Rupture nucleation and fault slip: Fracture versus friction

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Given the societal disruption associated with earthquakes in recent years, there is widespread interest in the laboratory investigation of fault mechanics and slip behavior. In the continental crust, earthquakes typically nucleate within the upper 15–20 km (Sibson, 1983; Scholz, 2002), with most of the large, damaging earthquakes nucleating near the base of this regime. Slip velocities during earthquakes range from ~10^{-4} ms^{-1} to at least 10 ms^{-1} (Rowe and Griffith, 2015).

Understanding rupture nucleation and subsequent slip is critical for learning what factors influence whether ruptures grow to become large, damaging earthquakes, or die out as minor events. The dynamic evolution of the strength of fault slip surfaces governs whether they slip aseismically (stable sliding), or rupture in fast, seismogenic events (unstable slip). Experimentally based rate- and state-dependent friction (RSF) laws have enjoyed success in describing the behavior of fault zones in terms of the velocity dependence of frictional sliding in faults (eg, Dieterich, 1978; Ruina, 1983). For these laws, once the transient perturbation associated with a velocity step is complete, the steady-state friction μ_{ss} at constant effective normal stress is given by

$$\mu_{ss} = \mu_0 + (a-b)\ln V/V_0 , \qquad (1)$$

where μ_0 is a reference friction value at slip velocity V_0. The parameters a and b are empirical constants (Marone, 1998). For simple spring-slider models commonly used in RSF laws, the key control on fault stability is whether the sliding fault surface is velocity-strengthening or velocity-weakening. A necessary, but not sufficient, criterion for slip instability is that the sliding surface is velocity-weakening. Fault instability thus requires $(a-b) < 0$. For $(a-b) > 0$, sliding is always stable.

Fault stability is also sensitive to the resistance of an elastic body to deformation, i.e., the stiffness k of the loading system (eg, Paterson and Wong, 2005). Slip instability requires not only that the fault surface is slip-weakening, but also that k becomes less than $d\tau/d\delta$, where τ is shear strength and δ is slip distance. The consequent force imbalance drives rapid unloading of stored elastic strain in the rock via fast slip on the fault surface. Gu et al. (1984) showed that, under quasi-static loading conditions, instability occurs when k becomes less than a critical stiffness k_c defined by

$$k_c = \sigma_n'(b-a)/D_c, \qquad (2)$$

where σ_n' is the effective normal stress and D_c is the characteristic slip distance over which friction evolves from an initial state to a new steady-state value in response to change in slip velocity. For $k > k_c$, sliding is considered to be stable.

The new work of Scuderi et al. (2017, p. 731 in the August issue of *Geology*) used experiments to explore how changes in stiffness of the loading system relative to k_c influence slip and microstructural evolution in a layer of incohesive quartz gouge. At effective normal stresses of 15–35 MPa, their experiments indicate that slip was stable with slip rates of ~10^{-5} ms^{-1} for $k/k_c > 0.9$. However, for $k/k_c < 0.7$, slip became unstable. Importantly, Scuderi et al. link the evolution of mechanical behavior to the evolution of microstructures in the gouge. A key finding is that a

steady-state microstructure evolves with increasing shear strain when slip localizes within narrow shear bands. Localization accompanies a transition from stable to unstable sliding, with peak slip velocities ranging from sub-seismic rates to more than 10^{-2} ms^{-1} as normal stresses increased. The microstructural evolution correlates with progressive changes in D_c. Interestingly, once localization occurs, the gouge microstructure is seemingly insensitive to slip rate over the approximate range of 10^{-4} to 10^{-2} ms^{-1}.

