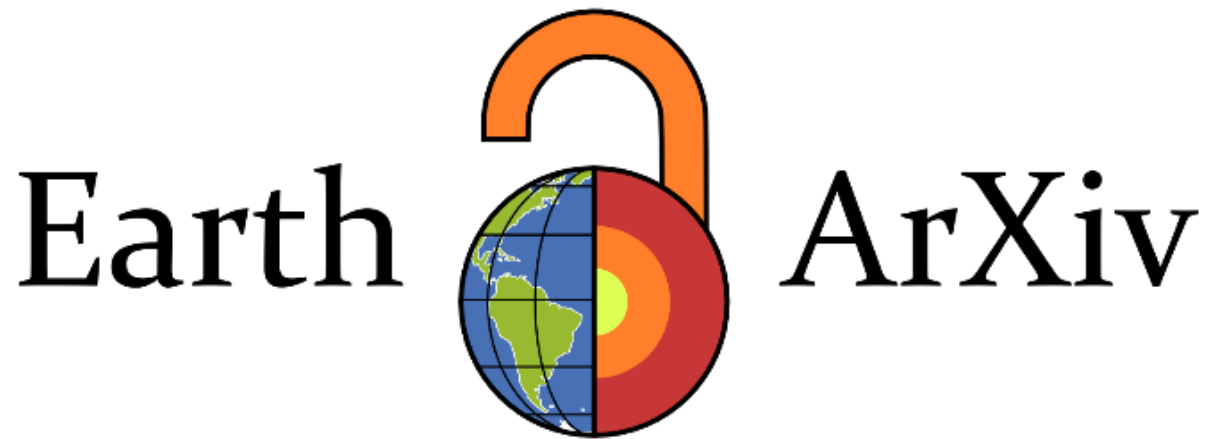




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Understanding Earthquake Physics with On-Fault Observatories

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Earthquakes often strike without warning. Current fault monitoring infrastructure is not sensitive enough to detect signals such as accelerating fault creep or dilation, which laboratory experiments and numerical models predict may precede large earthquakes. Here we argue that a paradigm shift is needed and technically achievable: from inferring faulting processes from a distance with surface arrays, to on-fault observatories (OFOs) that measure the processes directly on faults. And from accidental fault activation to controlled fault activation experiments. We discuss how the resulting observations could solve long-standing earthquake physics questions, and pave the way for more powerful earthquake risk mitigation strategies.

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1 Introduction

Earthquakes unfold mostly beyond our reach. The processes that govern fault preparation and rupture occur at depths that are largely inaccessible to direct observation. This fundamental observational gap limits our ability to resolve the physics of earthquake faulting and, ultimately, to predict when and how faults will fail. Without such predictive understanding, our ability to proactively manage earthquake risks is limited.

While modern probabilistic seismic hazard assessment can accurately quantify long-term average recurrence rates of large earthquakes and associated ground motions [1], we cannot anticipate the rupture time and size of any individual event. What is more, we also cannot anticipate how an ongoing earthquake sequence will develop: will a large mainshock be the first event of a doublet (e.g. 2023 Mw 7.8 and 7.5 Kahramanmaraş, Turkey)? Or will it be followed by even larger events (2019 Mw 6.4 and 7.1 Ridgecrest, California; 2016 Mw 6.0 and 6.5 Norcia, Italy)? Or will the sequence decay without further consequential events (e.g. 2025 Mw 7.7 Myanmar)? When will adjacent fault segments rupture, where a large earthquake has raised static stresses, e.g. after the Mw 9.1 Tohoku-Oki, Japan megathrust earthquake, or on the North Anatolian and Dead Sea faults after the Kahramanmaraş earthquakes? And what are the tell-tale signs of an impending large rupture?

The devastating earthquakes of the past years have made it painfully clear that we do not know how to recognize critically stressed faults before they rupture. This raises the question of what the earthquake science community can do to improve our ability to anticipate large earthquakes. What are the most promising research avenues for substantially improving short-term hazard assessment, and the reliable estimation of large earthquake probabilities? In this paper, we argue that if we are to better anticipate large earthquakes, we need to make a step change in our understanding of faulting physics. This, in turn, requires a step change in how we monitor and study faults: we need to advance from regional and near-fault monitoring to on-fault monitoring, and from accidental fault activation and retroactive investigations to controlled fault activation experiments (Figure 1).

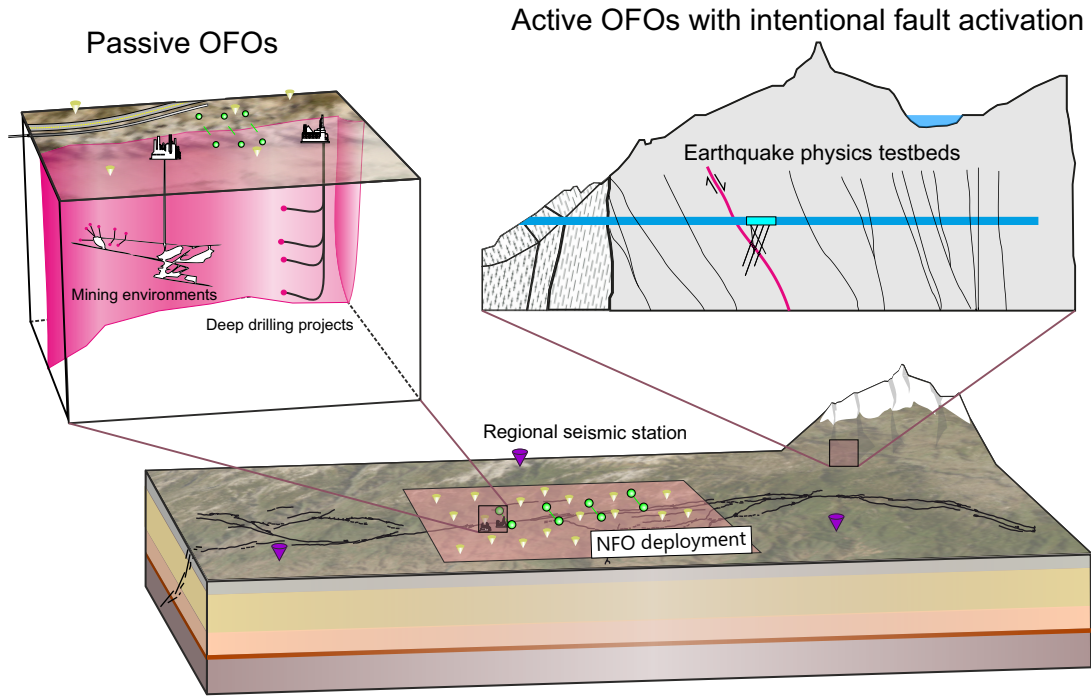


FIG. 1. On-Fault Observatories (OFOs) are networks of monitoring infrastructure with sensors installed directly on target faults. Their goal is to resolve faulting processes and fault zone properties at high resolution in both space and time. Passive OFOs monitor faults without attempting to influence their behaviour. Active OFOs, on the other hand, facilitate controlled fault activation experiments in places where the seismic risk is low.

Faulting processes are under-monitored Many of the most active tectonic faults are extensively instrumented with seismic and other monitoring networks. But, notably, none of the faults that caused the earthquakes listed above are equipped with on-fault sensors that would enable direct measurements of, for example, slow strain accumulation,

seismic velocity changes, pore-fluid pressure transients or nano- to micro-seismicity that may likely precede large ruptures [2–4]. Fault monitoring has tremendously improved over the past decades in terms of both monitoring hardware and data processing methods. Near-fault observatories (NFO) [5, 6] and ever denser regional networks have increased monitoring resolution and sensitivity by orders of magnitude [7, 8]. New monitoring technologies — for instance based on distributed fibre optic sensing (DFOS) [9–11] — are complementing and expanding the more traditional monitoring systems. Similarly, advances in air- and space-borne imaging techniques with satellites, airplanes and drones provide increasingly frequent and higher-resolution imaging of the Earth’s surface, e.g. before and after large ruptures [12, 13]. At the same time, game-changing machine learning methods [14–19] now facilitate the reliable automation of delicate signal processing tasks [19], and enable new workflows like high-fidelity signal denoising [20–23]. They thereby strongly increase the amount of information that can be extracted from network data. Yet, despite all these advances, a fundamental limitation remains: most observations are still made at some distance from the fault, limiting our ability to resolve subtle faulting processes in the run-up to large earthquakes.

Earthquake ruptures involve a cascade of coupled processes that span an exceptionally broad range of spatial and temporal scales—from grain-scale deformation to kilometre-scale faulting [24]. For instance, shear-induced fault dilatation that may occur at the onset of rupture can involve deformations of less than a millimetre, yet may play a crucial role in the overall frictional stability of a fault [25–28]. Conventional seismic data, on the other hand, e.g. recorded with 200 samples per second, have wavelengths on the order of hundreds of metres, and corresponding spatial resolution (**Figure 2**). Inferring processes occurring at millimeter to centimeter scales within the fault zone from off-fault observations therefore remains inherently challenging, even with NFOs.

Even larger-scale processes are often poorly constrained, if detected at all. Fluid flow and pressure distributions across fault networks, for example, exert a fundamental influence on fault strength and deformation dynamics [29], controlling phenomena such as earthquake triggering and aftershock sequences [30–32]. However, they cannot be measured with existing surface arrays. Rather, their inference usually relies on indirect proxy statistics, such as pressure-driven seismicity patterns [33]. As a result, we can almost never observe some of the most fundamental faulting processes in nature. Instead, their study is limited to numerical simulations or small-scale laboratory experiments.

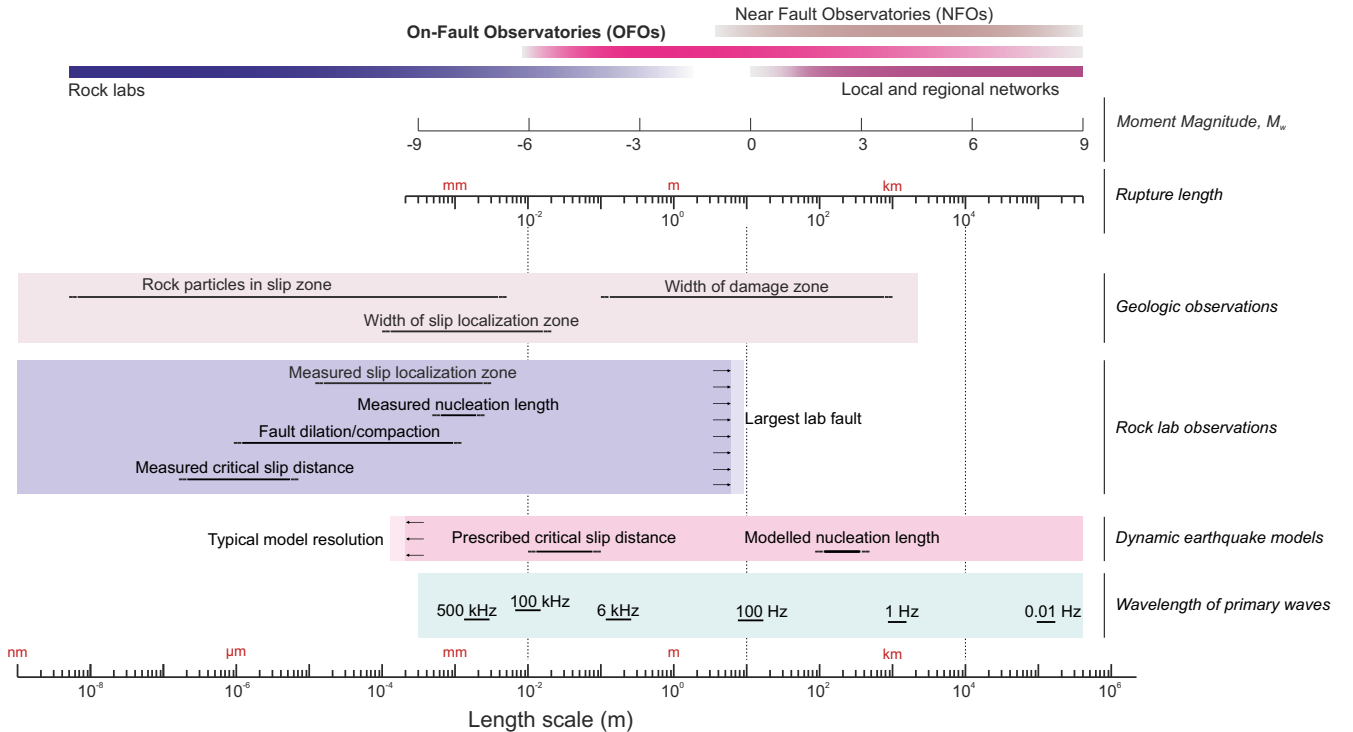


FIG. 2. Length scales of faulting processes, fault zone properties and of seismic observations. Many first order processes have length scales that are orders of magnitude smaller than those that can be resolved with off-fault surface instrumentation.

