Mori, J. J., Anderson, L., Brodsky, E. E., Eguchi, N., Scientists, E. ., Cook, B., Jeppson, T., Wolfson-Schwehr, M., Sanada, Y., Saito, S., Kido, Y., Hirose, T., Behrmann, J. H., Ikari, M., Ujiie, K., Rowe, C., Kirkpatrick, J., Bose, S., Regalla, C., Remitti, F., Toy, V., Fulton, P., Mishima, T., Yang, T., Sun, T., Ishikawa, T., Sample, J., Takai, K., Kameda, J., Toczko, S., Maeda, L., Kodaira, S., Hino, R., and Saffer, D. Stress State in the Largest Displacement Area of the 2011 Tohoku-Oki Earthquake. *Science*, 339(6120):687–690, 2013. doi: 10.1126/science.1229379.
- Lindsey, N. J. and Martin, E. R. Fiber-Optic Seismology. *Annual Review of Earth and Planetary Sciences*, 49(Volume 49, 2021):

- 309–336, 2021. doi: <https://doi.org/10.1146/annurev-earth-072420-065213>.
- Lockner, D. A., Morrow, C., Moore, D., and Hickman, S. Low strength of deep San Andreas fault gouge from SAFOD core. *Nature*, 472 (7341):82–85, April 2011. doi: [10.1038/nature09927](https://doi.org/10.1038/nature09927).
- Ma, K.-F., Tanaka, H., Song, S.-R., Wang, C.-Y., Hung, J.-H., Tsai, Y.-B., Mori, J., Song, Y.-F., Yeh, E.-C., Soh, W., Sone, H., Kuo, L.-W., and Wu, H.-Y. Slip zone and energetics of a large earthquake from the Taiwan Chelungpu-fault Drilling Project. *Nature*, 444 (7118):473–476, November 2006. doi: [10.1038/nature05253](https://doi.org/10.1038/nature05253).
- Ma, K.-F., von Specht, S., Kuo, L.-W., Huang, H.-H., Lin, C.-R., Lin, C.-J., Ku, C.-S., Wu, E.-S., Wang, C.-Y., Chang, W.-Y., and Jousset, P. Broad-band strain amplification in an asymmetric fault zone observed from borehole optical fiber and core. *Communications Earth & Environment*, 5(1):402, July 2024. doi: [10.1038/s43247-024-01558-6](https://doi.org/10.1038/s43247-024-01558-6).
- Ma, T., Chen, P., and Zhao, J. Overview on vertical and directional drilling technologies for the exploration and exploitation of deep petroleum resources. *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, 2(4):365–395, December 2016. doi: [10.1007/s40948-016-0038-y](https://doi.org/10.1007/s40948-016-0038-y).
- Majer, E. L., Baria, R., Stark, M., Oates, S., Bommer, J., Smith, B., and Asanuma, H. Induced seismicity associated with Enhanced Geothermal Systems. *Geothermics*, 36(3):185–222, 2007. doi: <https://doi.org/10.1016/j.geothermics.2007.03.003>.
- Massiot, C., Célérrier, B., Doan, M.-L., Little, T. A., Townend, J., McNamara, D. D., Williams, J., Schmitt, D. R., Toy, V. G., Sutherland, R., Janku-Capova, L., Upton, P., and Pezard, P. A. The Alpine Fault Hangingwall Viewed From Within: Structural Analysis of Ultrasonic Image Logs in the DFDP-2B Borehole, New Zealand. *Geochemistry, Geophysics, Geosystems*, 19(8):2492–2515, 2018. doi: <https://doi.org/10.1029/2017GC007368>.
- McLaskey, G. C. Earthquake Initiation From Laboratory Observations and Implications for Foreshocks. *Journal of Geophysical Research: Solid Earth*, 124(12):12882–12904, 2019. doi: <https://doi.org/10.1029/2019JB018363>.
- Mellors, R. J., Abbott, R., Steedman, D., Podrasky, D., and Pitarka, A. Modeling Subsurface Explosions Recorded on a Distributed Fiber Optic Sensor. *Journal of Geophysical Research: Solid Earth*, 126(12):e2021JB022690, 2021. doi: <https://doi.org/10.1029/2021JB022690>.
- Moore, D. E. and Rymer, M. J. Correlation of clayey gouge in a surface exposure of serpentinite in the San Andreas Fault with gouge from the San Andreas Fault Observatory at Depth (SAFOD). *Journal of Structural Geology*, 38:51–60, 2012. doi: <https://doi.org/10.1016/j.jsg.2011.11.014>.
