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## Extreme dynamic weakening of faults during dehydration by coseismic shear heating

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[1] The dynamic strength of seismogenic faults has a critical effect on earthquake slip instability and seismic energy release. High velocity friction experiments on simulated faults in serpentinite at earthquake slip conditions show a decrease in friction coefficient from 0.6 to 0.15 as the slip velocity reaches 1.1 m/s at normal stresses up to 24.5 MPa. The extraordinary reduction in fault strength is attributed to flash heating at asperity contacts of gouge particles formed during sliding. The rapid heating at asperities causes serpentine dehydration. In impermeable fault zones in nature, serpentine dehydration and subsequent fluid pressurization due to coseismic frictional heating may promote further weakening. This dynamic fault-weakening mechanism may explain the lack of pronounced heat flow in major crustal faults such as the San Andreas. **Citation:** Hirose, T., and M. Bystricky (2007), Extreme dynamic weakening of faults during dehydration by coseismic shear heating, *Geophys. Res. Lett.*, 34, L14311, doi:10.1029/2007GL030049.

### 1. Introduction

[2] Knowledge of the mechanical properties of faults at a wide range of slip velocities, and especially at seismic slip velocities, is essential to understand the dynamics of fault motion during earthquake cycles. Integrated seismological, heat flow and stress measurements in major fault zones suggest that faults are relatively weak at least during large earthquakes [e.g., *Brune et al.*, 1969]. By contrast, deep borehole measurements worldwide show that average stresses in the crust must generally be high [*Brudy et al.*, 1997] and low-velocity friction experiments indicate high frictional resistance to sliding on faults [*Byerlee*, 1978]. To resolve these inconsistencies, many theoretical models for the dynamic weakening of fault zones have been proposed, including thermal pressurization of pore fluid [*Lachenbruch*, 1980], normal interface vibrations [*Brune et al.*, 1993], acoustic fluidization [*Melosh*, 1996], and elastohydrodynamic lubrication [*Brodsky and Kanamori*, 2001].

[3] Recently, experiments at velocities approaching seismic slip velocities have shown that formation of a silica gel layer in quartz rocks [*Goldsby and Tullis*, 2002; *Di Toro et al.*, 2004], thermal decomposition of carbonates [*Han et al.*, 2007] and frictional melting [*Tsutsumi and Shimamoto*, 1997; *Hirose and Shimamoto*, 2005] result in a major

decrease in fault strength. However, evidence of these weakening mechanisms is still lacking or rare in natural mature faults. A common hypothesis is that fault strength may be related to the abundant presence in mature faults of low-strength phyllosilicate minerals formed by fluid-rock interaction during the interseismic period of the seismic cycle [e.g., *Wu et al.*, 1975]. However, the frictional properties of phyllosilicates at low slip velocities alone cannot explain the apparent weakness of major faults [*Moore et al.*, 1996; *Tembe et al.*, 2006]. In this study, we propose that frictional heating weakens a fault during dehydration of existing hydrous minerals at the initiation of earthquake slip. As phyllosilicates are common in major fault zones, this mechanism may form the basis for a realistic model for the dynamic weakening of faults during earthquakes.

### 2. Experimental Procedures

[4] To test this hypothesis, we conducted high velocity friction (HVR) experiments on natural serpentinite from Taiwan using a rotary shear apparatus at Kyoto University [*Hirose and Shimamoto*, 2005]. The serpentinite is composed of >95% antigorite, with a starting grain size of  $\sim 80 \mu\text{m}$ . We chose serpentinite because it is a representative phyllosilicate whose frictional properties are often used to model the strength of the San Andreas fault [*Moore et al.*, 1996]. Slip on an artificial fault under normal stress was obtained by pressing together a pair of cylindrical specimens with a diameter of 22.8 mm, and keeping one specimen stationary while rotating the other one at high speed. Before each experiment, specimen surfaces were polished with 80# SiC powders. The experiments were performed at slip velocities of 0.003 to 1.1 m/s and normal stresses of 1.3 to 24.5 MPa to displacements of over 3 m under unconfined and drained conditions. Thus, the experimental conditions are representative of natural earthquake conditions, especially in terms of slip velocity and displacement. In order to monitor the progress of serpentine dehydration during sliding, the specimen chamber was filled with nitrogen ( $\sim 1\%$  humidity condition) and a capacitive type humidity sensor was placed 25 mm away from the sliding surfaces.