Direct access to faults through fault-crossing boreholes provides an important step towards overcoming this observational gap. A small number of projects have drilled into or across active faults: Nojima in Japan [34], the Chelungpu fault [35] and Milun fault (MiDAS) [10, 36] in Taiwan, the San Andreas fault at SAFOD [28] in the USA,

the Pretorius fault [37] and the source volume of the 2014 Orkney earthquake (DSeis) [38] in South Africa, the Alpine fault in New Zealand (DFDP) [39], and Koyna in India [40, 41]. These boreholes provide sparse but detailed in-situ characterization of fault zone structure and state, and facilitate the direct measurement of key faulting observables, such as strain, pressure and temperature (Box 2) with high sensitivity and resolution. They demonstrate both the scientific value and the technical feasibility of bringing observations directly to active faults.

Learning from induced seismicity Furthermore, since the pioneering deep geothermal energy project in Basel, Switzerland, was suspended in 2006 and formally abandoned in 2009 due to unexpected levels of induced seismicity [42, 43], much has been learned about earthquake physics from induced seismicity sequences. Such projects facilitate the study of artificially induced but otherwise natural earthquakes under in-situ conditions. Because with fluid injections we can, to some extent, induce earthquakes “on demand”, monitoring equipment can in principle be placed closer to the active faulting processes than in the case of natural earthquakes. At the same time, fluid injection experiments also showcase how limited our control over fault activation remains: projects around the world are haunted by the usually unlikely but always possible large magnitude events [32, 44]. If a nearby fault is critically stressed over a sufficiently large volume, “accidental” fault activation can result, with potentially severe consequences, as in the 2017 Mw 5.5 Pohang, South Korea earthquake [45–47], or in the 1967 Mw 6.3 reservoir-triggered earthquake in Koyna, India. Importantly, for most induced seismicity projects earthquakes are a nuisance rather than a focus. Activating a fault deliberately for scientific purposes, in locations where little harm can be done, has been proposed in the past [48], but only a small number of such projects have been realised to date, and on a limited scale [49–53]. This is arguably a missed opportunity, since learning more about the conditions that govern the nucleation, growth and arrest of larger ruptures may ultimately help us understand how to control or even prevent them [54].

On-fault observatories and controlled earthquake experiments Here we argue that, if we are to advance our understanding of how faults fail, the earthquake science community should strongly expand efforts to build dedicated on-fault observatories (OFOs): installations designed to measure faulting processes and fault-zone properties directly where they occur, with the highest achievable spatial and temporal resolution and sensitivity. These include processes that control faulting (e.g. fault dilatation and slow shearing) and their consequences (e.g. fault heating and fluid-pressure transients). We should build both large scale observatories that passively monitor major fault zones with on-fault instrumentation, as well as smaller scale observatories on faults with limited hazard that can be purposefully activated, in order to induce the faulting processes we aim to understand. That is, we should realize a research agenda that moves us from the largely accidental activation of faults in past fluid stimulation projects towards a more controlled approach, in which massively instrumented fault segments are activated by design.

While challenging and expensive to build, the small number of existing fault drilling and activation projects show that this is indeed technically feasible. In the following we discuss how building more and larger OFOs will allow us i) to achieve a step-change in our understanding of faulting physics, ii) to better anticipate future earthquakes, iii) to inform a new generation of risk mitigation strategies, and iv) to develop safer fluid injection protocols, e.g. for large-scale production of clean deep geothermal energy. In Section 2 we describe a range of possible observatory designs, using the small number of existing OFOs as examples. In Section 3 we discuss the scientific advances that on-fault observations may enable. In Section 4 we outline how OFOs can be built, discuss their limitations, and show how recent hardware advances have substantially improved their robustness and scientific potential.

Box 1: Four outstanding questions in earthquake physics

How do earthquake ruptures nucleate? Earthquake nucleation is believed to be controlled by the local stress state, fault-zone structure and frictional properties, pore-fluid pressure, and aseismic deformation [55]. Static and dynamic stress perturbations may further promote or trigger nucleation on faults that are already close to failure. What remains unclear are the roles these factors play in nature, the scales at which they operate and how they interact. Do faults progressively weaken and localize strain through damage in the fault zone as they prepare for larger events [3, 56]? Do earthquake ruptures start gradually or relatively abruptly [57, 58]? And does how they start determine how big they can grow [57, 59–63]? The debate continues on whether earthquake preparation is a cascading failure process or driven by a hard-to-observe aseismic process. Laboratory experiments and theoretical models provide insights, but natural earthquake observations remain elusive due to the limitations of standard observatories.

How do earthquake ruptures propagate?

Why do some ruptures accelerate into large, destructive events, while most do not? Rupture propagation is governed by an energy balance involving stored elastic strain energy, fracture energy, frictional heating, off-fault damage, and radiated seismic energy [64]. Numerous models explain the drop in shear resistance needed for dynamic ruptures to propagate. While they predict different evolutions of temperature and pore pressure, we do not have any direct in-situ observations from natural earthquakes that would discriminate between the proposed models.

How do earthquake ruptures arrest?

What is the principal rupture arrest mechanism? Do ruptures gradually run out of energy or stop abruptly due to strong mechanical barriers [65–67]? Predicting the arrest of frictional ruptures is possible in controlled laboratory experiments [68] where rupture occurs along a single frictional interface between elastic blocks. Extending these predictions to natural earthquakes is difficult, due to complex (and usually under-constrained) fault zone properties and the complex interplay between different components of the earthquake energy budget.

How predictable are earthquake ruptures?

The prediction of individual large earthquakes has been a long-standing and so far unattainable goal for decades of earthquake research [69]. Many large earthquakes are reported to be preceded by precursory signals, but in virtually all cases these signals were identified as precursory only after the mainshock had occurred and none has proven diagnostic in a way that would allow forecasts with high probability gain [70]. Furthermore, some exceptionally well-monitored earthquakes showed none of the precursory signals predicted by specific nucleation theories, even though the quality of the observations should have been sufficient to rule out, or strongly constrain, such signals (e.g. in the 2004 M_w 6.0 Parkfield, California earthquake [71–73]). Even the evolution of an accelerating rupture after nucleation may be unpredictable if small and large earthquakes have identical onsets [61–63].

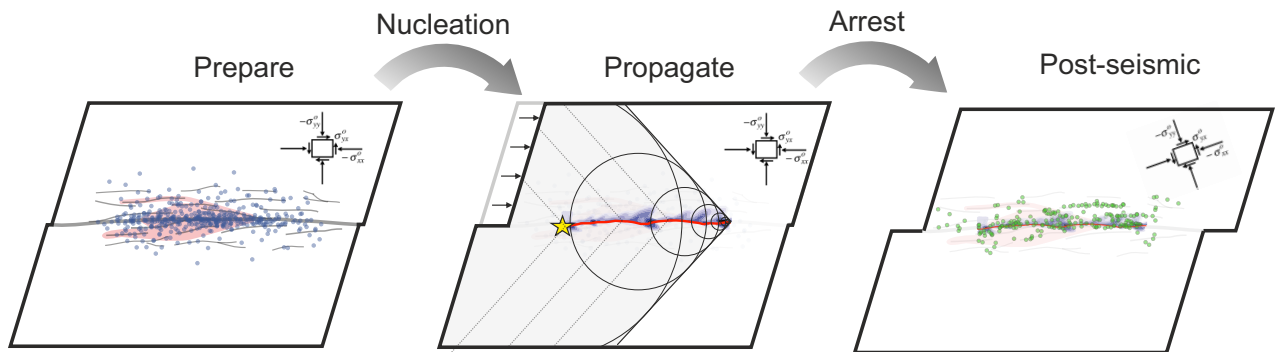


Figure B1: Throughout the seismic cycle, various fault deformation and instability mechanisms interact, most of which are strongly under-constrained by current fault monitoring networks.

2 On-Fault Observatories

An On-Fault Observatory (OFO) is a network of monitoring infrastructure placed directly on and around a fault zone. What distinguishes an OFO is monitoring proximity: sensors are placed directly on active fault strands or, at minimum, inside the damage zone of an identified target fault. Sensors for any of the key observables (Box 2) can be installed via fault-crossing boreholes and/or tunnels, or on fault zone outcrops, including on the seafloor. Observatories that monitor active faults but do not reach the target structure are considered near-fault observatories (NFOs; Figure 3).

The design of any particular OFO strongly depends on its scientific objectives, technical feasibility, as well as on budgetary and logistical constraints. Some of the main defining characteristics of an OFO include i) the monitoring infrastructure (boreholes, tunnels, monitoring hardware), ii) the spatial and temporal scales of the target processes the OFO can resolve, iii) the depth range it can reach, and iv) the observables it targets. On-fault instrumentation may be placed permanently, or until it fails [e.g. 74], for a limited amount of time, e.g. for a single experiment [e.g. 49]. *Passive OFOs* are built to monitor hazardous or scientifically significant fault zones at close range, without intentionally affecting fault behavior. *Active OFOs*, on the other hand, are built on faults that can be purposefully activated, e.g. via fluid injections. They are typically constructed on small-to-moderate sized fault zones with limited hazard potential, or in remote locations with low seismic risk. This enables controlled perturbations of the fault while directly monitoring its response, allowing faulting processes to be investigated within the operational lifetime of the observatory [54].

OFOs

1. SURF
2. BedrettoLab
3. LSBB
4. MIDAS/TCDP
5. SAFOD
6. DAFSAM-NELSAM
7. DSEIS
8. Koyna dam
9. Nojima
10. DFDP
11. Mont Terri
12. Grimsel test site
13. Tournemire

URLs

14. AECL URL
15. Boulby
16. KURT
17. HADES
18. Äspö
19. ANDRA
20. Horonobe
21. Reiche Zeche
22. KTB

NFOs

- A. Marmara
- B. Vrancea
- C. Corinth Rift
- D. Isparta
- E. Alto Tiberina
- F. Valais
- G. NanTroSEIZE
- H. Hi-net NEID array
- I. Taiwan (TEC)
- J. Hikurangi
- K. Parkfield
- L. S-NET/DONET/N-NET

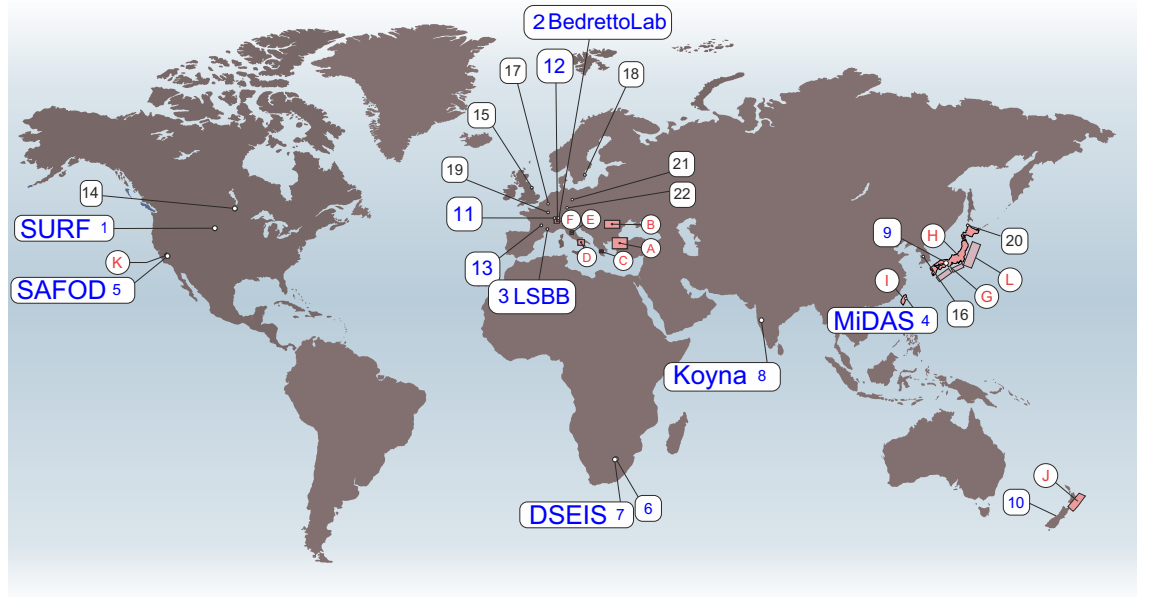


FIG. 3. Only a small number of On-Fault Observatories have been built to date. Most of the existing Underground Research Laboratories (URLs, black) and Near-Fault Observatories (NFOs, red) do not host monitoring equipment directly on geologic target structures, but they provide complementary information and insights.

