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How dynamic weakening makes faults stronger: The role of melting in post-seismic healing

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Temperature rise due to coseismic frictional sliding should be sufficient to melt rocks at seismogenic depths, a fact that has been recognized for over half a century (Jeffreys, 1942; McKenzie and Brune, 1972). Under dry, adiabatic conditions, this temperature rise is linearly proportional to slip rate, duration of sliding, and shear traction (assumed to be equal to the normal stress times the coefficient of friction) on the fault (McKenzie and Brune, 1972; Sibson, 1973). Due to the short sliding duration of earthquakes and low thermal conductivity of common minerals, heat loss due to conduction is negligible (Lachenbruch, 1980; Yao et al., 2016). Early workers speculated that melting is likely an important mechanism for weakening rock frictional resistance from static to reduced kinetic values, thus enabling the rapid stress drop required for unstable slip and earthquake rupture. A large body of experimental and theoretical work following this assertion has focused on understanding the effects of rock melting on frictional resistance (e.g., Di Toro et al., 2009). However, comparably little work has addressed the effect of solidified melt—known as pseudotachylyte (PST)—on the long-term strength of fault zones. Two papers published in this issue of *Geology* tackle this question by combining field observations with triaxial rock mechanics experiments.

Mitchell et al. (2016, p. 1059 in this issue) work from two observations that are common in PST-bearing exhumed faults. First, faults that host PST are typically geometrically complex, with interconnected strands of individual faults containing PST (Grocott, 1981; Swanson, 1992; Di Toro and Pennacchioni, 2005; Allen and Shaw, 2011; Melosh et al., 2014). Second, in many cases the individual PST fault veins show evidence of having been formed during an individual slip event (e.g., Di Toro and Pennacchioni, 2005; Griffith et al., 2008; Alder et al., 2016). Mitchell et al. hypothesize that these observations could be explained if melt quenching results in a complete restoration of strength relative to the virgin host rock. Post-seismic strength recovery due to such a fault welding process could result in subsequent ruptures jumping to weaker neighboring discontinuities rather than exploiting the same fault strand twice—a process contradicting the common expectation of progressive smoothing and strain localization (Chester and Chester, 1998; Brodsky et al., 2011).

To test their hypothesis, Mitchell et al. collected PST-bearing rocks from two well-known fault zones (the Alpine fault in New Zealand and the Gole Larghe Fault Zone [GLFZ] in the Italian Southern Alps). PST fault veins in the Alpine fault samples are thin (<1 mm) and distributed across preexisting mylonitic foliation, whereas PST veins in the GLFZ are thick—up to several centimeters—accumulate along faults that grew from preexisting joints through otherwise isotropic tonalite. Mitchell et al. subjected the natural samples to expected *in situ* stress conditions in the laboratory and compared the measured strength to that of both the intact host rock and saw-cut interfaces in the same rocks. Their results suggest that PST-welded faults are as strong as the virgin host rock; therefore, once a fault has been welded, subsequent ruptures preferably branch onto neighboring fractures or foliation planes. This is an inherently delocalizing process, in contrast to the expected slip localization that occurs along mature faults at shallower crustal levels. Furthermore, even though the melting process results in weakening on coseismic time scales, it keeps faults strong throughout longer time scales encompassing the complete seismic cycle.

The rock samples that Mitchell et al. collected in the field are millions of years old and exhumed from seismogenic depths (~5–15 km in the continental crust). But do processes alter the pseudotachylyte during exhumation (e.g., devitrification of quenched glass) and change the strength of the rock? Perhaps very little, according to Proctor and Lockner (2016, p. 1003 in this issue), who investigate the role of newly formed melt on strength recovery.