[5] Temperature rise on the sliding surface due to high-velocity slip was calculated by the two-dimension finite element method (FEM), using radial symmetry appropriate for our specimen assembly. Half of the sliding surface was divided into five units and the average heat flux from the sliding surface was determined for each unit from time-varying shear stress and slip rate data. It was assumed that all frictional work converts into heat. The radial surface of the specimen was treated as a heat transfer boundary to air. Heat loss due to extrusion of gouge from the sliding surface

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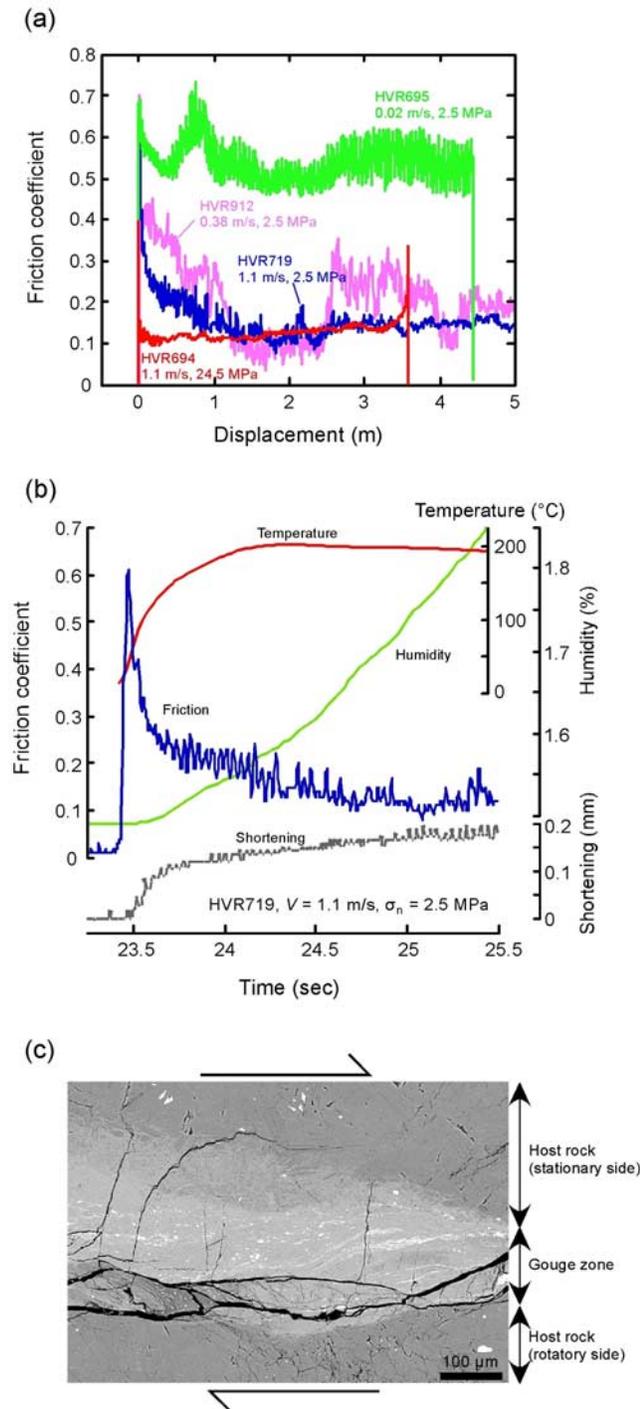
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was not incorporated into the calculation. Thermal properties of serpentinite used in the calculation are: thermal conductivity of 2 W/mK, specific heat capacity of 800 J/kgK, density of 2600 kg/m<sup>3</sup>, and heat transfer coefficient of 150 W/m<sup>2</sup>K in flowing air. Temperatures at asperities where rough surfaces are in contact, called “flash temperatures”, are much higher than calculated values by FEM [Archard, 1958; Rice, 2006]. We also estimated the flash temperatures using the method of Archard [1958], assuming a contact diameter of 5  $\mu$ m and a local shear strength of 3 GPa at asperities.