Box 2: Key observables

All six key observables that underpin earthquake mechanics can vary strongly, over a wide range of space and time scales, including over very small scales. Critically, they are coupled: pore pressure determines effective stress, coseismic slip generates heat, fault dilation can reduce pressure, among others.

Geology The boreholes and tunnels of an OFO facilitate an unusually detailed in-situ characterization of target fault zones and host rocks, with the established range of borehole logging and characterization methods [75, 76]. Drill cores provide samples for accompanying rock mechanic laboratory studies, which constrain the petrophysical properties of host rock and fault zone materials [e.g. 77].

Strain of a fault zone usually has to be inferred via inversions of off-fault data. For large earthquakes its surface expression can be monitored with airborne imaging methods. With strain probes in fault-crossing boreholes, deformation can be measured directly on the fault instead. State-of-the-art probes have the sensitivity and resolution to measure even very low amplitude signals, e.g. from subtle phenomena like micrometer-scale pre-seismic fault dilation [78]. Somewhat less sensitive but spatially continuous measurements are possible with downhole Distributed Acoustic (DAS) and Strain (DSS) sensing technologies [11].

Stress field amplitudes and orientations can be measured along boreholes with a wide range of active and passive borehole methods [79], e.g. to infer how stress fields vary and rotate around individual structures and prominent fault zones [80], or before and after major ruptures [e.g. 81]. Furthermore, average stress fields can be estimated indirectly across larger rock volumes, e.g. by inverting earthquake focal mechanisms [82–85] using sensitive seismic networks deployed in close proximity to a target fault zone.

Pressure and fluid flow can be measured on faults with e.g. with quartz gauges, or via flow lines that connect a pressure membrane installed in a borehole with a sensor at the borehole mouth [51]. However, constraining fluid fields with direct measurements will remain challenging: while fault strain may be dominated by a small number of important structures, hydraulic regimes may be very complicated, and affected by a distributed network of permeable structures.

Temperature measurements may constrain how much elastic strain energy is transferred coseismically to heat, and how this is distributed across the fault zone. They can also be diagnostic of fluid flow and break-throughs if e.g. an injection fluid has a different temperature than the host rock [86]. Similar to DSS, Distributed Temperature Sensing (DTS) with fault-crossing fiber optic cables can now provide distributed temperature measurements with up to centimeter spatial resolution at high sampling rates, and allow distinguishing between processes on individual fault strands (Figure 7).

Ground motion observations constrain seismicity, which is the only process that can be accurately characterized from some distance. Seismic sensors need to be close to the process zone but can largely be organised in an off-fault network. Seismic instrumentation may be designed to characterize both earthquake source properties and the medium properties that affect seismic wave propagation. Near-source observations can also constrain slip velocity, directly linking rupture kinematics to fault stress evolution and dynamic weakening processes. Multiple sensor types are necessary to cover the huge range of scales that seismic events encompass [7, 51].

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2.1 Passive On-Fault Observatories

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Passive OFOs extend the monitoring of active faults by using on-fault sensors to observe a wide range of faulting processes directly where they occur. A distributed strain sensing cable cemented into a fault-crossing borehole, for instance, can monitor slow fault shear or fault normal deformation with high sensitivity, and distributed across a fault zone. Because passive monitoring does not affect earthquake occurrence, it can be deployed on the most hazardous and relevant faults. Given the immense hazard that comes from such faults, it is remarkable how rare on-fault instrumentation remains. Here we briefly discuss some of the most notable passive OFO examples.

The San Andreas Fault Observatory At Depth (**SAFOD**) is a relatively deep passive OFO, consisting of a 2.7

149

150 km vertical fault-crossing borehole and a 2.2 km vertical pilot borehole. It was drilled to study the physical and
 151 chemical processes controlling faulting and earthquake generation along a major plate boundary fault [28]. Mechanical
 152 properties of the drill cores and stress measurements confirm that the fault is operating at low effective stress [87, 88].
 153 Borehole seismometers have recorded repeating earthquakes Mw -3 to 2 at distances of 150 m or less over the past
 154 2 decades multiple times. The larger events, Mw 0 to 2, are observed to begin abruptly, reaching a dynamic stress
 155 drop of several MPa in 1 millisecond or less and without evidence of a slow seismic nucleation phase [89]. The
 156 harsh conditions within the fault zone presented major challenges for long-term operation of instruments, with most
 157 seismometer deployments limited to 2-3 years, most recently in 2022-2024. Since April 2026, an optical fiber with a
 158 DAS interrogator has been recording the continuous seismic wavefield over a broad frequency range from near- to the
 159 far field, above a geophone sensor at ca 2.5 km in the borehole.

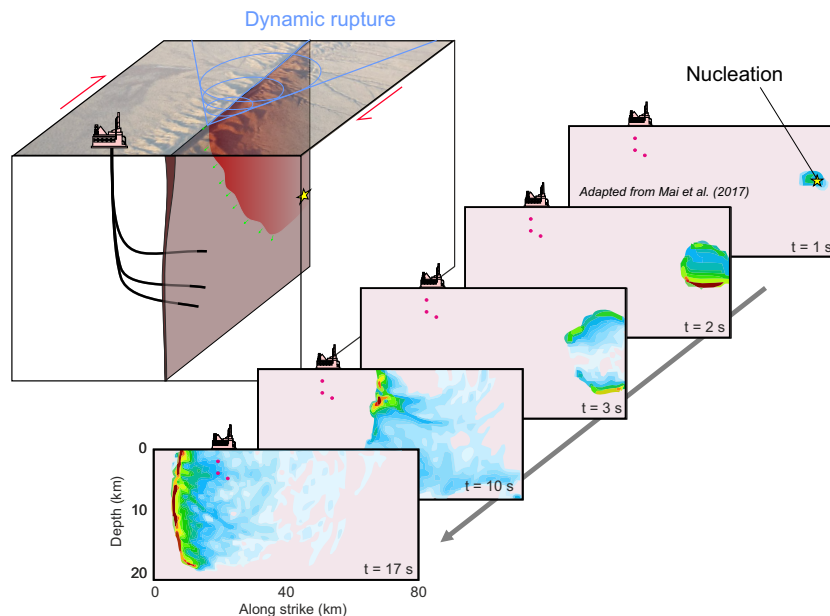


FIG. 4. Schematic depiction of a large-scale, passive, long-term OFO on a major plate-boundary fault. The boreholes that cross the target fault at various depths and locations facilitate high-sensitivity on-fault measurements during inter-, co- or post-seismic phases.

160 In the **DSeis** project in the Moab Khotsong mine (South Africa), inclined boreholes drilled from a mine shaft at
 161 2.9 km depth reached the rupture volume of the 2014 ML 5.5 Orkney earthquake [38, 90, 91]. DSeis represents
 162 an end-member OFO, focused primarily on in-situ characterization of a fault that had already ruptured rather than
 163 on continuous monitoring of an active fault. The **Koyna** region in the southern Deccan Traps, India, suffered the
 164 largest reservoir-triggered earthquake (1967 Mw 6.3), in addition to seismicity driven by monsoon-related water-
 165 level changes of the Koyna reservoir [40, 41]. Exploratory drilling to 1.0 - 1.5 km at 9 sites in 2012-2014 revealed
 166 granitic basement directly below the Deccan Traps basalt. These holes were instrumented with seismometers to better
 167 constrain hypocentral locations of reservoir triggered seismicity [92], defining a target location for drilling the source
 168 fault of the M6.3 at approximately 6 km depth. A 3 km deep pilot hole was successfully drilled in 2016-2017 and a
 169 dedicated research laboratory was constructed nearby [93]. As of this writing, preparations are being made for the
 170 drilling of the 6 km deep main hole into the active microearthquake zone.

171 The **MiDAS** (Milun-fault Drilling and All-inclusive Sensing) project established one of the first 3D distributed
 172 optical-fiber sensing networks across an active fault zone, integrating surface and borehole distributed acoustic and
 173 temperature sensing observations with a 700 m deep fault-crossing borehole. The system enables continuous high-
 174 resolution monitoring of strain and fault-zone behavior under both natural and dynamic perturbations. Initial obser-
 175 vations reveal strong strain amplification within a narrow fault core (~ 20 m wide), reflecting significant mechanical
 176 contrasts associated with weak fault gouge materials [10, 36].

177 These selected passive OFOs demonstrate that, despite all technical challenges, on-fault instrumentation can be
 178 installed and maintained at considerable, seismically relevant depths. Furthermore, the hardware innovations from
 179 the past two decades have substantially raised the scientific potential of such installations. Distributed fiber optic

sensing techniques now provide simple and robust multi-disciplinary measurements, along entire boreholes, without any electronics downhole. Continuous innovation in borehole logging probes lead to equipment that operates robustly even in extreme conditions [e.g. 94–96], and innovative drilling techniques increase the possibilities for OFO design, all while reducing drilling costs [97].

Of course, even with the most advanced technologies, there are fundamental limitations to what passive OFOs can deliver. Boreholes can reach only the uppermost portion of the seismogenic zone, leaving deeper portions beyond the scope of direct observation. Arguably the most significant limitation lies in the low recurrence rates of large events: even on the most active faults, medium-to-large earthquakes may not happen for decades or even centuries. Thus, most passive OFOs will primarily capture interseismic and transient fault processes rather than large ruptures. If an OFO does manage to capture a large earthquake during its operational lifetime, on-fault data of e.g. strain and temperature evolutions would likely be the most direct and constraining observations made for large ruptures to date. Rapid drilling operations after major ruptures can further enable the study of post-seismic processes [98, 99].

Complementary approaches are therefore needed to study faulting physics under more controlled conditions, where the processes we aim to understand can be deliberately induced.

2.2 Active On-Fault Observatories

In active OFOs, faulting processes are induced with fluid injections or alternative activation mechanisms, in proximity to the placed on-fault instrumentation. Over the past decade, a small number of such fault activation experiments have been realized with on-fault instrumentation, at relatively small (metre- to hecto-metre) scales, on natural faults, with largely natural stress, lithological and hydro-mechanical conditions. Deliberately activating densely instrumented target faults in this manner opens a new and more controlled avenue for studying faulting processes. The main challenge is to reach experiment depths and scales that are representative of natural faulting processes. At the depth ranges where active OFOs can realistically be built, a wide range of monitoring equipment can be installed on-fault, in both open and cemented boreholes (**Figure 7**).

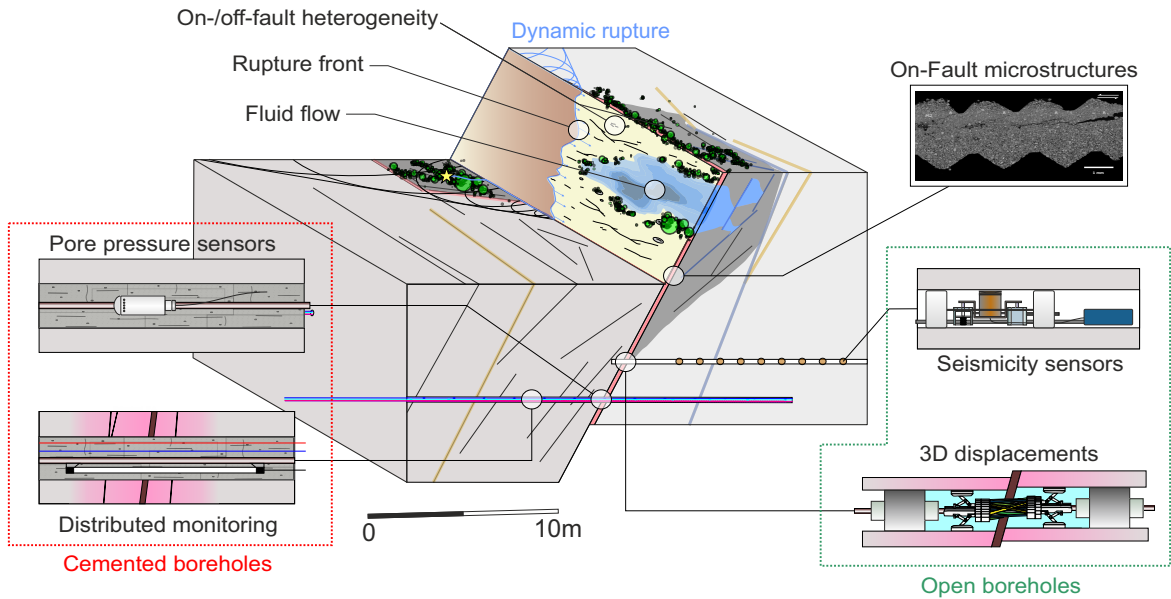


FIG. 5. Active OFOs facilitate the deliberate activation of massively instrumented natural fault zones in places where this can be done safely. Cemented fault-crossing boreholes support e.g. across-fault distributed fibre optic sensing and pore pressure measurements. Open boreholes accommodate e.g. probes measuring three-dimensional displacement across the fault, and can be re-instrumented over time.