In contrast to Mitchell et al., who tested the shear strength of natural PST, Proctor and Lockner started with standard saw-cut surfaces in cylindrical specimens of Westerly Granite—a standard fine-grained granite used in rock mechanics experiments worldwide—and observed stick-slip events in the laboratory under dry and wet conditions and effective confining pressures ranging from 50 to 400 MPa. They followed these experiments by conducting constant normal stress re-strengthening experiments to investigate post-slip healing and concomitant strength recovery. During these re-strengthening experiments, dry samples with nearly complete stress drops showed significant strength recovery, such that the shear strength of the faults approached that of the virgin Westerly Granite, whereas wet samples and previously undeformed saw-cut samples were characterized by quasi-stable sliding. Microstructural examination of the post-mortem slip surfaces revealed evidence of thin melt patches in both dry and wet specimens, and for dry specimens, patches of the slip surface were completely welded together by melt. At lower confining pressures, in the dry samples the melt was confined to isolated patches, but at higher confining pressures, during experiments for which stress drops and strength recovery were nearly complete, the entire slip surface was covered with melt. The lack of welded patches and absence of strength recovery under wet conditions was attributed to thermal pressurization, a process wherein heat generated during frictional sliding results in the expansion of pore fluids and reduction of the effective normal stress, buffering against further temperature rise (Sibson, 1973; Lachenbruch, 1980). Combined with the mechanical data, the microstructural observations were interpreted in terms of melt-welding of the fault surface. Perhaps most notably, Proctor and Lockner demonstrate that at sufficient confining pressure, and under very small net slip (<6.5 mm in their experiments), freshly quenched melt can be a significant source of strength heterogeneity in fault zones.

Despite the expected proliferation of melting along seismogenic faults noted by earlier workers, reports of PST are famously rare (Sibson and Toy, 2006; Kirkpatrick et al., 2009; Rowe and Griffith, 2015). Several explanations for their apparent paucity have been given, including lack of stability and preservation of glass, as well as oversight, but a distinct possibility is that other processes such as thermal pressurization prevent melting from occurring in the first place. Even so, some workers have described natural PST that formed under wet conditions, possibly due to lowering of the bulk melting temperature of the melting rocks (Rowe et al., 2005), enhanced normal stress at restraining bends on rough faults (Griffith et al., 2010), or decompression melting (Bjørnerud and Magloughlin, 2004). A phenomenal result from the combined work of

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Mitchell et al. and Proctor and Lockner is that regardless of scale, fault welding resulting from melting represents a significant source of rapid strength recovery and persistent strength asperities that can influence the long-term strength of faults within the seismogenic zone.

These new results have some critical implications for the mechanics of seismic slip on faults in the present day. First, melting can strengthen faults rapidly. Mitchell et al. note that cooling of GLFZ fault veins occurred as quickly as 5 s, and the thinner fault veins of the Alpine fault in <<1 s. Furthermore, as demonstrated by the experiments of Proctor and Lockner, this process is effective even with very small melt volumes.

The combined results of Mitchell et al. and Proctor and Lockner suggest that whether melting is widespread (e.g., the GLFZ), diffuse (e.g.. the Alpine fault), or discontinuous, as may be the more common case, melting and subsequent quenching should result in strength asperities throughout the seismogenic zone. And if melt welding is indeed widespread in the seismogenic zone, so too may be the process of slip delocalization. Increasing fault smoothness with fault maturity has become the accepted paradigm consistent with expectations from field observations and fault mechanics theory (Wesnousky, 1988; Chester and Chester, 1998; Brodsky et al., 2011; Newman and Griffith, 2014), yet the possibility that even mature faults may be geometrically complex at seismogenic depths has major implications for the mechanics of earthquakes and faulting. Strength heterogeneity plays a role in earthquake nucleation, propagation, and cessation, as well as off-fault deformation. Structural complexity in the form of fault roughness may add additional shear resistance to slip such that faults may remain macroscopically strong even with local, dynamic weakening (Fang and Dunham, 2013), perhaps explaining why most crustal earthquakes appear to be strong.

In contrast, the lack of re-strengthening under wet conditions in Proctor and Lockner's experiments seems to suggest that whereas thermal pressurization, like melting, is an effective dynamic weakening mechanism, it may differ fundamentally from melting in terms of how it affects long-term fault strength. If correct, this raises the question of the role of the myriad other thermally driven dynamic weakening mechanisms (Di Toro et al., 2011) in post-seismic strength recovery and subsequent seismicity (McLaskey et al., 2012). It could be argued that the role of post-seismic fault healing over the seismic cycle deserves as much focus as the prevailing "hot" topic of dynamic frictional weakening.

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