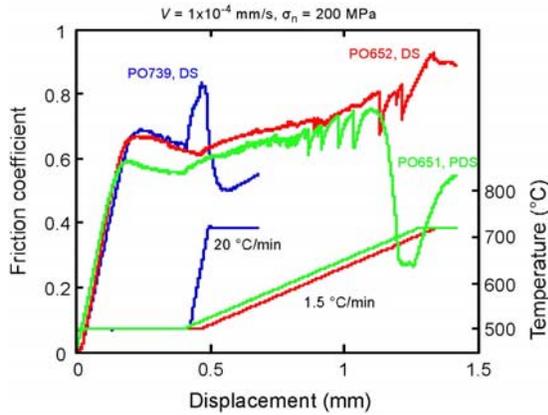
[6] In order to investigate the effect of dehydration of serpentinite on fault strength, we also carried out high temperature and pressure torsion (HTPT) experiments on specimens cored from the same serpentinite block in a Paterson gas-medium torsion apparatus at ETH Zurich [Paterson and Olgaard, 2000]. We prepared pairs of hollow cylindrical specimens with outer and inner diameters of the sliding surfaces of 10 and 2 mm, respectively, or solid specimens with a diameter of the sliding surfaces of 10 mm. In both cases, specimens were jacketed in iron and specimen ends were connected to atmosphere pressure through porous end-spacers and pore-pressure tubing; therefore our experiments were performed under drained conditions. Experiments were conducted at a confining pressure (equal to normal stress) of 200 MPa and a slip velocity of 10<sup>-4</sup> mm/s, seven orders of magnitude lower than that in the HVR experiments. Temperature was first increased to 500°C using an internal furnace, and then sliding was started. Once fault slip achieved a steady state, we increased temperature from 500 to 720°C at a ramping rate of 1.5 or 20°C/min. Thus, dehydration occurred during frictional sliding on the fault as dehydration conditions for antigorite serpentinite were reached.

### 3. Experimental Results

[7] Representative mechanical behaviors of serpentinite in HVR experiments are shown in Figure 1. The frictional coefficient  $\mu$  varies between 0.5 and 0.7 at low slip velocities  $V$  and low normal stresses  $\sigma_n$  (Figure 1a), consistent with Byerlee’s rock friction law [Byerlee, 1978]. At these conditions, no humidity change was detected (i.e., no dehydration took place on the sliding surfaces). As  $V$  is increased to 0.38 m/s at  $\sigma_n = 2.5$  MPa,  $\mu$  oscillates between 0.4 and 0.1 with a slight increase in humidity at the beginning of slip by  $\sim 0.1\%$  in 20 seconds. In contrast, at  $V = 1.1$  m/s and  $\sigma_n = 2.5$  MPa,  $\mu$  increases to 0.61 at the onset of slip and immediately drops to a steady-state value of 0.15 with slip. The slip weakening distance  $d_c$ , over which friction decreases from peak to steady-state value, is  $\sim 1.5$  m. An even more extraordinary degree of slip weakening ( $d_c = \sim 0.1$  m) is observed when  $\sigma_n$  is increased to 24.5 MPa at  $V = 1.1$  m/s. Thus, an increase in either  $V$  or  $\sigma_n$  causes a marked slip weakening and a strong decrease in  $d_c$ . At high slip velocities and normal stresses (i.e.,  $V > 0.15$  m/s