The Low-Noise Underground Laboratory (**LSBB**) in Rustrel, France pioneered the use of “SIMFIP” probes [78] to measure flow-rate, pressure and in-situ 3D strain directly at the injection point, with high sensitivity, on a ~ 280 m deep natural fault zone in carbonate rocks [49]. They have been able to resolve how subtle (<1 mm) fault dilation preceded the ensuing aseismic shear deformation. This is the scale of microphysical processes that may govern fault

stability, but which could never be resolved with a surface monitoring array, however dense it may be.

The Sanford Underground Research Facility (**SURF**) in South Dakota, USA, is a deep underground laboratory with a focus on particle and astro-physics [100], but it also hosts intensely monitored fluid injection and fault activation experiments, notably the EGS Collab project [52, 53, 86]. They use multi-domain 3D monitoring arrays to study how fault and fracture networks form and activate in response to 10 m scale fluid stimulations at depths of up to 1.5 km. They use distributed acoustic, strain and temperature sensing, in boreholes that cross active geologic target structures. With this set-up they can observe e.g. fluid breakthroughs via their temperature signature, and establish whether strain excursions on the same structures occur before, during or after the breakthrough [86]. The experiments also serve as in-situ validation testbeds for digital geothermal reservoir models (see Section 4).

The Earthquake Physics Testbed (**ETB**) at the BedrettoLab in Switzerland facilitates fault activation experiments at the 100 m scale, on a heavily instrumented natural Alpine target fault zone at a depth of >1 km [54]. The testbed was constructed between 2023 - 2026 for the Fault Activation and Earthquake Rupture (FEAR) project, with the goal of inducing $M_w \sim 1.0$ earthquakes via fluid injection. The monitoring array consists of >10 fault-crossing and >30 near-fault boreholes, and a 110 m long fault-parallel access tunnel. The instrumentation combines SIMFIP probes and fault-crossing high resolution DAS, DSS and DTS fibre optic sensing systems, with a dense 3D multi-scale, extremely broadband (0 - 100,000 Hz) high-resolution seismic network. The monitoring and hydraulic control systems are remotely controlled.

Major ETB experiments typically trigger several thousand to tens of thousands of events spanning up to six magnitude units. Because hypocenter location errors are on the order of a few cm [101], the resulting seismicity distributions resolve the 3D geometry of the activated fault and fracture networks in detail (**Figure 6**). The resolved magnitude range of 6 units ($M_w \sim -5$ to 1) is at least equivalent to the range that passive regional networks accumulate over years to decades (e.g. $M_1 - M_7$). At the same time, active OFOs like the ETB can provide a wide range of complementary direct observations of strain, pressure and other key observables that are rarely available for natural, tectonic seismicity.

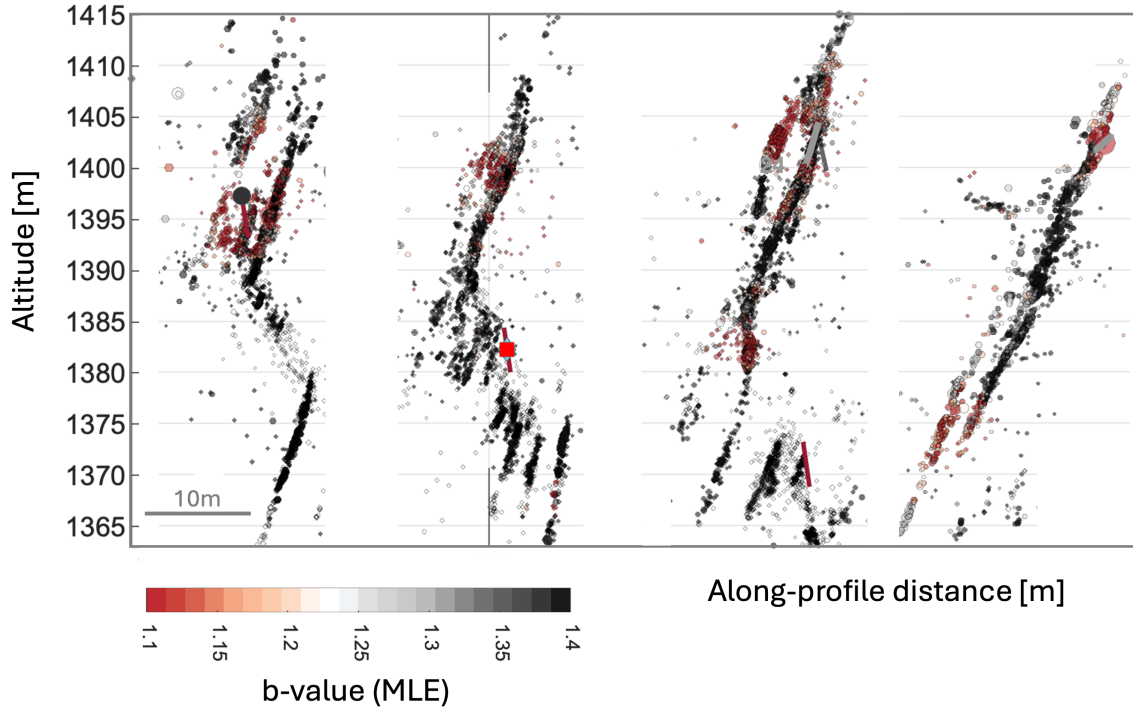


FIG. 6. Four vertical profiles through 8,900 micro-earthquakes (coloured circles) induced in a BedrettoLab fault activation experiment with magnitudes ranging from $M_w -5.0$ to -0.5 . The activated fault and fracture network spans tens of metres, and its detailed 3D geometry is revealed by micro-seismicity. Gutenberg-Richter b-values show that larger magnitude events are more probable in certain parts of a natural fault network (red colours), often around geometric network complexities. Events within ± 1 m of the profile plane are shown. Injection interval is highlighted with a red square.

Beyond these selected examples, there are additional relevant laboratories, including the Tournemire laboratory in France, and sections of the Grimsel Test Site [102] and Mont Terri Underground Research Laboratory in Switzerland [103]. Many of the other existing URLs (**Figure 3**) have not been designed to study faulting processes and focus on

other topics instead. They often produce insights that are of high relevance for earthquake science, but they do so without on-fault instrumentation on specific target faults, and hence would not qualify as OFOs.

Can we control fault activation? Our ability to study dynamic rupture processes in active OFOs critically hinges on our ability to induce earthquakes within a limited magnitude window. Events must not exceed a critical magnitude, so as not to pose a threat to nearby people and infrastructure or to the observatory itself. At the same time, they must be large enough so that the details of rupture evolution can be resolved with the installed instrumentation. For the former, careful site selection and state-of-the art risk analysis are paramount [e.g. 104].

Reaching sufficiently large magnitudes is generally challenging at the relatively shallow depth ranges at which active OFOs can be realised. It is yet unclear to what extent induced dynamic ruptures can be maintained, in the relatively low-stress conditions that prevail at such depths [67]. In fluid injection experiments, we often find distinct correlations between injection volumes and flowrates with the number of induced events [e.g. 105, 106], or maximum induced magnitudes [e.g. 107–110], albeit with strong variability. However, the largest events often occur in unforeseen locations, at considerable distance from the injection intervals [e.g. 45], and with substantial delays [e.g. 111]. This makes it more difficult to capture the dynamic rupture processes with installed on-fault instrumentation. More tightly controlling fault activation via injection protocols and laboratory infrastructure will be an important branch of research that affects the scientific and practical potential of active OFOs.

Synergies with industry and infrastructure Access to faults at depth will be a major cost driver for future OFOs. In this context, the current development of large-scale enhanced geothermal systems (EGS) offers important synergies. Because larger induced earthquakes are a major risk for EGS operators, there is a shared interest in understanding what controls them. Operators may be willing to allow research institutions to instrument fault zones within or adjacent to their reservoirs. Research institutions profit from the fluid injection infrastructure, while EGS operators gain from lower monitoring costs, from research insights on how to prevent fault activation, and from increased public and regulatory acceptance. Similar synergies exist with large-scale infrastructure projects, most notably tunnels that cross major fault zones [e.g. 112]. Basic passive monitoring, for instance with along-tunnel cemented fibre-optics sensing cables, can be installed at limited additional costs. At the same time, such instrumentation supports structural and tunnel health monitoring during construction and operation, rapid impact assessment during or after incidents such as fires, rock bursts or train derailments and next-generation earthquake early warning (EEW) systems [113].

3 Scientific potential of On-Fault Observatories

Direct on-fault measurements of the key observables (Box 2), in both passive and active OFOs, can resolve several long-standing questions in earthquake physics. In the following we list a selection of questions where OFO observations can lead to a decisive advance.

Preparatory processes and precursory signals

Precursory phenomena have been reported to occur prior to some large earthquakes, including changes in seismic [57, 114] and aseismic deformation [115, 116], as well as a degradation in near-fault zone properties [56], but their prognostic value remains unproven. It is unclear whether such signatures systematically precede earthquakes and how their occurrence and characteristics scale with event magnitude. When reported, they are often subtle and, in the absence of direct on-fault measurements, require substantial data processing or inversion, leaving their interpretation strongly debated [117]. While precursory signals are often and readily observable in laboratory experiments [e.g. 118–121], they may be near — or potentially below — the noise floor in natural scale observatories [8], making it challenging to determine if they are ubiquitous also at the natural scale [3, 58, 122]. The proximity of OFO instrumentation to the process zone can facilitate the high-sensitivity measurements needed to detect and characterize potential precursory signals, or to rule out their presence with confidence.

Hydro-mechanics of natural fault zones

On-fault pressure and temperature observations will help constrain realistic, natural fluid regimes. With such data we can move beyond simplistic models of diffusive or isotropic flow, and towards more accurate representations of complex, channelized flow in real rock [124, 125]. Furthermore, post-rupture drilling campaigns in active OFOs will facilitate a direct comparison of pre- and post-rupture microstructures. This may reveal how complex hydro-mechanic flow regimes develop in the first place, e.g. when faulting-induced growth of clays and other minerals affect fracture permeability [126], or when cross-fault permeability is reduced by localized, fine-grained shear structures [127–129].

Slow fault deformation

Slow fault deformation may play an important role in earthquake preparation, nucleation, and stress redistribution [130, 131], yet its spatial extent and relation to seismic slip remain difficult to constrain without on-fault measurements.

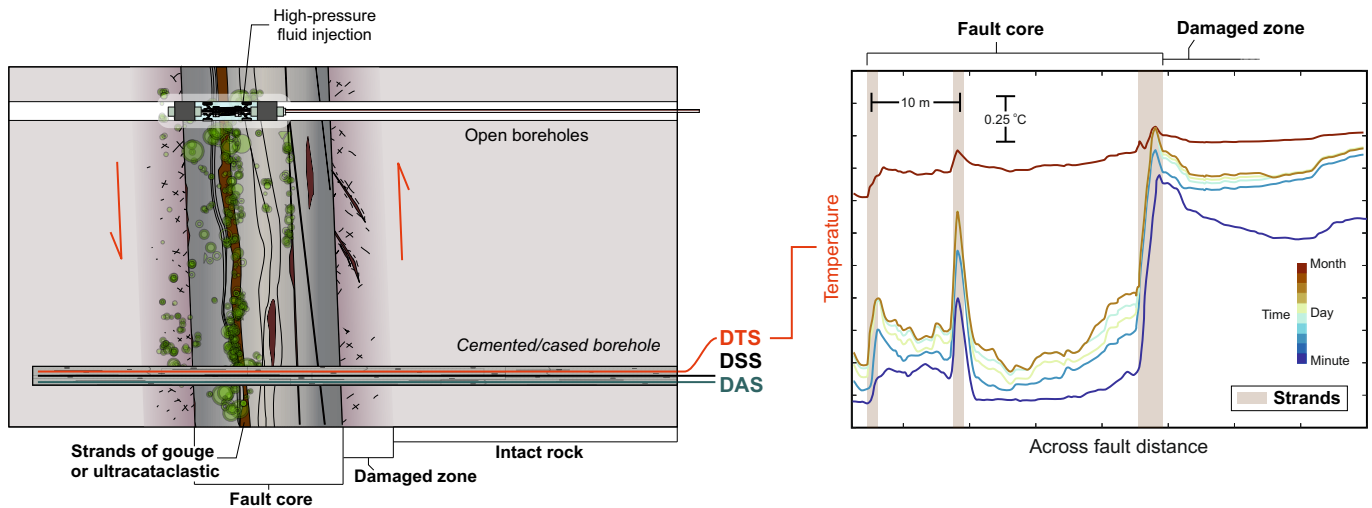


FIG. 7. Distributed sensing in fault-crossing boreholes facilitates measurements of e.g. how temperature, strain and pressure vary across a complex fault zone. Fluid injections and pressure measurements can be made in open boreholes with packer systems. A hypothetical example of temperature profiles across a complex fault zone is shown in the right panel [inspired by 123].

