

# Connections between fault roughness, dynamic weakening, and fault zone structure

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An enduring question in fault mechanics is that of how to read slip history from the information recorded in fault rocks and fault zone structure (e.g., Rowe and Griffith, 2015). Fault rocks routinely record slip direction, which is written in the form of slip-parallel scratches, tool marks, and slickenlines, but what about further details? Is it possible to read fault strength from fault roughness, or to infer dynamic properties of earthquake rupture such as slip patch size and velocity? Two works published in this issue of *Geology* shed light on these questions (Brodsky et al., 2016, p. 19–22; Yao et al., 2016, p. 63–66).

Brodsky et al. (2016) take a fresh look at the historically thorny problem of how fault roughness relates to strength, and they suggest a new metric to address it based on the ratio of asperity height,  $H$ , to the observation length,  $L$ . They report roughness measurements from a variety of complex fault zones and conclude that  $H$  scales with  $L$  in a power-law form. An interesting implication of the power-law scaling of roughness is that shear-driven wear of the bounding surfaces does not cease when the local gouge zone width exceeds  $H$ , although it may decrease at larger scales (Savage and Brodsky, 2011). Moreover, Brodsky et al. found similar roughness properties for a variety of tectonic faults, both at the outcrop dimension and at the hand-sample size for shear surfaces within the fault zones, which illuminates some new problems for consideration.

Brodsky et al. (2016) argue that fault roughness provides a record of previous slip events and also dictates the conditions for future rupture. It is worth asking how earthquakes and fault slip affect fault roughness, and vice versa. Do faults become rougher or smoother as a function of accumulated slip, and does fault roughness impose limits on earthquake magnitude and stress drop (e.g., Candela et al., 2011; Fang and Dunham, 2013)? Basic considerations of fault formation and growth indicate that faults become smoother with slip, at least in the early stages of fault growth (Brodsky et al., 2011). Fault zone step-overs and structural complexity are progressively smoothed by accumulated displacement (e.g., Wesnousky, 1988). Yet faulting involves several processes that may increase or maintain roughness with increasing net displacement, such as wear, brecciation, and branching during dynamic rupture. Do these processes leave fingerprints in fault roughness spectra?

Brodsky et al. (2016) report measurements of fault roughness ranging from the field scale (tens of meters) to the lab scale (millimeters) and propose that the aspect ratio of surface asperities is a key parameter. Their non-dimensionalization circumvents some of the problems with traditional measurements of roughness that rely on defining it at a particular spatial scale. Brodsky and co-workers use concepts from fractal geometry to argue that although fault roughness may be self-similar at some scales, when fault surfaces are analyzed in detail, the relationship between power spectral density and wavelength is better described as self-affine; that is, the scaling is different parallel to slip than perpendicular to slip. The anisotropic nature of fault roughness is a familiar feature, often manifest as slickenlines and mullions oriented in the slip-parallel direction.

A major contribution of Brodsky et al.'s (2016) work is the recognition that the scale dependence of the roughness ratio  $H/L$  implies that fault rocks are stronger at smaller scales because roughness is greater for length scales of 1–10 mm than for 1–10 m. On the one hand, this result is consistent with existing data and theory, which indicate that the strength of ma-

terials scales inversely with size. However, it is also surprising given the range of processes known to operate at the diverse spatiotemporal scales of tectonic faulting. One might guess that the processes affecting roughness on different spatiotemporal scales, or in different tectonic environments, would result in different scaling relations for roughness. However, the analysis of Brodsky et al. suggests otherwise. Does this imply that different spatial scales of fault roughness are produced during different periods of the seismic cycle or in different sections of an earthquake rupture patch? How does fault roughness relate to earthquake magnitude? Are smooth faults required to generate large earthquakes?

Brodsky et al. (2016) propose a model in which the roughness ratio  $H/L$  defines a critical strain for failure between fault-zone asperities, no matter whether they occur in the wall rock, or correspond to fault-zone lithons separated by shear surfaces within the fault zone. Their observations of the scale dependence of roughness suggest the possibility of learning more about how the strength of fault rocks impacts fault mechanics and earthquake physics as well as extending studies (e.g., Fondriest et al., 2013) that address connections between fault roughness and laboratory studies of fault-zone friction at high velocity, as documented in the work of Yao et al. (2016, p. 63–66 in this issue of *Geology*).

A large body of laboratory data shows that the frictional strength of rock drops dramatically for shearing velocities above ~0.1 m/s (Di Toro et al., 2011). The origin of this dynamic weakening and its application to earthquake faulting and the seismic cycle is still under debate. Candidate processes include velocity weakening, flash heating, thermochemical pressurization, and lubrication associated with nanoparticles. Differentiating among these processes has proven difficult because of their close coupling in lab experiments, which typically include contributions from many or all of the candidate mechanisms (e.g., Niemeijer et al., 2011).