**Figure 1.** (a) Representative frictional coefficient versus displacement curves from HVR experiments on serpentinite at normal stresses of 2.5 and 24.5 MPa and slip velocities of 0.02, 0.38 and 1.1 m/s. (b) Mechanical data at normal stress of 2.5 MPa and slip velocity of 1.1 m/s, plotted together with change in measured humidity, axial shortening of specimen due to gouge extrusion from sliding surfaces and calculated maximum temperature on sliding surfaces. (c) Backscattered electron image showing representative microstructure of a fault zone after 3.6 m sliding at a normal stress of 24.5 MPa and a slip velocity of 1.1 m/s. A completely dehydrated gouge layer with  $\sim 100$   $\mu$ m thickness developed during sliding. Sense of shear is dextral. Visible cracks all formed after the experiment during specimen recovery from the apparatus.



**Figure 2.** Frictional coefficient versus displacement curves from high temperature torsion experiments, plotted with paths of temperature rise. Experiments were performed at a normal stress of 200 MPa and a slip velocity of  $1 \times 10^{-4}$  mm/s. DS, drained specimen (hollow-cylindrical shape); PDS, partially drained specimen (solid-cylindrical shape).

and  $\sigma_n > 1.5$  MPa), an increase in humidity is always measured during the experiments, indicating that at coseismic conditions frictional sliding inevitably produces enough heat for the release of water from serpentinite.

[8] In order to investigate whether the initiation of slip weakening is associated with dehydration by frictional heating, we compared the early stage of slip weakening behavior with measured changes in humidity and maximum temperatures on the sliding surface calculated by FEM (Figure 1b). In experiment HVR719 ( $v = 1.1$  m/s,  $\sigma_n = 2.5$  MPa), humidity rise due to dehydration starts at  $\sim 23.5$  seconds, almost simultaneously with the onset of slip weakening. The maximum calculated temperature by FEM within the fault 2 mm away from the outer fault surface increases by  $\sim 200^\circ\text{C}$  in 0.6 second after the onset of sliding. Although this temperature is far below the one needed to dehydrate antigorite serpentinite (i.e.,  $\sim 500^\circ\text{C}$ ) [Ulmer and Trommsdorff, 1995], the estimated flash temperature by the Archard [1958] method is  $\sim 1250^\circ\text{C}$  at a slip velocity of 1.1 m/s and for a friction coefficient of 0.5 (at the elapsed time of 0.1 second). Thus, temperature at asperities is high enough to induce serpentinite dehydration in the experiments at high slip velocities.

[9] Additional evidence of dehydration was also found in recovered specimens. Powdered rock (gouge) was continuously produced by wear of initially bare fault surfaces during sliding and expelled from the sliding surfaces at high slip velocities, because the fault was not confined in our experiments. Despite that, a gouge zone  $\sim 100$   $\mu\text{m}$  in thickness developed between the sliding surfaces under all experimental conditions (Figure 1c). No slip surface is visible in the gouge zone. Homogeneous deformation in the gouge lead to the development of a foliation defined by aligned opaque grains. Chemical spot-analysis by SEM-EDX indicates a total weight percent of oxides in the gouge of  $\sim 100$  wt%, implying that the gouge particles are completely dehydrated during the experiment (representative major composition of gouge particles:  $\text{SiO}_2$  of 48.8 wt%,