Although the new experimental results demonstrate the association between k/k_c and fault stability in incohesive materials, the application of the results to understanding how stiffness and effective normal stress might influence stability and slip velocities in natural faults remains contentious. In particular, it is unclear to what extent RSF laws may apply at seismogenic slip rates. High-velocity rotary shear experiments demonstrate that dynamic weakening occurs at slip rates greater than ~10^{-2} ms^{-1} (e.g., Di Toro et al., 2006, 2011). Sliding friction drops from values of ~0.7 at subseismic slip velocities, to values commonly less than 0.2 at slip rates > 10^{-1} ms^{-1}. These reductions are much larger than those associated with velocity-dependent friction effects described by RSF laws. Unfortunately, most rotary shear experiments have been conducted at normal stresses that are low relative to those at depth in the crustal seismogenic regime.

Dynamic weakening involves various processes, including flash weakening due to heating of asperities (Rice, 2006; Goldsby and Tullis, 2011; Hayward et al., 2016), frictional melting (Hirose and Shimamoto, 2005; Di Toro et al., 2006, 2011), thermal pressurization of pore fluids in the slip zone (Rice, 2006), lubricating effects associated with formation of silica gels (Goldsby and Tullis, 2002; Di Toro et al., 2004), the lubricating effects of pore fluids (Kanamori and Brodsky, 2004), and nanoparticle lubrication (Han et al., 2007; Reches and Lockner, 2010; De Paola et al., 2011). The nature of the dominant dynamic weakening processes is influenced especially by slip rate, slip distance, effective normal stress, and the mineralogical composition of the sliding interface (Niemeijer et al., 2012). Significantly, triaxial experiments at normal stresses comparable to those in the mid-crust demonstrate that melting can occur during rapid slip over distances as small as several tens of microns (Hayward et al., 2016). These distances are much lower than those associated with the onset of frictional melting in rotary shear apparatus at low normal stresses. Clearly, there is still much to learn about how dynamic weakening processes influence rupture nucleation and propagation, especially at conditions comparable to those deep in the seismogenic regime.

Although recent studies have focused on frictional evolution of incohesive slip zones, observations of faults exhumed from seismogenic depths indicate that, especially in the presence of reactive pore fluids, faults can regain cohesive strength between rupture episodes (e.g., Angevine et al., 1982; Cox and Munroe, 2016). Banded cataclasites in exhumed faults commonly contain fragments of earlier generations of cohesive cataclasite, and demonstrate that recovery of cohesive strength can be rapid on the time scales of rupture recurrence. Interseismic recovery of cohesive strength is caused by compaction of gouges by dissolution-precipitation creep, and by sealing of fractures and pore spaces by mineral deposition from pore fluids. These observations are supported by experimental studies conducted at hydrothermal conditions (Cox and Paterson, 1991; Chester and Higgs, 1992; Karner et al., 1997; Kanagawa et al., 2000;

Tenthorey and Cox, 2006; Giger et al., 2008). If frictional melting occurs during slip, melt welding provides an additional mechanism for recovery of cohesive strength after seismogenic slip events (Mitchell et al., 2016; Proctor and Lockner, 2016). When faults recover cohesive strength, rupture nucleation is likely controlled by shear fracture and associated rapid stress drop, rather than by frictional sliding. However, after shear fracture and slip weakening in the first milliseconds of slip, dynamic weakening processes are then likely to govern ongoing slip as stored elastic strain continues to be released.

In recent years, laboratory studies have provided exciting insights about the ways that shear failure and frictional sliding processes influence fault slip. Understanding rupture nucleation and fault stability requires a better understanding of the time-dependence of cohesive strength recovery and the processes of shear failure in cohesive fault materials. Progress will be stimulated by experimentalists developing an improved capacity to explore shear fracture and frictional behavior over a wide range of slip velocities and slip distances, at conditions that are comparable to those relevant to deep seismogenic settings where large ruptures nucleate. An exciting challenge will be to up-scale results obtained from laboratory experiments and numerical modeling to the length scales of natural faults. Earthquake science will continue to advance via the integration of results of physical and numerical experiments with (1) studies of active faults via geophysical observations and deep drilling, and (2) studies of exhumed ancient faults that preserve a record of processes that operated in deep, currently inaccessible, seismogenic settings.

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