Yao et al. have made a major advance using a clever experimental design that disentangles the main effects. Their results show that temperature rise is the key factor causing frictional weakening in laboratory faults sheared at high velocity. Yao et al. conducted identical experiments with a variety of thermal boundary conditions to isolate the effect of temperature on fault weakening. They find that when heat is removed from the fault zone more efficiently, faults are stronger than in cases where the fault zone is better insulated and temperature rises more quickly with slip. The critical slip distance for thermal weakening is a few meters for the conditions of their experiments with gabbro fault blocks, and increases by a factor of nearly 10 for brass, which has a thermal conductivity that is ~40 times greater than gabbro. Thermomechanical analysis of their data points to flash heating as the most likely origin of dynamic weakening. They show that the critical velocity for weakening is a decreasing function of ambient temperature, consistent with the fact that flash heating causes weakening via thermally activated processes. It is important to appreciate the elegance of their analysis, which robustly predicts the change in macroscopic friction coefficient based on the time that contacts spend in the thermally weakened versus unweakened state. Their work yields a critical weakening velocity of ~2 m/s and a flash weakening temperature of ~300 °C.

Yao et al. highlight the role of heat production rate during fault slip, which is a function of the effective normal stress, the friction coefficient,

and the shear velocity. As applied to earthquake fault zones, their work suggests that faults may undergo dynamic weakening after slip distances of 0.1–1 m. Their data clearly indicate that flash heating and thermally-activated mechanisms are responsible for dynamic frictional weakening, and they rule out powder lubrication, velocity weakening via contact aging, and thermochemical pressurization as contributors, consistent with other recent works (e.g., Violay et al., 2014). Further investigation will be needed to confidently reject other potential contributors when fault zones have different mineralogy and/or greater geologic complexity.

Important questions remain about how these data apply to tectonic faults. For example, why is evidence of shear melting in fault zones so rare? Lab results indicate that if slip is sufficiently localized, shear heating should cause bulk melting and routine production of pseudotachylite. However, the laboratory experiments are conducted on relatively smooth surfaces that are flat at long wavelength. Is it possible that greater roughness on tectonic faults results in wider shear zones and thus lower peak temperatures during earthquake slip? Or, does shear melting only occur for earthquakes above a critical size dictated by the thermal weakening distance? Based on the work of Brodsky et al. (2016), one could ask if the decrease in the roughness ratio,  $H/L$ , above ~1 m reflects a transition to dynamic weakening via flash heating and thermal softening. The results of Yao et al. raise interesting questions about the relationship between shear heating, fault roughness, and shear localization.

Yao et al.'s data may also shed light on a puzzle related to the application of high-velocity friction data to earthquakes. In the lab, dramatic weakening occurs for slip rates above ~0.1 m/s. If faults undergo similar dynamic weakening, then earthquake stress drops should be larger for events that have sustained slip rates above the critical value. Theoretical and laboratory studies indicate that peak slip velocities can reach 0.1 m/s or higher for even small-magnitude earthquakes. However, Yao et al. show that temperature rise is the key factor for fault weakening, and that it takes a certain amount of displacement to accrue the temperature rise necessary for the onset of dynamic weakening. Their data suggest that dynamic weakening is a robust feature of many rock types, and that the threshold weakening velocity varies in a fairly narrow range. This implies that bulk fault-zone weakening requires a critical earthquake magnitude, because small events may not slip long enough and far enough to generate sufficient heat and temperature rise to induce full-scale dynamic weakening of the sort documented in lab tests. If such a critical magnitude for dynamic weakening exists, one might expect to see its signature in earthquake source scaling relations and stress drop. Yet, such a scaling break is not apparent in existing compilations of seismic moment and source dimension, nor is it seen in frequency-magnitude statistics. Possibly this elusive scaling break is masked because earthquake source parameters are routinely determined as static averages over the entire rupture area of a large event. Could the fingerprints of the dynamically weakened patches be discerned from fault roughness measurements?

Pulling together the results of Brodsky et al. (2016) and Yao et al. suggests some interesting interpretations of the relationship between fault strength and fault-zone structure. If the roughness features measured by Brodsky et al. are produced by fault slip, as seems clear given the self-affine power law scaling, two important questions arise: (1) can we read fault slip velocity and the seismic or aseismic character of fault slip from

the roughness spectra, and (2) does dynamic fault weakening above a critical slip velocity impart a thermally controlled signature to roughness?

Key fault-zone structural features include the geometry of shear localization and the ratio of fault-zone width to fault roughness. Brodsky et al.'s (2016) roughness parameter  $H/L$  adds an additional important parameter for studies of fault zone structure and together with Yao et al.'s work suggests possible connections with dynamic fault weakening. Is it possible that differences in fault roughness below a threshold scale length have an impact on earthquake source properties? For example, do small sub-events within a larger co-seismic fault patch, or perhaps processes in the breakdown zone at the rupture front, reflect the greater roughness and stronger nature of smaller asperities? Yao et al.'s work suggests the existence of a critical slip velocity for dynamic weakening. Could this have a structural signature within fault zones? The works of Yao et al. and Brodsky et al. point to a number of interesting questions about the connections between fault roughness, dynamic weakening and earthquake source properties that are likely to guide future work in this area for many years.

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**Notes**