- Oskoin, M., Perg, L., Blumentritt, D., Mukhopadhyay, S., and Iriondo, A. Slip rate of the Calico fault: Implications for geologic versus geodetic rate discrepancy in the Eastern California Shear Zone. *Journal of Geophysical Research: Solid Earth*, 112(B3), 2007. doi: <https://doi.org/10.1029/2006JB004451>.
- Parolai, S. and Oth, A. On the Limitations of Spectral Source Parameter Estimation for Minor and Microearthquakes. *Bulletin of the Seismological Society of America*, 112(5):2364–2375, July 2022. doi: [10.1785/0120220050](https://doi.org/10.1785/0120220050).
- Petersen, M. D., Shumway, A. M., Powers, P. M., Field, E. H., Moschetti, M. P., Jaiswal, K. S., Milner, K. R., Rezaeian, S., Frankel, A. D., Llenos, A. L., Michael, A. J., Altekruze, J. M., Ahdi, S. K., Withers, K. B., Mueller, C. S., Zeng, Y., Chase, R. E., Salditch, L. M., Luco, N., Rukstales, K. S., Herrick, J. A., Girot, D. L., Aagaard, B. T., Bender, A. M., Blanpied, M. L., Briggs, R. W., Boyd, O. S., Clayton, B. S., DuRoss, C. B., Evans, E. L., Haeussler, P. J., Hatem, A. E., Haynie, K. L., Hearn, E. H., Johnson, K. M., Korum, Z. A., Kwong, N. S., Makdisi, A. J., Mason, H. B., McNamara, D. E., McPhillips, D. F., Okubo, P. G., Page, M. T., Pollitz, F. F., Rubinstein, J. L., Shaw, B. E., Shen, Z.-K., Shiro, B. R., Smith, J. A., Stephenson, W. J., Thompson, E. M., Jobe, J. A. T., Wirth, E. A., and Witter, R. C. The 2023 US 50-State National Seismic Hazard Model: Overview and implications. *Earthquake Spectra*, 40(1): 5–88, 2024. doi: [10.1177/87552930231215428](https://doi.org/10.1177/87552930231215428).
- Prieto, G. A., Thomson, D. J., Vernon, F. L., Shearer, P. M., and Parker, R. L. Confidence intervals for earthquake source parameters. *Geophysical Journal International*, 168(3):1227–1234, March 2007. doi: [10.1111/j.1365-246X.2006.03257.x](https://doi.org/10.1111/j.1365-246X.2006.03257.x).
- Reches, Z. and Ito, H. *Scientific Drilling of Active Faults: Past and Future*, pages 235–258. Springer Berlin Heidelberg, Berlin, Heidelberg, 2007. doi: [10.1007/978-3-540-68778-8_6](https://doi.org/10.1007/978-3-540-68778-8_6).
- Ross, Z. E., Cochran, E. S., Trugman, D. T., and Smith, J. D. 3D fault architecture controls the dynamism of earthquake swarms. *Science*, 368(6497):1357–1361, 2020. doi: [10.1126/science.abb0779](https://doi.org/10.1126/science.abb0779).
- Rowe, C. D. and Griffith, W. A. Do faults preserve a record of seismic slip: A second opinion. *Journal of Structural Geology*, 78:1–26, 2015. doi: <https://doi.org/10.1016/j.jsg.2015.06.006>.
- Ruhl, C. J., Abercrombie, R. E., Smith, K. D., and Zaliapin, I. Complex spatiotemporal evolution of the 2008 Mw 4.9 Mogul earthquake swarm (Reno, Nevada): Interplay of fluid and faulting. *Journal of Geophysical Research: Solid Earth*, 121(11): 8196–8216, 2016. doi: <https://doi.org/10.1002/2016JB013399>.
- Ruiz, S., Metois, M., Fuenzalida, A., Ruiz, J., Leyton, F., Grandin, R., Vigny, C., Madariaga, R., and Campos, J. Intense foreshocks and a slow slip event preceded the 2014 Iquique Mw 8.1 earthquake. *Science*, 345(6201):1165–1169, 2014. doi: [10.1126/science.1256074](https://doi.org/10.1126/science.1256074).
- Savage, H. M., Kirkpatrick, J. D., Mori, J. J., Brodsky, E. E., Ellsworth, W. L., Carpenter, B. M., Chen, X., Cappa, F., and Kano, Y. Scientific Exploration of Induced Seismicity and Stress (SEISMS). *Scientific Drilling*, 23:57–63, 2017. doi: [10.5194/sd-23-57-2017](https://doi.org/10.5194/sd-23-57-2017).
- Shearer, P. M., Prieto, G. A., and Hauksson, E. Comprehensive analysis of earthquake source spectra in southern California. *Journal of Geophysical Research: Solid Earth*, 111(B6), 2006. doi: <https://doi.org/10.1029/2005JB003979>.