Collocated pressure and strain measurements will verify proposed mechanisms for slow fault deformation [130] in real geology and across the fault core.

Rupture energy balance and rupture dynamics

One major knowledge gap in seismology is that we lack a detailed understanding of how stored tectonic strain energy is dissipated and partitioned into fracture energy sustaining rupture front propagation, frictional heat (i.e., on-fault frictional dissipation) and damage (i.e., off-fault energy dissipation) during dynamic ruptures [64, 132]. In particular, our understanding of energy dissipation near the rupture front relies on conceptual models and theoretical assumptions about shear stress evolution during fault dynamic weakening. Direct observations of rupture-induced heat anomalies exist only in a handful of cases, and all of them have been made with significant delay [98, 133, 134]. They suggest that frictional dissipation is of the same order as radiated seismic energy [99]. Recording thermal anomalies as they occur, e.g. on a fault-crossing cemented DTS cable (**Figure 7**) [86, 123] would constrain the frictional energy budget directly, up to the point where the cable may rupture.

Rupture termination

How ruptures arrest is inherently hard to study, and fundamentally important, since it determines the final size of an earthquake. Do larger ruptures terminate abruptly at structural complexities, with corresponding stress field anomalies [65]? Or are they self-arresting, stopping more gradually as the available elastic driving stress is used up and the rupture energy balance becomes negative [67]? Most tectonic earthquakes occur on fault zones whose geometry is poorly known. The detailed fault zone characterisation and dense observations enabled by OFOs (Figure 6) allow us to study rupture dynamics within a known structural framework and identify observational signatures, including in the near-field seismic radiation, that may distinguish different arrest mechanisms.

Co-seismic fault weakening

The dramatic reduction in shear resistance that occurs at the rupture front as it propagates along a fault is one of the most fundamental — and at the same time most under-constrained — aspects of dynamic rupture, controlling stress drop, fracture energy, and seismic radiation [135, 136]. Numerous mechanisms have been proposed to explain this dynamic weakening [e.g. 137–140]. They operate across scales, from microscopic asperity interactions to deformation across the principal slip zone, and are strongly coupled to pore-fluid pressure and fault-zone temperature. Direct on-fault measurements are needed to constrain the evolution of stress, pressure, and temperature during rupture and discriminate among competing proposed weakening mechanisms [26, 141].

High-resolution seismic source characterization

OFO seismic arrays can resolve source processes that are difficult to access with conventional networks. Their key advantage is proximity: on-fault recordings better constrain the spatial and temporal evolution of rupture, including rapid slip processes, while reducing propagation effects and preserving the high-frequency radiation needed to resolve small-scale source complexity. This is evident from the recordings of an induced M_w -0.95 event at the BedrettoLab [123] (**Figure 8**): sensors that recorded the event from <150 m allow an essentially unperturbed estimation of the

source corner frequency ($f_c^{source} \sim 370 \text{ Hz}$) and corresponding static stress drop ($\Delta\sigma \sim 2 \text{ MPa}$). Records from larger distances ($> 1\text{km}$) have apparent corner frequencies that are strongly reduced by the low-pass filtering effect of anelastic attenuation ($f_c^{apparent} \sim 60 \text{ Hz}$). The joint availability of on- and near-fault records thereby also provide a strong test for the ubiquitously used attenuation models in standard seismic monitoring.

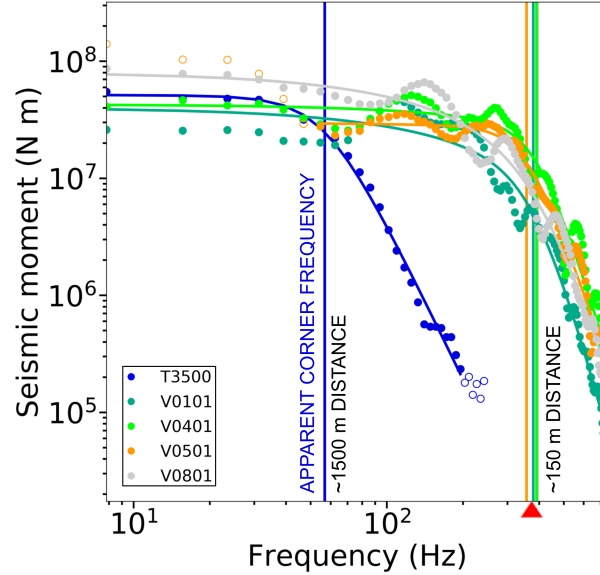


FIG. 8. Short distance ($\sim 150 \text{ m}$) recordings from an OFO seismic array provide minimally perturbed estimates of the true source corner frequency f_c^{source} (vertical bars, and red triangle) from observed displacement amplitude spectra (dots). More distant ($\sim 1500 \text{ m}$) records are strongly affected by anelastic attenuation, and yield apparent corner frequencies $f_c^{apparent} \ll f_c^{source}$. The spectral inversions [142] assume a generalized Brune's model (fitted lines) [143].

Earthquake forecasting and blind prediction experiments

Active OFOs may also enable the controlled community forecasting experiments and prospective in-situ hypothesis tests that the earthquake sciences largely lack today. Before a fault activation experiment, competing models, from statistical models to 3D dynamic rupture and seismic cycle simulations and scientific machine learning algorithms, may forecast seismicity, maximum rupture size, arrest locations, or energy partitioning, conditioned on the measured stress, structure and hydraulic state prior the experiment. Models that assimilate on-fault observations, e.g. of aseismic slip and pore pressure, can be compared to simpler, established models within community frameworks for transparent, prospective forecast testing [144, 145]. Repeated over successive experiments, such blind tests will help to establish which model ingredients are necessary to capture natural faulting behavior, to better quantify the predictive limits of current earthquake physics-based modeling, and to establish which observables need to be better monitored on natural faults to better anticipate large earthquakes.

4 Building On-Fault Observatories

Today, it is challenging but possible to build the OFOs that provide the data to advance the science objectives described above. OFO design requires the navigation of numerous trade-offs, e.g. between spatial resolution, target depth and cost. Drilling deep or numerous boreholes is expensive, not only because of direct drilling costs, but also due to the extensive logistical and operational infrastructure required. Increasing the number of boreholes allows for more distributed sensor placement and more comprehensive sampling of the fault zone. Yet, each additional borehole raises costs and introduces operational and geological risks: every borehole perturbs the fault zone to some degree and can potentially alter the very processes an observatory seeks to monitor. Instrumentation trade-offs arise because of the wide range of relevant observables and scales: Ideally, one could monitor all relevant observables at each borehole/fault intersection. In practice, there are strong limitations on the number and type of sensors that can be placed in each borehole, or borehole section.

Drilling through fault zones

Generally, drilling through faults and instrumenting such boreholes tend to be challenging endeavors, with serious

technical and operational risks. While advanced drilling techniques have substantially expanded the design possibilities for OFOs, fault zones tend to be mechanically weak, which can cause borehole instability, deviation, or collapse [28, 134]. Borehole probes can get stuck at depth, and potentially prevent further access to the target fault zone. Borehole trajectories can be deflected as they approach mechanically distinct fault materials, as experienced in Hole A from the DSeis project [38]. Intersecting active or fluid-rich faults can also trigger water inflows, and mud and gas outflows, complicating both drilling and instrumentation [38, 47, 146].

Furthermore, fault zones are extreme environments for instrumentation. High temperatures, elevated pore pressures, increasing lithostatic stresses, chemically aggressive fluids, and boreholes stability and integrity can lead to rapid sensor degradation and failure. Locating electronic components outside the borehole is possible for some sensor types but not for all. Weak amplitude ground motion signals, for example, usually need to be pre-amplified at short distances to the sensor, i.e. inside the borehole. This is one key advantage of distributed fiber-optic systems: they can operate passively over long distances with minimal electronics in situ.

Digital On-Fault Observatories

To realize the full scientific potential of OFOs, they need to be embedded in modern digital environments that dynamically couple the extensive OFO data streams with fault-process models in a two-way feedback loop. In one direction, OFO observations parameterize and validate faulting process models: modern computational methods simulate seismic and aseismic slip across geometrically complex fault systems, including cascading ruptures, the evolution of fluid pressure, temperature and off-fault damage [e.g., 29, 147, 148]. In-situ measurements of fault geometry, stress state and hydro-mechanical properties constrain the model set-up, while model predictions, e.g. of rupture nucleation, style and extent, or co-seismic temperature evolution, can be tested against, and falsified by, the on-fault measurements. In the reverse direction, models help design and operate the observatories themselves: experiment simulations predict where signals are expected and at what amplitudes, and can thereby be used to optimize borehole layouts, sensor placement and required instrument sensitivities before drilling begins. In this sense, a digital OFO is not merely a data portal but a digital twin of the instrumented fault zone: an evolving virtual representation that is continuously updated with assimilated observations, has predictive capability, and informs decisions [e.g., 149–153].

A prerequisite is an analysis- and model-ready data environment. Systematic data management for OFOs is a challenge in its own right, because of large data volumes and the large variety of data types [e.g., 54]. Distributed acoustic sensing alone can generate terabytes of data per day [e.g. 154, 155]. These data streams need to be quality-controlled and openly archived following FAIR principles [156], building on the data infrastructures developed for NFOs [6], preserving sensor metadata and measurement uncertainty, allowing model- and AI-ready representations of the physical OFO. Open access to data, models, and testing workflows will extend each observatory beyond its physical site and operational lifetime, allowing the wider community to reproduce analyses, benchmark methods, conduct virtual experiments, and test hypotheses against on-fault observations.

A bold research agenda to understand earthquake physics

Despite the challenges, building OFOs is what we — the earthquake science community — need to do if we are to advance our understanding of faulting physics, and to achieve a step-change in how we manage earthquake hazard and risk. The risks and challenges of OFO operations are offset by the high potential gains: earthquakes represent ~25% of global economic disaster losses, kill tens of thousands of people per year on average, and have caused trillions (USD) in economic losses over the last half century [157]. With the strong growth of mega-cities in direct proximity with often unknown active fault zones, global seismic risk will continue to increase [158]. We need on-fault instrumentation in order to advance on a large number of fundamental science questions, which have remained unanswered for decades. With the continuously improving technical capabilities for borehole drilling, instrumentation and data management, placing instrumentation on-fault is now mainly a matter of priorities. How do we allocate the available research funding, to reach the best improvements of the risk mitigation products we can offer to society?

Given the importance of the earthquake problem, the current level of existing on-fault instrumentation is surprisingly low. As it stands, one of the most active and best-studied faults in the world — the San Andreas Fault — hosts one single fault-crossing borehole with a DAS cable and one geophone. We propose the wider earthquake science community make full use of today’s technical opportunities, and strongly expand their efforts to place monitoring equipment directly onto, close to, and around natural fault zones. These efforts should include OFO construction across the entire spectrum of possibilities. With passive OFOs, we can strongly improve the monitoring of some of the world’s most relevant faults, by extending existing regional network and NFO infrastructure, in line with a key-science theme of the International Continental Scientific Drilling Programme [159]. With active OFOs, we achieve a more controlled way to study faulting processes, with massively instrumented in-situ research facilities. The success of such ambitious efforts will crucially depend on the long-term commitment to build, use, and maintain observational facilities on a large scale, which is common in other science domains [160], and which can only be achieved by the collective

and coordinated action of numerous stakeholder institutions, from academia, civil engineering, social sciences, and beyond.

Activating large-scale faults?

The highest scientific potential may lie in the implementation of an active OFO on a large natural fault. That is, to instrument a fault that is able to host large events, and then to purposefully induce large-magnitude ruptures on it. Such an OFO would necessarily have to be located in an isolated part of the world, where no people can be harmed and not much infrastructure is at stake. Potential candidate sites that have been discussed for such experiments include transform faults at a mid-ocean ridge, or onshore faults far from population centers, e.g. in a desert [48]. On-fault instrumentation will be a crucial element for such a high-stakes experiment.

The need for better earthquake risk mitigation products is urgent, and all technology to create OFO infrastructure exists. Arguably, the conditions have never been better for the earthquake science community to come together, and to build OFOs, in a bold attempt to move our understanding of earthquake physics forward.