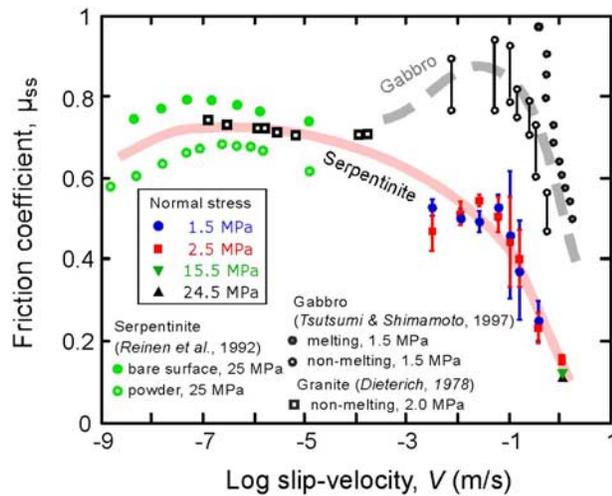
$\text{Al}_2\text{O}_3$  of 2.0 wt%,  $\text{Fe}_2\text{O}_3$  of 3.5 wt% and  $\text{MgO}$  of 45.1 wt%). Dehydration also took place in some grains in the host rock next to the sliding surface. The gouge zone mainly consists of dehydrated serpentinite with grain sizes of less than 5  $\mu\text{m}$ . Grain size reduction may have resulted from the combined effects of milling and dehydration. Although the serpentinite dehydration reaction yields olivine and talc, these reaction minerals could not be identified by either chemical analysis or X-ray diffraction analysis.

[10] Figure 2 shows representative mechanical behaviors, plotted with paths of temperature rise from HTPT experiments. Mechanical data were corrected for the effect of jacket strength using flow laws for iron. The dehydration reaction starts around  $620^\circ\text{C}$  along the sliding surfaces and no more serpentinite remains in the assembly at temperatures above  $700^\circ\text{C}$ . Friction gradually increases from  $\sim 0.6$  at  $500^\circ\text{C}$  to 0.85 at  $720^\circ\text{C}$ , accompanied by stick-slip behavior for runs at a ramping rate of  $1.5^\circ\text{C}/\text{min}$ . The stick-slip behavior is induced by an increase in local fluid pressure in the fault zone due to dehydration. When using a setup with solid specimens (PDS in Figure 2), where fluid cannot escape easily from the fault zone, the frictional coefficient drops markedly to 0.25 at  $\sim 700^\circ\text{C}$ . In experiments using hollow specimens (DS), such a drop is not observed at a ramping rate of  $1.5^\circ\text{C}/\text{min}$ , but occurs when the ramping rate is increased to  $20^\circ\text{C}/\text{min}$ . Thus, rapid heating tends to generate high local pore pressure, because the rate of fluid production by dehydration is faster than the rate of fluid escape. The experiments allowed us to investigate solely the effect of dehydration on fault strength, by avoiding the rapid temperature rise at asperity contacts observed at high velocities.

#### 4. Discussion and Conclusion

[11] Water is present in serpentinite as hydroxyls in the crystal structure and as adsorbed water. The humidity increase observed at lower velocities and normal stresses or at the initiation of slip is likely due to the release of adsorbed water. However, the chemical analysis of gouge particles formed at  $V = 1.1$  m/s implies that the dehydration reaction (the release of structural water in serpentinite) by frictional heating took place at least at some point during sliding (Figure 1c). The dehydration reaction requires a temperature of at least  $\sim 500^\circ\text{C}$  [Ulmer and Trommsdorff, 1995]. For the experiments at  $V = 1.1$  m/s and  $\sigma_n = 2.5$  MPa (Figure 1b), such temperature can be reached only by considering the flash temperature at asperity contacts. Our rough estimation of the flash temperature involves many uncertainties including size and shear strength of asperities and velocity at sliding asperities in the gouge zone. How the reaction took place without formation of identifiable reaction products (olivine and talc) is unclear. Nevertheless, a key observation in the HVR experiments is that dehydration can occur by rapid frictional heating in a short period during coseismic slip.

