Laboratory experiments in the Next Earthquake Center
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Quantifying earthquake processes use theories that were discovered and verified with laboratory experiments (Paterson and Wong, 2005): Hooke's law for elasticity, linear elastic fracture mechanics for fracture propagation, Amontons-Coulomb law for static friction, critical phase transition for rupture nucleation, and rate-and-state friction law for static and dynamic friction. However, these theories fail to predict the entire rupture process, from nucleation to propagation, coalescence, localization, and the arrest of a dynamic rupture, and so do not provide a unique framework for brittle deformation. Two main factors must be considered when quantifying rupture and fault slip in the Earth's upper crust. First, there is a **separation of time scales in the earthquake processes**, with elastic waves and earthquake fronts propagating at velocities of several kilometers per second, tectonic loading occurring at velocities of centimeters per year and fault slip occurring with a wide range of velocities from centimeters per month during permanent or transient creep, to meter per second during earthquakes. Second, the presence of heterogeneities at all scales makes it difficult to **identify a representative system size** in natural systems, whereas in laboratory experiments and theoretical studies the boundaries of the system define a finite system size.

In the field, limitations in understanding earthquakes processes can arise from the distance at which observations are made, several kilometers away from where they occur at depth. Outcrops of fault zones record fossil earthquakes. However, it is difficult to separate the effect of individual ruptures or even to identify the last slip surface in such outcrops. Even when it is possible to do so, the pre-existing state of stress and its evolution during past earthquakes are unknown.

Laboratory experiments may overcome some of the limitations described above by reproducing fracture development and slip under well-controlled conditions. The first rock physics apparatus was developed by T. von Kàrmàn in the 1910's. This apparatus helped identify the brittle-ductile transition in rocks with increasing confining pressure. In the second half of the 20th century, series of experiments developed in Japan (e.g., Mogi 1962) and USA (e.g., Brace et al., 1966) identified that rock rupture is preceded by precursor phenomena that include the opening of microfractures that produce dilatancy, and the increasing nucleation and growth of microfractures that may evolve into a fault (Lockner et al., 1991). A paradigm shift occurred when earthquakes were proposed to result from a frictional instability on a pre-existing fault (Brace and Byerlee, 1966) which led to the development of experiments of rock-on-rock friction (Dieterich, 1972) and to the discovery of the phenomenological rate-and-state friction law, now widely used to model earthquake instabilities (Marone, 1998). However, this law is phenomenological and relies on at least five empirical parameters (μ_0, a, b, D_c, V^*) that do not have yet interpretations based on first principles, contrary to Hooke's law or the theory of linear elastic fracture mechanics. More recently, experiments studying friction under high velocities proposed that dynamic weakening occurs in a fault zone during seismic slip (e.g. di Toro et al., 2011). With the development of apparatuses with higher pressure and temperature conditions, experiments can now reproduce conditions of 30-100 km depth on small samples, and so identify the nucleation mechanisms of intermediate and deep earthquakes (Schubnel et al., 2013).

Most laboratory experiments have some limitations because they rely on sensors located at some distance from the fault plane. For example acoustic emission sensors record elastic waves emitted during rock deformation experiments (i.e., the dynamic part of deformation), but are unable to detect aseismic slip and creep. Some of these experiments are also performed at temperature and stress conditions far from those at depth where earthquakes occur, adding another level of complexity when extrapolating laboratory results to natural pressure and temperature conditions. Recent experimental studies have overcome some of these difficulties by being able to either increase the dimensions of the samples (Yamashita et al., 2018, McLaskey, 2019) or to image the entire sample in 4D during deformation at in situ conditions by using synchrotron X-ray tomography (Renard et al, 2019).

The **Next Earthquake Center** will need to support efforts dedicated to perform laboratory experiments to **identify and validate theories of brittle deformation**. Several outstanding scientific questions require laboratory developments to progress on earthquake mechanics.

Rupture nucleation. There is no accepted theory on how rupture nucleation occurs at microscale. The concept of critical nucleation length provides a useful framework to predict at which length scale a dynamic rupture can propagate (Ohnaka and Shen, 1999) and the concept of critical phase transition provides another framework on the acceleration of damage before failure (Renard et al., 2019). However, the deformation processes that occur on and off the fault before this length scale is reached in the system remain largely unknown. These processes involve stress transfer by several processes such as aseismic slip, the cascading of small earthquakes and/or fluid diffusion. Laboratory experiments that image and characterize these processes at all scales are required to progress toward a unified nucleation theory. Such experiments should be performed at various scales (cm to m), use a large number of sensors to record and image both the seismic and aseismic component of deformation, and be comparable to results from outcrop scale field experiments (Guglielmi et al., 2015).

Role of water. Laboratory and field measurements and numerous studies on induced seismicity have demonstrated the key chemical and mechanical effects of water in controlling faulting and earthquakes. Between earthquakes, healing, sealing, and creep control the strengthening and the permeability of the fault zone (Renard et al., 2000; Niemeijer and Spiers, 2006), which may be a barrier to fluid circulation, leading to the build-up of pressure gradients (Sibson, 1992). Aseismic slip in the presence of fluids can modify permeability by propagating and opening fractures (French et al., 2017). There is however a gap of knowledge on the role of fluids during dynamic rupture, in the process zone of an earthquake or in the fault damage zone around it. Potential transient high pressure gradients and water vaporization processes may modify the permeability and control transient fluid flows. Experiments of dynamic rupture in the presence of water with high resolution spatial monitoring techniques and megaHerz resolution recording and imaging will help shed light on the interaction of these processes.

On- and off-fault damage: Microseismicity and damage near active plate boundaries occur in a volume larger than the fault zones (Mitchell and Faulkner, 2006; Ross et al., 2017). If off-fault deformation represents only a small fraction (< 5%) of the strain energy dissipated before and during earthquakes, the question however arises of how this energy dissipation localizes in time and space when approaching earthquakes. Experiments that combine on- and off-fault monitoring are therefore required to progress on a theory of localization.

Predicting the distance to failure: The occurrence of catastrophic failure in laboratory experiments is in most cases preceded by precursory signals that evolve toward failure including aseismic slip, dilatancy and microfracture development. These signals are often weak, but have the potential to be used to estimate how far the system is from failure. Using data science, it is now possible to detect and classify such signals, and then propose a framework of how these signals may predict failure proximity (Rouet-Leduc et al., 2017; McBeck et al., 2020). Developing laboratory experiments that record numerous sensors will be critical to detect and analyse these weak signals.

To solve these questions the **Next Earthquake Center will benefit from supporting and initiating research activities to perform laboratory experiments** and aimed at:

- Developing and sharing unique experimental facilities that cover a range of spatial scales from centimeter to meter scale samples, including real rock and analogue materials, and a range of monitoring systems from long-term experiments to fast rupture dynamics.
- Collaborating within the NSF sponsored research collaboration network *In situ* Studies of Rock Deformation (https://www.isrdrcn.org/) that develops experiments and activities on large-scale instruments such as synchrotron, neutron source and X-ray free electron laser facilities that allow imaging samples in 3D or 4D at high spatial and temporal resolutions.
- Ensuring that the experimental facilities are open to external collaborations and that data are freely accessible.
- Developing the next generation of models of brittle deformation, in collaboration with theoreticians, field scientists, and seismologists who observe earthquakes and fault zones.

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