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- [1] S. Wiemer, D. Giardini, D. Fäh, N. Deichmann, and S. Sellami, Probabilistic seismic hazard assessment of switzerland: best estimates and uncertainties, *Journal of Seismology* **13**, 449 (2009).
 - [2] T. E. Tullis, Rock friction and its implications for earthquake prediction examined via models of parkfield earthquakes, *Proceedings of the National Academy of Sciences* **93**, 3803 (1996).
 - [3] A. Kato and Y. Ben-Zion, The generation of large earthquakes, *Nature Reviews Earth & Environment* 10.1038/s43017-020-00108-w (2020).
 - [4] C. H. Scholz, L. R. Sykes, and Y. P. Aggarwal, Earthquake Prediction: A Physical Basis, *Science* **181**, 803 (1973).
 - [5] L. Chiaraluce, G. Festa, P. Bernard, A. Caracausi, I. Carluccio, J. F. Clinton, R. Di Stefano, L. Elia, C. Evangelidis, S. Ergintav, *et al.*, The near fault observatory community in europe: a new resource for faulting and hazard studies, *Annals of Geophysics* **65**, DM316 (2022).
 - [6] M. Cocco, C. Freda, K. Atakan, D. Bailo, K. S. Contell, O. Lange, and J. Michalek, The epos research infrastructure: a federated approach to integrate solid earth science data and services, *Annals of Geophysics* **65**, DM208 (2022).
 - [7] M. Bohnhoff and P. Malin, Borehole seismic networks and arrays, in *Encyclopedia of solid earth geophysics* (Springer, 2021) pp. 44–52.
 - [8] G. Kwiatek and Y. Ben-Zion, Theoretical limits on detection and analysis of small earthquakes, *Journal of Geophysical Research: Solid Earth* **121**, 5898 (2016).
 - [9] J. Blum, H. Igel, and M. Zumberge, Observations of rayleigh-wave phase velocity and coseismic deformation using an optical fiber, interferometric vertical strainmeter at the safod borehole, california, *Bulletin of the Seismological Society of America* **100**, 1879 (2010).
 - [10] H.-H. Huang, K.-F. Ma, E.-S. Wu, Y.-Z. Cheng, C.-J. Lin, C.-S. Ku, P.-L. Su, and M. W. Group, Spatiotemporal monitoring of a frequent-slip fault zone using downhole distributed acoustic sensing at the midas project, *Distributed Acoustic Sensing in Borehole Geophysics*, 459 (2024).
 - [11] Y. Sun, J. Liu, Z. Xue, Q. Li, C. Fan, and X. Zhang, A critical review of distributed fiber optic sensing for real-time monitoring geologic CO₂ sequestration, *Journal of Natural Gas Science and Engineering* **88**, 103751 (2021).
 - [12] M. Simons, Y. Fialko, and L. Rivera, Coseismic deformation from the 1999 m w 7.1 hector mine, california, earthquake as inferred from insar and gps observations, *Bulletin of the Seismological Society of America* **92**, 1390 (2002).
 - [13] J.-P. Avouac, F. Ayoub, S. Leprince, O. Konca, and D. V. Helmberger, The 2005, mw 7.6 kashmir earthquake: Sub-pixel correlation of aster images and seismic waveforms analysis, *Earth and Planetary Science Letters* **249**, 514 (2006).
 - [14] S. M. Mousavi and G. C. Beroza, Deep-learning seismology, *Science* **377**, eabm4470.
 - [15] S. M. Mousavi and G. C. Beroza, Machine Learning in Earthquake Seismology, *Annual Review of Earth and Planetary Sciences* **51**, 105 (2023), type: Journal Article.
 - [16] G. C. Beroza, M. Segou, and S. Mostafa Mousavi, Machine learning and earthquake forecasting—next steps, *Nature Communications* **12**, 4761 (2021).
 - [17] K. J. Bergen, P. A. Johnson, V. Maarten, and G. C. Beroza, Machine learning for data-driven discovery in solid earth geoscience, *Science* **363**, eaau0323 (2019).
 - [18] Q. Kong, D. T. Trugman, Z. E. Ross, M. J. Bianco, B. J. Meade, and P. Gerstoft, Machine learning in seismology: Turning data into insights, *Seismological Research Letters* **90**, 3 (2019).
 - [19] Z. E. Ross, M.-A. Meier, E. Hauksson, and T. H. Heaton, Generalized seismic phase detection with deep learning, *Bulletin of the Seismological Society of America* **108**, 2894 (2018).
 - [20] W. Zhu, S. M. Mousavi, and G. C. Beroza, Seismic Signal Denoising and Decomposition Using Deep Neural Networks, *IEEE Transactions on Geoscience and Remote Sensing* **57**, 9476 (2019).
 - [21] N. Dahmen, J. Clinton, S. Stähler, M.-A. Meier, S. Ceylan, F. Euchner, D. Kim, A. Horleston, C. Durán, G. Zenhäusern, C. Charalambous, T. Kawamura, and D. Giardini, Revisiting Martian seismicity with deep learning-based denoising, *Geophysical Journal International* **239**, 434 (2024).
 - [22] N. Dahmen, J. Clinton, M.-A. Meier, and L. Scarabello, Toward operational earthquake seismogram denoising, *Bulletin of the Seismological Society of America* **116**, 923 (2026).
 - [23] D. Trappolini, L. Laurenti, G. Poggiali, E. Tinti, F. Galasso, A. Michelini, and C. Marone, Cold diffusion model for seismic denoising, *Journal of Geophysical Research: Machine Learning and Computation* **1**, e2024JH000179 (2024).
 - [24] Y. Ben-Zion, Collective behavior of earthquakes and faults: Continuum-discrete transitions, progressive evolutionary changes, and different dynamic regimes, *Reviews of Geophysics* **46** (2008).
 - [25] P. Segall and J. R. Rice, Dilatancy, compaction, and slip instability of a fluid-infiltrated fault, *Journal of Geophysical Research: Solid Earth* **100**, 22155 (1995).
 - [26] B. Proctor, D. Lockner, B. Kilgore, T. Mitchell, and N. Beeler, Direct evidence for fluid pressure, dilatancy, and compaction affecting slip in isolated faults, *Geophysical Research Letters* **47**, e2019GL086767 (2020).
 - [27] L. Dal Zilio, N. Lapusta, and J.-P. Avouac, Unraveling scaling properties of slow-slip events, *Geophysical Research Letters* **47** (2020).
 - [28] M. Zoback, S. Hickman, W. Ellsworth, S. S. Team, *et al.*, Scientific drilling into the san andreas fault zone—an overview of safod’s first five years, *Scientific Drilling* **11**, 14 (2011).
 - [29] W. Zhao, M. An, L. Dal Zilio, L. Zhao, H. Zhu, X. Shen, Q. Gan, F. Zhang, and D. Elsworth, Coupled evolution of seismicity and permeability in fault zones, *Communications Earth & Environment* **6**, 918 (2025).
 - [30] R. H. Sibson, Crustal stress, faulting and fluid flow, Geological Society, London, Special Publications **78**, 69 (1994),

<http://sp.lyellcollection.org/content/78/1/69.full.pdf>.

- [31] W. L. Ellsworth, Injection-induced earthquakes, *Science* **341** (2013).
- [32] M. J. Moein, C. Langenbruch, R. Schultz, F. Grigoli, W. L. Ellsworth, R. Wang, A. P. Rinaldi, and S. Shapiro, The physical mechanisms of induced earthquakes, *Nature Reviews Earth & Environment* **4**, 847 (2023).
- [33] S. A. Shapiro, E. Huenges, and G. Borm, Estimating the crust permeability from fluid-injection-induced seismic emission at the ktb site, *Geophysical journal international* **131**, F15 (1997).
- [34] K. Tadokoro, M. Ando, and K. Nishigami, Induced earthquakes accompanying the water injection experiment at the nojima fault zone, japan: seismicity and its migration, *Journal of Geophysical Research: Solid Earth* **105**, 6089 (2000).
- [35] Y.-Y. Lin, K.-F. Ma, and V. Oye, Observation and scaling of microearthquakes from the taiwan chelungpu-fault borehole seismometers, *Geophysical Journal International* **190**, 665 (2012).
- [36] K.-F. Ma, S. von Specht, L.-W. Kuo, H.-H. Huang, C.-R. Lin, C.-J. Lin, C.-S. Ku, E.-S. Wu, C.-Y. Wang, W.-Y. Chang, *et al.*, Broad-band strain amplification in an asymmetric fault zone observed from borehole optical fiber and core, *Communications Earth & Environment* **5**, 402 (2024).
- [37] Z. Reches, Building a natural earthquake laboratory at focal depth (dafsam-nelsam project, south africa), *Scientific Drilling* **3**, 30 (2006).
- [38] H. Ogasawara, Y. Yabe, T. Ito, G. van Aswegen, A. Cichowicz, and R. Durrheim, Drilling into seismogenic zones of m2. 0–m5. 5 earthquakes in deep south african gold mines (dseis), *European Geosciences Union, General Assembly* (2016).
- [39] J. Townend, R. Sutherland, and V. Toy, Deep fault drilling project–alpine fault, new zealand, *Scientific drilling* **8**, 75 (2009).
- [40] H. K. Gupta, Reservoir triggered seismicity (rts) at koyna, india, over the past 50 yrs, *Bulletin of the Seismological Society of America* **108**, 2907 (2018).
- [41] R. Gomila, A. Chiesurin, E. Spagnuolo, S. Masoch, N. Preto, S. Roy, and G. Di Toro, Fault Zone Rocks Associated With the Reservoir-Triggered Seismicity of the Koyna-Warna Region (India), *Geophysical Research Letters* **52**, e2025GL115072 (2025).
- [42] M. O. Häring, U. Schanz, F. Ladner, and B. C. Dyer, Characterisation of the basel 1 enhanced geothermal system, *Geothermics* **37**, 469 (2008).
- [43] D. Giardini, Geothermal quake risks must be faced, *Nature* **462**, 848 (2009).
- [44] L. Li, K. Im, and J.-P. Avouac, Large-magnitude events unlikely in induced earthquake sequences, *Nature Communications* **17**, 4192 (2026).
- [45] F. Grigoli, S. Cesca, A. P. Rinaldi, A. Manconi, J. A. Lopez-Comino, J. F. Clinton, R. Westaway, C. Cauzzi, T. Dahm, and S. Wiemer, The november 2017 m w 5.5 pohang earthquake: A possible case of induced seismicity in south korea, *Science* **360**, 1003 (2018).
- [46] W. L. Ellsworth, D. Giardini, J. Townend, S. Ge, and T. Shimamoto, Triggering of the Pohang, Korea, earthquake (Mw 5.5) by enhanced geothermal system stimulation, *Seismological Research Letters* **90**, 1844 (2019).
- [47] S. Park, K.-I. Kim, L. Xie, H. Yoo, K.-B. Min, M. Kim, B. Yoon, K. Y. Kim, G. Zimmermann, F. Guinot, and P. Meier, Observations and analyses of the first two hydraulic stimulations in the Pohang geothermal development site, South Korea, *Geothermics* **88**, 101905 (2020).
- [48] H. M. Savage, J. D. Kirkpatrick, J. J. Mori, E. E. Brodsky, W. L. Ellsworth, B. M. Carpenter, X. Chen, F. Cappa, and Y. Kano, Scientific exploration of induced seismicity and stress (seisms), *Scientific Drilling* **23**, 57 (2017).
- [49] Y. Guglielmi, F. Cappa, J.-P. Avouac, P. Henry, and D. Elsworth, Seismicity triggered by fluid injection–induced aseismic slip, *Science* **348**, 1224 (2015).
- [50] L. De Barros, F. Cappa, Y. Guglielmi, L. Duboeuf, and J.-R. Grasso, Energy of injection-induced seismicity predicted from in-situ experiments, *Scientific reports* **9**, 4999 (2019).
- [51] K. Plenkers, A. Reinicke, A. Obermann, N. Gholizadeh Doonechaly, H. Krietsch, T. Fechner, M. Hertrich, K. Kontar, H. Maurer, J. Philipp, *et al.*, Multi-disciplinary monitoring networks for mesoscale underground experiments: Advances in the bedretto reservoir project, *Sensors* **23**, 3315 (2023).
- [52] T. J. Kneafsey, P. Dobson, C. Ulrich, C. Hopp, V. Rodríguez-Tribaldos, Y. Guglielmi, D. Blankenship, P. C. Schwing, M. Ingraham, J. A. Burghardt, *et al.*, The egs collab project–stimulations at two depths, in *ARMA US Rock Mechanics/Geomechanics Symposium* (ARMA, 2022) pp. ARMA–2022.
- [53] M. Schoenball, J. B. Ajo-Franklin, D. Blankenship, C. Chai, A. Chakravarty, P. Dobson, C. Hopp, T. Kneafsey, H. A. Knox, M. Maceira, *et al.*, Creation of a mixed-mode fracture network at mesoscale through hydraulic fracturing and shear stimulation, *Journal of Geophysical Research: Solid Earth* **125**, e2020JB019807 (2020).
- [54] M.-A. Meier, P. Selvadurai, V. Gischig, M. Hertrich, E. Tinti, A. P. Rinaldi, M. Jalali, E. Spagnuolo, A. Zappone, L. Dal Zilio, *et al.*, Activating a natural fault zone in the swiss alps, *Seismica* **5** (2026).
- [55] D. Faulkner, C. Jackson, R. Lunn, R. Schlische, Z. Shipton, C. Wibberley, and M. Withjack, A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones, *Journal of Structural Geology* **32**, 1557 (2010).
- [56] Y. Ben-Zion and I. Zaliapin, Localization and coalescence of seismicity before large earthquakes, *Geophysical Journal International* **223**, 561 (2020).
- [57] W. Ellsworth and G. Beroza, Seismic evidence for an earthquake nucleation phase, *Science* **268**, 851 (1995).
- [58] J. Gombert, Unsettled earthquake nucleation, *Nature Geoscience* **11**, 463 (2018).
- [59] G. C. Beroza and W. L. Ellsworth, Properties of the seismic nucleation phase, **261**, 209.
- [60] E. L. Olson and R. M. Allen, The deterministic nature of earthquake rupture, **438**, 212.
- [61] S. Ide and H. Aochi, Earthquakes as multiscale dynamic ruptures with heterogeneous fracture surface energy, *Journal of*

Geophysical Research: Solid Earth **110** (2005).

