Studying Exhumed Faults Is Necessary for Understanding Earthquake Physics

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Synopsis: *Rock record studies of seismogenic faults are paramount to future advances in earthquake science, and should be included as a distinct focus area of any new earthquake center funded by the National Science Foundation. In this letter, we argue that "exhumed analog" faults - which are exposed at the surface but record deformation at conditions typical of the seismogenic crust - provide the most effective avenue for identifying the primary controls on earthquake nucleation and growth. Field and micro-scale observations are a necessary prerequisite for forming the next generation of hypotheses testable with laboratory measurements and for providing the context necessary to understand numerical models. Further, although a new earthquake science center may operate within a specific geographic scope or area of interest, relevant exhumed analog faults may be located anywhere in the world. Thus, geographic restrictions on research scope should be sufficiently flexible to allow new advances to be achieved from any appropriate analog sites.*

Field observations of fault rocks, exhumed from depths relevant to the earthquake cycle, are the only way to identify and contextualize the processes that act to control strength and the time scales of deformation during plate motions (Chester et al., 2004; Moore et. al. 2007). Active plate boundary faults cannot be sampled at the key depths where locking and earthquake rupture nucleation are controlled, even through drilling and core recovery. By taking advantage of exhumed structures, rock record studies can provide insights into earthquake source physics that cannot be obtained through geophysical, experimental, or numerical methods alone. Specifically, rock record studies can define the processes controlling the seismic cycle and the mechanisms governing both intrinsic (e.g. geometry, deformation mechanisms, chemical reactions) and effective (e.g. pore-fluid pressure cycling) fault strength (e.g. Meneghini and Moore, 2007; Rowe et al., 2012; Niemeijer et al. 2012; Compton et al., 2017, Dascher-Cousineau et al., 2018). Exhumed analog faults and shear zones are common in the continental crust so field studies *need not be near to the modern structures they are to be compared with*, but may instead be sought from anywhere in the world. Studies of exhumed structures are increasingly interdisciplinary, typically comprising iteration between field work (mapping, observation of defining structural elements and deformation histories, measurement of fabrics, fractures and other structures, sample collection, etc.) and laboratory characterization (microstructural, geochemical, geochronological, and/or mechanical analyses). These studies are absolutely essential for making new discoveries in fault mechanics, the mechanisms controlling them, and their operative time scales within the seismic cycle. Only exploratory observations of a variety of fault systems can develop a thorough inventory of the diversity of processes active in seismogenic faults.

Below, we provide examples of how field observations of seismogenic faults multiply the potential of complimentary sciences (laboratory investigations, numerical modeling, geophysical and geodetic observation, etc.) by providing real world parameters and context that cannot be acquired or verified any other way. We divide these examples into three key areas which are well positioned to provide new breakthroughs in earthquake science over the next decade. The results may pave the way for linking deformation across the full breadth of spatial and temporal scales relevant to the seismic cycle, potentially allowing the earthquakes to be modeled with naturalistic rheological properties and geometries (c.f. Moore et al., 2007, Niemeijer et al., 2012, Lapusta et al., 2018).

***Physical Properties of Fault Rocks and Related Materials*:** The physical properties of fault rocks govern the stability and style of fault slip in addition to the magnitude and distribution of radiated energy during earthquakes. Fault-rock properties are typically measured through laboratory or seismological approaches. However, field studies are needed to determine the relevant materials, and how experimental results can be scaled and applied to complex geological structures. Additionally, some properties, such as the geometry of structures and the development of fabrics during deformation can only be measured from exhumed analogs. For example, what do laboratory friction values necessarily imply about the mechanics of a fault zone 10's of meters wide and 100's of km in length? Over what spatial scales are those values applicable? Do they continually vary through time or eventually reach a steady state? How do shear resistance effects from material properties vs. geometry interact to produce macroscopic strength? These and other important questions can only be answered through an increased emphasis on holistic earthquake science, including studies of the rock record. Recent work demonstrates the transformative nature of such approaches. For example, coordinated outcrop, geochemical, and rock mechanics experiments can be leveraged to understand strength evolution of faults during all stages of the earthquake cycle (e.g. Smith et al. 2008, Yamaguchi et al. 2011). Integration of numerical modeling with such data have yielded insights into strength change in subduction thrusts with temporal precisions on the order of a few months (Taetz et al., 2018; Ujiie et al., 2018). Thus, exhumed analog faults have much to offer in revealing changes in fault strength and other properties over human time scales, in addition to understanding the cumulative effects of deformation on fault strength.