- Silva, V., Pagani, M., Schneider, J., and Henshaw, P. Assessing seismic hazard and risk globally for an earthquake resilient world | UNDRR. Global Assessment Report on Disaster Risk Reduction., 2019. <https://www.undrr.org/publication/assessing-seismic-hazard-and-risk-globally-earthquake-resilient-world>.
- Sone, H. and Uchide, T. Spatiotemporal evolution of a fault shear stress patch due to viscoelastic interseismic fault zone rheology. *Tectonophysics*, 684:63–75, 2016. doi: <https://doi.org/10.1016/j.tecto.2016.04.017>.
- Takano, S., Hiramatsu, Y., and Yukutake, Y. The role of fluids in earthquake swarms in northeastern Noto Peninsula, central Japan: insights from source mechanisms. *Earth, Planets and Space*, 76(1):151, November 2024. doi: [10.1186/s40623-024-02099-0](https://doi.org/10.1186/s40623-024-02099-0).
- Talukdar, M. and Sone, H. Time-Dependent Deformation in the Damage Zone of the Chelungpu Fault System and Potential Stress Relaxation. *Geophysical Research Letters*, 51(2):e2023GL106237, 2024. doi: <https://doi.org/10.1029/2023GL106237>.
- Talukdar, M., Sone, H., and Kuo, L.-W. Lithology and Fault-Related Stress Variations Along the TCDP Boreholes: The Stress State Before and After the 1999 Chi-Chi Earthquake. *Journal of Geophysical Research: Solid Earth*, 127(2):e2021JB023290, 2022. doi: <https://doi.org/10.1029/2021JB023290>.
- Teodoriu, C. and Bello, O. An Outlook of Drilling Technologies and

- Innovations: Present Status and Future Trends. *Energies*, 14 (15), 2021. doi: 10.3390/en14154499.
- Tobin, H., Hirose, T., Ikari, M., Kanagawa, K., Kimura, G., Kinoshita, M., Kitajima, H., Saffer, D., Yamaguchi, A., Eguchi, N., Maeda, L., and Toczko, S. *Expedition 358 Preliminary Report: NanTro-SEIZE Plate Boundary Deep Riser 4: Nankai Seismogenic/Slow Slip Megathrust*. International Ocean Discovery Program, October 2019. doi: 10.14379/iodp.pr.358.2019.
- Townend, J., Sutherland, R., and Toy, V. Deep Fault Drilling Project – Alpine Fault, New Zealand. *Scientific Drilling*, 8:75–82, 2009. doi: 10.2204/iodp.sd.8.12.2009.
- Wetzler, N., Brodsky, E. E., and Lay, T. Regional and stress drop effects on aftershock productivity of large megathrust earthquakes. *Geophysical Research Letters*, 43(23):12,012–12,020, 2016. doi: <https://doi.org/10.1002/2016GL071104>.
- White, J. A. and Foxall, W. Assessing induced seismicity risk at CO2 storage projects: Recent progress and remaining challenges. *International Journal of Greenhouse Gas Control*, 49:413–424, 2016. doi: <https://doi.org/10.1016/j.ijggc.2016.03.021>.
- Williams, R. T. and Fagereng, Å. The Role of Quartz Cementation in the Seismic Cycle: A Critical Review. *Reviews of Geophysics*, 60(1):e2021RG000768, 2022. doi: <https://doi.org/10.1029/2021RG000768>.
- Yamada, Y., Dugan, B., Hirose, T., and Saito, S. Riser Drilling: Access to Deep Subseafloor Science. *Oceanography*, 32(1):95–97, March 2019. doi: 10.5670/oceanog.2019.127.
- Zhang, O. and Schmitt, D. Seismic Anisotropy of the Alpine Fault: Application of Machine Learning to Distributed Acoustic Sensing Borehole Seismics. *59th U.S. Rock Mechanics/Geomechanics Symposium*, page D041S056R004, June 2025. doi: 10.56952/ARMA-2025-0806.
- Zoback, M., Hickman, S., Ellsworth, W., and the SAFOD Science Team. Scientific Drilling Into the San Andreas Fault Zone – An Overview of SAFOD’s First Five Years. *Scientific Drilling*, 11:14–28, 2011. doi: 10.2204/iodp.sd.11.02.2011.
- Zoback, M. D. and Healy, J. H. In situ stress measurements to 3.5 km depth in the Cajon Pass Scientific Research Borehole: Implications for the mechanics of crustal faulting. *Journal of Geophysical Research: Solid Earth*, 97(B4):5039–5057, 1992. doi: <https://doi.org/10.1029/91JB02175>.
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