[12] We now consider what mechanisms are responsible for the marked fault weakening in HVR experiments. A possible weakening mechanism, excess pore pressure built by dehydration, is unlikely due to the following two reasons. (1) The gouge zone developed during sliding at  $\sigma_n < 25$  MPa does not have a permeability low enough to



**Figure 3.** Dependence of steady-state friction on slip velocity. Friction data for serpentinite at slip velocities  $>0.004$  m/s from this study are compared with literature data for serpentinite at low slip velocities and for gabbro at a wide range of slip velocities. For our data, vertical error bars indicate one standard deviation.

maintain an elevated pore pressure. Indeed, at low effective pressures ( $<30$  MPa) the permeability of natural fault gouges which have not experienced higher pressures is greater than  $10^{-18}$  m<sup>2</sup> [e.g., *Noda and Shimamoto, 2005*], while a value smaller than  $10^{-18}$  m<sup>2</sup> is needed for pore pressurization [*Mase and Smith, 1987*]. (2) The minimum flow rate of water in the fault zone is expected to be given by the extrusion rate of gouge, as water in the vapor state is more mobile than gouge due to its low viscosity. The average extrusion rate of gouge is  $\sim 2.6$  mm/s, as calculated from  $\bar{U}_r = U_s R / 2h$  with the assumption that the rate of gouge production is equal to that of gouge loss from a radial surface with constant gouge zone thickness ( $\bar{U}_r$ : average extrusion rate of gouge,  $U_s$ : axial shortening rate of 0.045 mm/s for HVR719 in Figure 1b,  $R$ : sample radius and  $h$  gouge thickness of 100  $\mu$ m in Figure 1c). This value implies that water will escape the specimen immediately after it is released, hindering pore pressure build-up in the gouge zone. Measurement and calculation of permeability of the fault zone are needed in the future to test the issues addressed here.

[13] Considering that no frictional melt was observed and fluid pressurization in our HVR experiments is unlikely, thermal weakening by flash heating [*Rice, 2006*] at asperities of gouge particles is the most probable mechanism for the pronounced weakening of the serpentinite fault. Our HTPT experiments at low velocities but high temperatures showed a higher friction coefficient (Figure 2), implying that high velocities, likely accompanied by flash heating, are necessary to cause the observed low friction in HVR experiments. When increasing the temperature ramping rate in HTPT experiments (Figure 2), a marked stress drop occurs even under drained conditions, due solely to the effect of a rise in pore pressure by dehydration when the normal stress is high (for instance  $\sim 200$  MPa). Therefore, below a certain depth, an even more extreme reduction in fault strength could occur during earthquakes in natural

fault zones by thermal weakening associated with serpentinite dehydration and subsequent fluid pressurization due to rapid frictional heating.

[14] Dependence of steady-state friction ( $\mu_{ss}$ ) on slip velocity ( $V$ ) is summarized in Figure 3. Antigorite serpentinite has a friction coefficient similar to other rocks at  $V < 10^{-4}$  m/s [*Reinen et al., 1992*].  $\mu_{ss}$  of serpentinite decreases with increasing slip velocity and starts to vary between 0.3 and 0.6 at  $V \sim 0.1$  m/s as serpentinite dehydrates due to frictional heating. With slip velocity increasing further towards seismic slip velocities,  $\mu_{ss}$  drops sharply to 0.15. Thus, serpentinite weakens continuously with increasing slip velocity for slip rates higher than  $\sim 10^{-7}$  m/s. By contrast, a frictional barrier is observed for gabbro at intermediate slip rates of  $10^{-3} \sim 10^{-1}$  m/s, and the friction coefficient for gabbro at coseismic slip rates is over twofold higher than the one for serpentinite [*Tsutsumi and Shimamoto, 1997*]. Therefore, earthquake slip will propagate much more efficiently in a serpentinite-bearing fault than in gabbro.

