

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 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

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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REFERENCES CITED

Alder, S., Smith, S.A.F., and Scott, J.M., 2016, Fault-zone structure and weakening processes in basin-scale reverse faults: The Moonlight Fault Zone, South Island, New Zealand: *Journal of Structural Geology*, v. 91, p. 177–194, doi:10.1016/j.jsg.2016.09.001.

Allen, J.L., and Shaw, C.A., 2011, Seismogenic structure of a crystalline thrust fault: Fabric anisotropy and coeval pseudotachylite–mylonitic pseudotachylite in the Grizzly Creek shear zone, Colorado: *Geological Society of London Special Publications*, v. 359, p. 135–151, doi:10.1144/SP359.8.

Bjørnerud, M., and Magloughlin, J.F., 2004, Pressure-related feedback processes in the generation of pseudotachylites: *Journal of Structural Geology*, v. 26, p. 2317–2323, doi:10.1016/j.jsg.2002.08.001.

Brodsky, E.E., Gilchrist, J.J., Sagy, A., and Collettini, C., 2011, Faults smooth gradually as a function of slip: *Earth and Planetary Science Letters*, v. 302, p. 185–193, doi:10.1016/j.epsl.2010.12.010.

Chester, F.M., and Chester, J.S., 1998, Ultracataclasite structure and friction processes of the Punchbowl fault, San Andreas system, California: *Tectonophysics*, v. 295, p. 199–221, doi:10.1016/S0040-1951(98)00121-8.

Di Toro, G., Han, R., Hirose, T., De Paola, N., Nielsen, S., Mizoguchi, K., Ferri, F., Cocco, M., and Shimamoto, T., 2011, Fault lubrication during earthquakes: *Nature*, v. 471, p. 494–498, doi:10.1038/nature09838.

Di Toro, G., Pennacchioni, G., & Nielsen, S., 2009, Pseudotachylites and earthquake source mechanics: *International Geophysics*, v. 94, p. 87–133.

Di Toro, G., and Pennacchioni, G., 2005, Fault plane processes and mesoscopic structure of a strong type seismogenic fault in tonalites (Adamello batholith, Southern Alps): *Tectonophysics*, v. 402, p. 55–80, doi:10.1016/j.tecto.2004.12.036.

Fang, Z., and Dunham, E.M., 2013, Additional shear resistance from fault roughness and stress levels on geometrically complex faults: *Journal of Geophysical Research: Solid Earth*, v. 118, p. 3642–3654.

Griffith, W.A., Di Toro, G., Pennacchioni, G., and Pollard, D.D., 2008, Thin pseudotachylites in faults of the Mt. Abbot quadrangle, Sierra Nevada: Physical constraints for small seismic slip events: *Journal of Structural Geology*, v. 30, p. 1086–1094, doi:10.1016/j.jsg.2008.05.003.

Griffith, W.A., Nielsen, S., Di Toro, G., and Smith, S.A., 2010, Rough faults, distributed weakening, and off-fault deformation: *Journal of Geophysical Research: Solid Earth*, v. 115, B8, doi:10.1029/2009JB006925.

Grocott, J., 1981, Fracture geometry of pseudotachylite generation zones: A study of shear fractures formed during seismic events: *Journal of Structural Geology*, v. 3, p. 169–178, doi:10.1016/0191-8141(81)90012-2.

Jeffreys, H., 1942, On the mechanics of faulting: *Geological Magazine*, v. 79, p. 291–295, doi:10.1017/S0016756800076019.

Kirkpatrick, J.D., Shipton, Z.K., and Persano, C., 2009, Pseudotachylites: rarely generated, rarely preserved, or rarely reported?: *Bulletin of the Seismological Society of America*, v. 99, p. 382–388, doi:10.1785/0120080114.

Lachenbruch, A.H., 1980, Frictional heating, fluid pressure, and the resistance to fault motion: *Journal of Geophysical Research: Solid Earth*, v. 85, B11, p. 6097–6112, doi:10.1029/JB085B11p06097.

McKenzie, D., and Brune, J.N., 1972, Melting on fault planes during large earthquakes: *Geophysical Journal International*, v. 29, p. 65–78, doi:10.1111/j.1365-246X.1972.tb06152.x.

McLaskey, G.C., Thomas, A.M., Glaser, S.D., and Nadeau, R.M., 2012, Fault healing promotes high-frequency earthquakes in laboratory experiments and on natural faults: *Nature*, v. 491, p. 101–104, doi:10.1038/nature11512.

Melosh, B.L., Rowe, C.D., Smit, L., Groenewald, C., Lambert, C.W., and Macey, P., 2014, Snap, Crackle, Pop: Dilational fault breccias record seismic slip below the brittle–plastic transition: *Earth and Planetary Science Letters*, v. 403, p. 432–445, doi:10.1016/j.epsl.2014.07.002.

Mitchell, T.M., Toy, V., Di Toro, G., Renner, J., and Sibson, R.H., 2016, Fault welding by pseudotachylite formation: *Geology*, v. 44, p. 1059–1062, doi:10.1130/G38373.1.

Newman, P.J., and Griffith, W.A., 2014, The work budget of rough faults: *Tectonophysics*, v. 636, p. 100–110, doi:10.1016/j.tecto.2014.08.007.

Proctor, B., and Lockner, D.A., 2016, Pseudotachylite increases the post-slip strength of faults: *Geology*, v. 44, p. 1003–1006, doi:10.1130/G38349.1.

Rowe, C.D., and Griffith, W.A., 2015, Do faults preserve a record of seismic slip: A second opinion: *Journal of Structural Geology*, v. 78, p. 1–26, doi:10.1016/j.jsg.2015.06.006.

Rowe, C. D., Moore, J. C., Meneghini, F., & McKeirnan, A. W., 2005, Large-scale pseudotachylites and fluidized cataclases from an ancient subduction thrust fault. *Geology*, v. 33(12), p. 937-940.

Sibson, R. H., 1973, Interactions between temperature and pore-fluid pressure during earthquake faulting and a mechanism for partial or total stress relief: *Nature*, v. 243, p. 66–68.

Sibson, R.H., and Toy, V.G., 2006, The habitat of fault-generated pseudotachylite: Presence vs. absence of friction-melt, in Abercrombie, R., et al., eds., *Earthquakes: Radiated Energy and the Physics of Faulting*: Washington, D.C., American Geophysical Union, p. 153–166, doi:10.1029/170GM16.

Swanson, M.T., 1992, Fault structure, wear mechanisms and rupture processes in pseudotachylite generation: *Tectonophysics*, v. 204, p. 223–242, doi:10.1016/0040-1951(92)90309-T.

Wesnousky, S., 1988, Seismological and structural evolution of strike-slip faults: *Nature*, v. 335, p. 340–343, doi:10.1038/335340a0.

Yao, L., Ma, S., Platt, J.D., Niemeijer, A.R., and Shimamoto, T., 2016, The crucial role of temperature in high-velocity weakening of faults: Experiments on gouge using host blocks with different thermal conductivities: *Geology*, v. 44, p. 63–66, doi:10.1130/G37310.1.

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