- [62] M.-A. Meier, T. Heaton, and J. Clinton, Evidence for universal earthquake rupture initiation behavior, *Geophysical Research Letters* **43**, 7991 (2016).
- [63] M.-A. Meier, J.-P. Ampuero, E. Cochran, and M. Page, Apparent earthquake rupture predictability, *Geophysical Journal International* **225**, 657 (2021).
- [64] M. Cocco, S. Aretusini, C. Cornelio, S. B. Nielsen, E. Spagnuolo, E. Tinti, and G. Di Toro, Fracture energy and breakdown work during earthquakes, *Annual Review of Earth and Planetary Sciences* **51** (2023).
- [65] R. H. Sibson, Stopping of earthquake ruptures at dilational fault jogs, *Nature* **316**, 248 (1985).
- [66] J. Kearsce and Y. Kaneko, Stopping phase reveals abrupt arrest of large strike-slip earthquakes, *Science*, eaef3733 (2026).
- [67] F. Mosconi, E. Tinti, M. Supino, A.-A. Gabriel, E. Casarotti, M.-A. Meier, A. P. Rinaldi, D. Giardini, and M. Cocco, Discriminating dynamic rupture arrest in fluid-induced microearthquakes using spectral inversion, *Earth and Planetary Science Letters* **678**, 119816 (2026).
- [68] C.-Y. Ke, G. C. McLaskey, and D. S. Kammer, Rupture termination in laboratory-generated earthquakes, *Geophysical Research Letters* **45**, 12 (2018).
- [69] R. J. Geller, Earthquake prediction: a critical review, *Geophysical Journal International* **131**, 425 (1997).
- [70] R. D. Cicerone, J. E. Ebel, and J. Britton, A systematic compilation of earthquake precursors, *Tectonophysics* **476**, 371 (2009).
- [71] W. H. Bakun, B. Aagaard, B. Dost, W. L. Ellsworth, J. L. Hardebeck, R. A. Harris, C. Ji, M. J. Johnston, J. Langbein, J. J. Lienkaemper, A. J. Michael, *et al.*, Implications for prediction and hazard assessment from the 2004 parkfield earthquake, *Nature* **437**, 969 (2005).
- [72] M. J. S. Johnston *et al.*, Continuous borehole strain and pore pressure in the near field of the 28 september 2004 m 6.0 parkfield, california, earthquake: Implications for nucleation, fault response, earthquake prediction, and tremor, *Bulletin of the Seismological Society of America* **96**, S56 (2006).
- [73] M. J. S. Johnston *et al.*, Seismomagnetic effects from the long-awaited 28 september 2004 m 6.0 parkfield earthquake, *Bulletin of the Seismological Society of America* **96**, S206 (2006).
- [74] M. D. Zoback and S. M. Gorelick, Earthquake triggering and large-scale geologic storage of carbon dioxide, *Proceedings of the National Academy of Sciences* **109**, 10164 (2012).
- [75] P. Montone, S. Pierdominici, M. T. Mariucci, F. Mirabella, M. Urbani, A. Akimbekova, L. Chiaraluce, W. Johnson, and M. R. Barchi, Geophysical downhole logging analysis within the shallow-depth icdp star drilling project (central italy), *Solid Earth* **15**, 1385 (2024).
- [76] P. Achtziger-Zupančič, A. Ceccato, A. S. Zappone, G. Pozzi, A. Shakas, F. Amann, W. M. Behr, D. Escallon Botero, D. Giardini, M. Hertrich, M. Jalali, X. Ma, M.-A. Meier, J. Osten, S. Wiemer, and M. Cocco, Selection and characterization of the target fault for fluid-induced activation and earthquake rupture experiments, *Solid Earth* **15**, 1087 (2024).
- [77] G. Volpe, G. Pozzi, C. Collettini, E. Spagnuolo, P. Achtziger-Zupančič, A. Zappone, L. Aldega, M. Meier, D. Giardini, and M. Cocco, Laboratory simulation of fault reactivation by fluid injection and implications for induced seismicity at the bedrettolab, swiss alps, *Tectonophysics* **862**, 229987 (2023).
- [78] Y. Guglielmi, F. Cappa, J. Rutqvist, C. Tsang, J. Wang, H. Lançon, J. Durand, and J. Janowczyk, Step-rate injection method for fracture in-situ properties (simfip): Monitoring fractures stimulation efficiency, in *ARMA US Rock Mechanics/Geomechanics Symposium* (Arma, 2014) pp. ARMA–2014.
- [79] B. Amadei and O. Stephansson, *Rock Stress and Its Measurement*, 1st ed. (Springer Dordrecht, 1997).
- [80] J. L. Hardebeck and E. Hauksson, Crustal stress field in southern california and its implications for fault mechanics, *Journal of Geophysical Research: Solid Earth* **106**, 21859 (2001).
- [81] M. Ickrath, M. Bohnhoff, F. Bulut, and G. Dresen, Stress rotation and recovery in conjunction with the 1999 izmit m w 7.4 earthquake, *Geophysical Journal International* **196**, 951 (2014).
- [82] A. J. Michael, Determination of stress from slip data: faults and folds, *Journal of Geophysical Research: Solid Earth* **89**, 11517 (1984).
- [83] J. L. Hardebeck and P. M. Shearer, A new method for determining first-motion focal mechanisms, *Bulletin of the Seismological Society of America* **92**, 2264 (2002).
- [84] V. Vavryčuk, Iterative joint inversion for stress and fault orientations from focal mechanisms, *Geophysical journal international* **199**, 69 (2014).
- [85] P. Martínez-Garzón, M.-A. Meier, C. Collettini, F. Lanza, and G. Dresen, Stress heterogeneities governed by fault structure and stress transfer: The 2016–2017 central italy seismic sequence, *Journal of Geophysical Research: Solid Earth* **130**, e2024JB029763 (2025).
- [86] T. Kneafsey, P. Dobson, D. Blankenship, P. Schwering, M. White, J. P. Morris, L. Huang, T. Johnson, J. Burghardt, E. Mattson, *et al.*, The egs collab project: Outcomes and lessons learned from hydraulic fracture stimulations in crystalline rock at 1.25 and 1.5 km depth, *Geothermics* **126**, 103178 (2025).
- [87] D. A. Lockner, C. Morrow, D. Moore, and S. Hickman, Low strength of deep san andreas fault gouge from safod core, *Nature* **472**, 82 (2011).
- [88] S. Hickman and M. Zoback, Stress orientations and magnitudes in the safod pilot hole, *Geophysical Research Letters* **31** (2004).
- [89] W. Ellsworth, From foreshocks to mainshocks: mechanisms and implications for earthquake nucleation and rupture propagation, in *Mechanics of Earthquake Faulting* (IOS Press, 2019) pp. 95–112.
- [90] Y. Yabe, S. Abe, G. Hofmann, D. Roberts, H. Yilmaz, H. Ogasawara, T. Ito, A. Funato, M. Nakatani, M. Naoi, *et al.*, Stress state in the source region of mw2. 2 earthquake in a deep gold mine in south africa determined from borehole cores,

Pure and Applied Geophysics **179**, 1679 (2022).

- [91] P. Voosen, Deep in a south african gold mine, scientists drill for the heart of an earthquake, *Science* (2017).
- [92] D. Shashidhar, P. Mahesh, S. Gupta, and K. Mallika, Sub-Basalt Velocity Image of the Main Seismogenic Fault at Koyna, an Intraplate Active Region in Western India, Using Borehole Seismic Network, *Seismological Research Letters* **97**, 897 (2026).
- [93] S. Roy, D. Goswami, V. V. Akkiraju, A. K. Sutar, S. Rohilla, C. Vishnu, and H. Chaube, New insights into recurrent reservoir triggered seismicity in koyna region, india from scientific deep drilling studies-a review, *Journal of the Geological Society of India* **101**, 748 (2025).
- [94] B. Holbein, breakthrough in permanent cooling of instrumentation electronics—results of systematic experimental & analytical refrigerant selection, dynamic seals evaluation and robust engine design,“, in *Geothermal Ressources Council, 42nd Annual Meeting* (2018) pp. 1–8.
- [95] R. Normann, C. Normann, J. Henfling, D. A. Glowka, and M. Soares, Development of a geothermal well inspection camera with active co2 cooling, *Geothermal Resources Council Transactions* **40** (2016).
- [96] J. Vedum, M. H. Røed, S. Kolberg, M. Hjelstuen, A. E. Liverud, and Ø. N. Starnes, Development of a novel logging tool for 450 ° c geothermal wells, in *Additional Conferences (Device Packaging, HiTEC, HiTEN, & CICMT)*, Vol. 2017 (International Microelectronics Assembly and Packaging Society, 2017) pp. 000011–000019.
- [97] R. Horne, A. Genter, M. McClure, W. Ellsworth, J. Norbeck, and E. Schill, Enhanced geothermal systems for clean firm energy generation, *Nature Reviews Clean Technology* **1**, 148 (2025).
- [98] F. M. Chester, J. J. Mori, S. Toczko, N. Eguchi, Y. Kido, S. Saito, Y. Sanada, L. Anderson, J. H. Behrmann, S. Bose, *et al.*, Integrated ocean drilling program expedition 343/343t preliminary report, japan trench fast drilling project (jfast), 1 april–24 may 2012 and 5–19 july 2012, Integrated Ocean Drilling Project Preliminary Report **343** (2012).
- [99] P. Fulton, E. E. Brodsky, Y. Kano, J. Mori, F. Chester, T. Ishikawa, R. Harris, W. Lin, N. Eguchi, S. Toczko, *et al.*, Low coseismic friction on the tohoku-oki fault determined from temperature measurements, *Science* **342**, 1214 (2013).
- [100] J. Heise, The sanford underground research facility at homestake, in *Journal of Physics: Conference Series*, Vol. 606 (IOP Publishing, 2015) p. 012015.
- [101] M. Roskopf, V. Durand, K. Plenkers, L. Villiger, D. Giardini, and A. Obermann, Accuracy of Picoseismic Catalogs in Hectometer-Scale In Situ Experiments, *Seismological Research Letters* **96**, 3814 (2025).
- [102] F. Amann, V. Gischig, K. Evans, J. Doetsch, R. Jalali, B. Valley, H. Krietsch, N. Dutler, L. Villiger, B. Brixel, *et al.*, The seismo-hydronechanical behavior during deep geothermal reservoir stimulations: open questions tackled in a decameter-scale in situ stimulation experiment, *Solid Earth* **9**, 115 (2018).
- [103] A. Zappone, A. P. Rinaldi, M. Grab, Q. C. Wenning, C. Roques, C. Madonna, A. C. Obermann, S. M. Bernasconi, M. S. Brennwald, R. Kipfer, F. Soom, P. Cook, Y. Guglielmi, C. Nussbaum, D. Giardini, M. Mazzotti, and S. Wiemer, Fault sealing and caprock integrity for CO2 storage: an in situ injection experiment, *Solid Earth* **12**, 319 (2021).
- [104] V. S. Gischig, A. P. Rinaldi, A. Alcolea, F. Bethman, M. Broccardo, K. Bröker, R. Castilla, F. Ciardo, V. Clasen Repollés, V. Durand, *et al.*, Updating induced seismic hazard assessments during hydraulic stimulation experiments in underground laboratories: workflow and limitations, *Solid Earth* **16**, 1153 (2025).
- [105] N. J. Van der Elst, M. T. Page, D. A. Weiser, T. H. Goebel, and S. M. Hosseini, Induced earthquake magnitudes are as large as (statistically) expected, *Journal of Geophysical Research: Solid Earth* **121**, 4575 (2016).
- [106] L. De Barros and D. Marsan, Theoretical maximum and cumulative seismic moment relationships confirm that injection volume controls the occurrence rate, but not the magnitude, of induced earthquakes, *Geophysical Research Letters* **53**, e2025GL117164 (2026).
- [107] A. McGarr, Seismic moments and volume changes, *Journal of geophysical research* **81**, 1487 (1976).
- [108] S. A. Shapiro, C. Dinske, C. Langenbruch, and F. Wenzel, Seismogenic index and magnitude probability of earthquakes induced during reservoir fluid stimulations, *The Leading Edge* **29**, 304 (2010).
- [109] A. McGarr, Maximum magnitude earthquakes induced by fluid injection, *Journal of Geophysical Research: solid earth* **119**, 1008 (2014).
- [110] M. Galis, J. P. Ampuero, P. M. Mai, and F. Cappa, Induced seismicity provides insight into why earthquake ruptures stop, *Science advances* **3**, eaap7528 (2017).
- [111] N. Deichmann and D. Giardini, Earthquakes induced by the stimulation of an enhanced geothermal system below Basel (Switzerland), *Seismological Research Letters* **80**, 784 (2009).
- [112] M. Petitta, M. Barberio, M. Barbieri, G. Cardello, V. Lorenzi, M. Manetta, E. Petrella, and C. Gissonni, Differentiating groundwater recharge flowpaths in fault-controlled karstic aquifers (gran sasso range, central italy): Structural, hydrochemical and isotopic investigations on the highway tunnel drainage, *Journal of Hydrology: Regional Studies* **65**, 103360 (2026).
- [113] S. Colombelli, A. Zollo, F. Carotenuto, A. Caruso, L. Elia, G. Festa, S. Gammaldi, A. G. Iaccarino, G. Iannaccone, A. Mauro, *et al.*, The first earthquake early warning system for the high-speed railway in italy: enhancing rapidness and operational efficiency during seismic events, *Natural Hazards and Earth System Sciences* **26**, 299 (2026).
- [114] K. Obara and A. Kato, Connecting slow earthquakes to huge earthquakes, *Science* **353**, 253 (2016).
- [115] Q. Bletery and J.-M. Nocquet, The precursory phase of large earthquakes, *Science* **381**, 297 (2023), <https://www.science.org/doi/pdf/10.1126/science.adg2565>.
- [116] E. A. Roeloffs, Evidence for aseismic deformation rate changes prior to earthquakes*, *Annual Review of Earth and Planetary Sciences* **34**, 591 (2006).
- [117] Q. Bletery and J.-M. Nocquet, Do large earthquakes start with a precursory phase of slow slip?, *Seismica* **3**, 10.26443/seismica.v3i2.1383 (2025).