[15] Dependence of friction on slip velocity is significant for determining whether rupture propagates by a crack-like or a pulse-like process [*Zheng and Rice, 1998*]. The strong velocity weakening behavior seen in our experiments is considered a necessary condition for rupture propagation by self-healing slip pulses. Although this rupture mode also needs rapid strength recovery as the velocity decreases, our results meet at least one condition for generation of slip pulses, which have been proposed to explain short slip durations determined for large seismic events [*Heaton, 1990*]. In addition, the slip-weakening distance  $d_c$  decreases with slip velocity and normal stress in our experiments; at conditions close to those for natural earthquakes ( $\sigma_n = 24.5$  MPa and  $V = 1.1$  m/s),  $d_c$  is  $\sim 0.1$  m, a value that is similar to the slip-weakening distances inferred from seismic data [*Ide and Takeo, 1997*]. Previous HVR experiments on natural fault gouge [*Mizoguchi et al., 2007*] and marble [*Han et al., 2007*] also show a similar velocity dependence of friction and slip weakening behaviors, presumably associated with flash heating. Thus high velocity friction in a fault can account for a range of phenomena observed during natural seismic events.

[16] The dehydration temperature of antigorite is higher than that of most other major hydrous minerals. Therefore, the pronounced weakening observed at high slip velocities in this study is likely to be representative of the coseismic behavior of all faults containing phyllosilicates. Dehydration of hydrous minerals within subducting slabs has a significant effect on the strength and stability of faults, and has been considered as a potentially crucial mechanism for the generation of earthquakes along subduction zones [e.g., *Hyndman and Wang, 1993*]. Our results show that even in shallow crustal fault zones, dehydration can occur as a result of rapid temperature rise due to coseismic frictional heating. During earthquakes the strength of seismogenic fault zones is thus much lower than that expected from Byerlee's friction law. In particular, it may well explain the lack of pronounced heat flow observed in major crustal faults such as the San Andreas fault [e.g., *Brune et al., 1969*], and the temperature anomaly recorded just after the Chi-Chi earthquake in Taiwan [*Kano et al., 2006*].