***Earthquake Processes in the Mid-Crust*:** Most large earthquakes nucleate in the mid-crust near the brittle-ductile transition (i.e. 10-15 km depth in continental crust but often deeper in subduction zones). Low-frequency earthquakes, slow slip events, and aseismic creep, which may all load the seismogenic zone, occur at still greater depths. Thus, the brittle-ductile transition is of fundamental importance for understanding the spatial and temporal scales of strain accumulation and release in the seismic cycle and how small, dynamic instabilities grow into fault-scale ruptures. Details of the structures, rock compositions, deformation mechanisms, and degree of heterogeneity at the scale of earthquake nucleation and coseismic slip and afterslip can only be resolved from studies of exhumed analog faults and shear zones. Slip weakening mechanisms necessary for earthquake slip, rate-limiting mechanisms that may be central to afterslip, and the mechanisms of fault healing over the seismic cycle can also be uniquely identified from studies of exhumed analog structures. For example, pseudotachylyte-bearing faults exhumed from hypocentral depths have provided information on rupture directivity and geometries in addition to earthquake-source parameters (e.g. Allen, 2005; Di Toro et al., 2009; Rowe et al., 2018). Combined brittle and ductile behavior and the relative rates of crack opening and healing have been shown to be important for episodic tremor and slow slip events from observation of exhumed analog faults (Fagereng et al., 2011; Ujiie et al., 2018). In combination with structurally-resolved geochronological analyses of syntectonic mineral phases, these data can be used to constrain both the timing of individual slip events slip events (e.g. Moser et al., 2017; Williams et al., 2017), the timescales of fault reactivation (e.g. Nuriel et al., 2019), and the rates of post-seismic fault/fracture healing (e.g. Williams et al., 2019a). The former were once considered the sole domain of paleoseismological studies of surficial deposits, and demonstrate the vast potential of detailed field mapping combined with microstructural analysis and high-precision dating techniques.

Links Between Seismic Faults and Ductile Shear Zones: Ductile shear zones, the deep extensions of major crustal faults, may influence the seismic cycle by redistributing stress over the multi-kilometer scale following earthquake related transients in strain rate (Pollitz et al., 2001). Understanding this process, however, requires information on the mechanical properties and stress-state of materials in the upper mantle and lowermost crust, which can be defined from the distribution, thermometry, and fabric of shear zones recorded in deeply exhumed crustal mylonites and mantle xenoliths (e.g. Titus et al., 2006; Toy et al., 2008; Behr and Platt, 2014; Menegon et al., 2017). Chatzaras et al. (2015), for example, determined the paleo-stress state of depth-resolved mantle xenoliths erupted from beneath the Calaveras Fault zone to define a "lithospheric-feedback" model, which proposes that the brittle crust and upper mantle act as an integrated mechanical system throughout the seismic cycle. These findings suggest the strength of the mantle beneath faults varies dramatically throughout the seismic cycle, much akin to the dynamic weakening and subsequent (re)healing experienced by fault rocks in the brittle crust. These studies highlight the potential variation in rock strength with depth in the crust and how different crustal layers may be mechanically linked. They also show that the rock record can be used to assess the mechanical properties and conditions of even an *active fault* as it extends into the upper mantle.

Moving Forward: Field and micro-analytical investigations are, and will continue to be, critical for new developments in earthquake physics. Any new earthquake science center funded by the NSF should include a specific emphasis on field-based studies of exhumed analog faults. Application of a variety of exhumed analog structures to faults or regions of interest must be encouraged. For example, the San Andreas system in California likely inherited many characteristics from the strike slip faults of the Farallon-North American subduction zone forearc (Kelsey and Cashman, 1983). Modern and ancient equivalents of these types of faults are present in places such as the Alaskan forearc (Pavlis et al., 2007). To fully leverage the primary observations from the rock record, we suggest an increased emphasis on the integration between the field, geophysical, experimental, and theoretical/numerical earthquake science communities. This integration is a requirement if the various processes governing fault stability and strength are going to be not only understood, but also linked over the full spectrum of spatial and temporal scales relevant to the seismic cycle. Toward that end, rock record studies should target both descriptive studies that define processes and relevant physical properties and geochemical signatures as well as studies that take a quantitative approach and/or develop large digital datasets that can be statistically characterized. For example, recent advances in statistical analysis have demonstrated the vast potential for improved quantification and more objective hypothesis testing in geological data sets (e.g. Roberts et al., 2019; Williams et al., 2019b) in addition to the potential for observation upscaling (e.g. Kirkpatrick et al., 2018). Further development of these techniques, in conjunction with the continued proliferation of geoscience specific data repositories (e.g. those developed by IRIS, StraboSpot, and others) can prompt the kind of "big data" explosion that is concurrently underway in genetics and other fields. In summary, we believe that full utilization of the rock record of exhumed seismogenic structures is critical to fostering the next generation of research in earthquake science. We hope that this vision will be achieved within a new earthquake science center which is focused on truly integrated studies in earthquake physics.

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