- [118] J. H. Dieterich, Modeling of rock friction: 1. experimental results and constitutive equations, *Journal of Geophysical Research: Solid Earth* **84**, 2161 (1979).
- [119] M. Ohnaka and L.-f. Shen, Scaling of the shear rupture process from nucleation to dynamic propagation: Implications of geometric irregularity of the rupturing surfaces, *Journal of Geophysical Research: Solid Earth* **104**, 817 (1999).
- [120] M. M. Scuderi, C. Marone, E. Tinti, G. Di Stefano, and C. Collettini, Precursory changes in seismic velocity for the spectrum of earthquake failure modes, *Nature geoscience* **9**, 695 (2016).
- [121] G. C. McLaskey, Earthquake initiation from laboratory observations and implications for foreshocks, *Journal of Geophysical Research: Solid Earth* **124**, 12882 (2019).
- [122] P. Martínez-Garzón and P. Poli, Cascade and pre-slip models oversimplify the complexity of earthquake preparation in nature, *Communications Earth & Environment* **5**, 120 (2024).
- [123] V. S. Gischig, M.-A. Meier, A. Lambiase, D. Jiang, M. Hertrich, N. Gholizadeh Doonechaly, M. Jalali, A. P. Rinaldi, S. Aretusini, K. Behnen, *et al.*, Hydraulic stimulation experiments attempting to enhance induced seismicity for earthquake physics research, *Journal of Geophysical Research: Solid Earth* **131**, e2026JB033768 (2026).
- [124] B. Brixel, M. Klepikova, M. R. Jalali, Q. Lei, C. Roques, H. Kriestch, and S. Loew, Tracking fluid flow in shallow crustal fault zones: 1. insights from single-hole permeability estimates, *Journal of Geophysical Research: Solid Earth* **125**, e2019JB018200 (2020).
- [125] H. Kriestch, L. Villiger, J. Doetsch, V. Gischig, K. F. Evans, B. Brixel, M. Jalali, S. Loew, D. Giardini, and F. Amann, Changing flow paths caused by simultaneous shearing and fracturing observed during hydraulic stimulation, *Geophysical Research Letters* **47**, e2019GL086135 (2020).
- [126] J. P. Evans and F. M. Chester, Fluid-rock interaction in faults of the san andreas system: Inferences from san gabriel fault rock geochemistry and microstructures, *Journal of Geophysical Research: Solid Earth* **100**, 13007 (1995).
- [127] Z. K. Shipton, J. P. Evans, K. R. Robeson, C. B. Forster, and S. Snelgrove, Structural heterogeneity and permeability in faulted eolian sandstone: Implications for subsurface modeling of faults, *AAPG bulletin* **86**, 863 (2002).
- [128] S. Zhang and T. E. Tullis, The effect of fault slip on permeability and permeability anisotropy in quartz gouge, *Tectonophysics* **295**, 41 (1998).
- [129] J. P. Evans, C. B. Forster, and J. V. Goddard, Permeability of fault-related rocks, and implications for hydraulic structure of fault zones, *Journal of structural Geology* **19**, 1393 (1997).
- [130] R. Bürgmann, The geophysics, geology and mechanics of slow fault slip, *Earth and Planetary Science Letters* **495**, 112 (2018).
- [131] G. C. Beroza and S. Ide, Slow earthquakes and nonvolcanic tremor, *Annual review of Earth and planetary sciences* **39**, 271 (2011).
- [132] D. S. Kammer, G. C. McLaskey, R. E. Abercrombie, J.-P. Ampuero, C. Cattania, M. Cocco, L. Dal Zilio, G. Dresen, A.-A. Gabriel, C.-Y. Ke, *et al.*, Earthquake energy dissipation in a fracture mechanics framework, *Nature communications* **15**, 4736 (2024).
- [133] Y. Kano, J. Mori, R. Fujio, H. Ito, T. Yanagidani, S. Nakao, and K.-F. Ma, Heat signature on the chelungpu fault associated with the 1999 chi-chi, taiwan earthquake, *Geophysical Research Letters* **33** (2006).
- [134] H. Tanaka, W. Chen, C. Wang, K. Ma, N. Urata, J. Mori, and M. Ando, Frictional heat from faulting of the 1999 chi-chi, taiwan earthquake, *Geophysical research letters* **33** (2006).
- [135] A. H. Lachenbruch, Frictional heating, fluid pressure, and the resistance to fault motion, *Journal of Geophysical Research: Solid Earth* **85**, 6097 (1980).
- [136] J. R. Rice, Heating and weakening of faults during earthquake slip, *Journal of Geophysical Research: Solid Earth* **111** (2006).
- [137] H. Jeffreys, On the mechanics of faulting, *Geological Magazine* **79**, 291 (1942).
- [138] R. Sibson, Interactions between temperature and pore-fluid pressure during earthquake faulting and a mechanism for partial or total stress relief, *Nature Physical Science* **243**, 66 (1973).
- [139] J. Rice, Flash heating at asperity contacts and rate-dependent friction, *Eos Trans. AGU* **80**, F471 (1999).
- [140] E. E. Brodsky and H. Kanamori, Elastohydrodynamic lubrication of faults, *Journal of Geophysical Research: Solid Earth* **106**, 16357 (2001).
- [141] N. Brantut, Dilatancy-induced fluid pressure drop during dynamic rupture: Direct experimental evidence and consequences for earthquake dynamics, *Earth and Planetary Science Letters* **538**, 116179 (2020).
- [142] M. Supino, G. Festa, and A. Zollo, A probabilistic method for the estimation of earthquake source parameters from spectral inversion: application to the 2016–2017 central italy seismic sequence, *Geophysical Journal International* **218**, 988 (2019).
- [143] J. N. Brune, Tectonic stress and the spectra of seismic shear waves from earthquakes, *Journal of geophysical research* **75**, 4997 (1970).
- [144] D. Schorlemmer, M. J. Werner, W. Marzocchi, T. H. Jordan, Y. Ogata, D. D. Jackson, S. Mak, D. A. Rhoades, M. C. Gerstenberger, N. Hirata, *et al.*, The Collaboratory for the Study of Earthquake Predictability: Achievements and priorities, *Seismological Research Letters* **89**, 1305 (2018).
- [145] E. Király-Proag, J. D. Zechar, V. Gischig, S. Wiemer, D. Karvounis, and J. Doetsch, Validating induced seismicity forecast models—Induced Seismicity Test Bench, *Journal of Geophysical Research: Solid Earth* **121**, 6009 (2016).
- [146] T. Diehl, T. Kraft, E. Kissling, and S. Wiemer, The induced earthquake sequence related to the St. Gallen deep geothermal project (Switzerland): Fault reactivation and fluid interactions imaged by microseismicity, *Journal of Geophysical Research: Solid Earth* **122**, 7272 (2017).
- [147] P. Romanet, H. S. Bhat, R. Jolivet, and R. Madariaga, Fast and slow slip events emerge due to fault geometrical

- complexity, *Geophysical Research Letters* **45**, 4809 (2018).
- [148] K. H. Palgunadi, A.-A. Gabriel, D. I. Garagash, T. Ulrich, and P. M. Mai, Rupture dynamics of cascading earthquakes in a multiscale fracture network, *Journal of Geophysical Research: Solid Earth* **129**, e2023JB027578 (2024).
- [149] M. G. Kapteyn, J. V. R. Pretorius, and K. E. Willcox, A probabilistic graphical model foundation for enabling predictive digital twins at scale, *Nature Computational Science* **1**, 337 (2021).
- [150] P. Bauer, B. Stevens, and W. Hazeleger, A digital twin of Earth for the green transition, *Nature Climate Change* **11**, 80 (2021).
- [151] National Academies of Sciences, Engineering, and Medicine, *Foundational Research Gaps and Future Directions for Digital Twins*, Tech. Rep. (The National Academies Press, Washington, DC, 2024).
- [152] K. Willcox and B. Segundo, The role of computational science in digital twins, *Nature Computational Science* **4**, 147 (2024).
- [153] S. Henneking, S. Venkat, V. Dobrev, J. Camier, T. Kolev, M. Fernando, A.-A. Gabriel, and O. Ghattas, Real-time Bayesian inference at extreme scale: A digital twin for tsunami early warning applied to the Cascadia subduction zone, in *Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis (SC '25)* (ACM, New York, NY, 2025) 2025 ACM Gordon Bell Prize.
- [154] J. B. Ajo-Franklin, S. Dou, N. J. Lindsey, I. Monga, C. Tracy, M. Robertson, V. Rodriguez Tribaldos, C. Ulrich, B. Freifeld, T. M. Daley, and X. Li, Distributed acoustic sensing using dark fiber for near-surface characterization and broadband seismic event detection, *Scientific Reports* **9**, 1328 (2019).
- [155] Z. Zhan, Distributed acoustic sensing turns fiber-optic cables into sensitive seismic antennas, *Seismological Research Letters* **91**, 1 (2020).
- [156] M. D. Wilkinson, M. Dumontier, I. J. Aalbersberg, *et al.*, The FAIR guiding principles for scientific data management and stewardship, *Scientific Data* **3**, 160018 (2016).
- [157] United Nations Office for Disaster Risk Reduction (UNDRR), *Gar 2025 hazard explorations: Earthquakes*, <https://www.undrr.org/gar/gar2025/hazard-exploration/earthquakes> (2025), accessed: 2026-08-17.
- [158] R. Bilham, The seismic future of cities, *Bulletin of Earthquake Engineering* **7**, 839 (2009).
- [159] M. Bohnhoff, Future challenges in continental scientific drilling, *Journal of the Geological Society of India* **97**, 971 (2021).
- [160] Y. Ben-Zion, G. C. Beroza, M. Bohnhoff, A.-A. Gabriel, and P. M. Mai, A grand challenge international infrastructure for earthquake science (2022).

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Author contributions

Competing interests

All authors declare no competing interests.