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## References

- Archard, J. F. (1958), The temperature of rubbing surfaces, *Wear*, *2*, 438–455.
- Brodsky, E. E., and H. Kanamori (2001), Elastohydrodynamic lubrication of faults, *J. Geophys. Res.*, *106*, 16,357–16,374.
- Brudy, M., M. D. Zoback, K. Fuchs, F. Rummel, and J. Baumgartner (1997), Estimation of the complete stress tensor to 8 km depth in the KTB scientific drill holes: Implications for crustal strength, *J. Geophys. Res.*, *102*, 18,453–18,475.
- Brune, J. N., T. L. Henyey, and R. F. Roy (1969), Heat flow, stress, and rate of slip along the San Andreas fault, California, *J. Geophys. Res.*, *74*, 3821–3827.
- Brune, J. N., S. Brown, and P. A. Johnson (1993), Rupture mechanism and interface separation in foam rubber models of earthquakes—A possible solution to the heat-flow paradox and the paradox of large overthrusts, *Tectonophysics*, *218*, 59–67.
- Byerlee, J. D. (1978), Friction of rocks, *Pure Appl. Geophys.*, *116*, 615–626.
- Dieterich, J. H. (1978), Time-dependent friction and the mechanics of stick slip, *Pure Appl. Geophys.*, *116*, 790–806.
- Di Toro, G., D. L. Goldsby, and T. E. Tullis (2004), Friction falls towards zero in quartz rock as slip velocity approaches seismic rates, *Nature*, *427*, 436–439.
- Goldsby, D. L., and T. E. Tullis (2002), Low frictional strength of quartz rocks at subseismic slip rates, *Geophys. Res. Lett.*, *29*(17), 1844, doi:10.1029/2002GL015240.
- Han, R., T. Shimamoto, T. Hirose, J. H. Ree, and J. Ando (2007), Ultralow friction of carbonate faults caused by thermal decomposition, *Science*, *316*, 878–881.
- Heaton, T. H. (1990), Evidence for and implications of self-healing pulses of slip in earthquake rupture, *Phys. Earth Planet. Inter.*, *64*, 1–20.
- Hirose, T., and T. Shimamoto (2005), Growth of molten zone as a mechanism of slip weakening of simulated faults in gabbro during frictional melting, *J. Geophys. Res.*, *110*, B05202, doi:10.1029/2004JB003207.
- Hyndman, R. D., and K. Wang (1993), Thermal constraints on the zone of major thrust earthquake failure: The Cascadia subduction zone, *J. Geophys. Res.*, *98*, 2039–2060.
- Ide, S., and M. Takeo (1997), Determination of constitutive relations of fault slip based on seismic wave analysis, *J. Geophys. Res.*, *102*, 27,379–27,391.
- Kano, Y., J. Mori, R. Fujio, H. Ito, T. Yanagidani, S. Nakao, and K.-F. Ma (2006), Heat signature on the Chelungpu fault associated with the 1999 Chi-Chi, Taiwan earthquake, *Geophys. Res. Lett.*, *33*, L14306, doi:10.1029/2006GL026733.
- Lachenbruch, A. H. (1980), Frictional heating, fluid pressure, and the resistance to fault motion, *J. Geophys. Res.*, *85*, 6097–6122.
- Mase, C. W., and L. Smith (1987), Effects of frictional heating on the thermal, hydrologic, and mechanical response of a fault, *J. Geophys. Res.*, *92*, 6249–6272.
- Melosh, H. J. (1996), Dynamical weakening of faults by acoustic fluidization, *Nature*, *379*, 601–606.
- Mizoguchi, K., T. Hirose, T. Shimamoto, and E. Fukuyama (2007), Reconstruction of seismic faulting by high-velocity friction experiments: An example of the 1995 Kobe earthquake, *Geophys. Res. Lett.*, *34*, L01308, doi:10.1029/2006GL027931.
- Moore, D. E., D. A. Lockner, R. Summers, M. Shengli, and J. D. Byerlee (1996), Strength of chrysotile-serpentine gouge under hydrothermal conditions: Can it explain a weak San Andreas fault?, *Geology*, *24*, 1041–1044.
- Noda, H., and T. Shimamoto (2005), Thermal pressurization and slip-weakening distance of a fault: An example of the Hanaore fault, southwest Japan, *Bull. Seismol. Soc. Am.*, *95*, 1224–1233.
- Paterson, M. S., and D. L. Olgaard (2000), Rock deformation tests to large shear strains in torsion, *J. Struct. Geol.*, *22*, 1341–1358.
- Reinen, L. A., T. E. Tullis, and J. D. Weeks (1992), Two-mechanism model for frictional sliding of serpentinite, *Geophys. Res. Lett.*, *19*, 1535–1538.
- Rice, J. R. (2006), Heating and weakening of faults during earthquake slip, *J. Geophys. Res.*, *111*, B05311, doi:10.1029/2005JB004006.
- Tempe, S., D. A. Lockner, J. G. Solum, C. A. Morrow, T. Wong, and D. E. Moore (2006), Frictional strength of cuttings and core from SAFOD drillhole phases 1 and 2, *Geophys. Res. Lett.*, *33*, L23307, doi:10.1029/2006GL027626.
- Tsutsumi, A., and T. Shimamoto (1997), High-velocity frictional properties of gabbro, *Geophys. Res. Lett.*, *24*, 699–702.
- Ulmer, P., and V. Trommsdorff (1995), Serpentine stability to mantle depths and subduction-related magmatism, *Science*, *268*, 858–861.
- Wu, F. T., L. Blatter, and H. Roberson (1975), Clay gouges in San Andreas fault system and their possible implications, *Pure Appl. Geophys.*, *113*, 87–95.
- Zheng, G., and J. R. Rice (1998), Conditions under which velocity-weakening friction allows a self-healing versus a cracklike mode of rupture, *Bull. Seismol. Soc. Am.*, *88*, 1466–1483.

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