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LABORATORY EXPERIMENTS ON ROCK FRICTION FOCUSED ON UNDERSTANDING EARTHQUAKE MECHANICS

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ABSTRACT

In order to determine where best to deploy limited resources for mitigating earthquake loss in the US, we need to understand when and where earthquakes may occur and how intense their accelerations can be. Every time an earthquake occurs, we gain more understanding of the earthquake problem through measurements of ground motion and modeling of seismic sources. In addition to information derived from earthquakes, we can also benefit from improved understanding of the seismic source through laboratory measurements and modeling, to anticipate what may occur in future earthquakes. One of the great gaps in our understanding of source processes is how shear resistance varies on a fault during seismic slip and what this implies about the magnitudes of stress drops and near-fault accelerations. We are helping to fill that gap through our laboratory experiments.

In recent years, we were concerned that the weakening we observe in lab tests and attribute to flash weakening might be significantly influenced by machine artifacts. During the last two years, through exhaustive machine testing and calibration, and additional flash-heating experiments, we have put those concerns to rest. Flash weakening has now been demonstrated to occur in two different apparatus in two different kinds of experiment – one using ring-shaped samples in the Instron apparatus at Brown University [*Goldsby and Tullis*, 2011; *Kohli et al.*, 2011] and one using the pin-on-disk apparatus in the Tribology Laboratory at Oak Ridge National Laboratory. Having conclusively demonstrated the occurrence of flash-weakening behavior, we have focused our efforts on two aspects of this behavior that are critical for understanding how to extrapolate this mechanism from the laboratory to natural faults – 1) the influence of temperature on the flash-weakening velocity, and 2) how distributed vs. localized slip affects the value of the weakening velocity. In the past year, flash-heating experiments at ambient temperatures up to those at the base of the seismogenic zone have revealed only minor influences of temperature on the value of the weakening velocity [*Passelegue et al.*, 2011].

The other focus of our research efforts has been investigation of thermal pore-fluid pressurization. Ours is the first study in which this mechanism will be isolated and characterized under controlled conditions on confined samples (e.g., with fully saturated rocks of controlled fluid pressure and proscribed permeabilities of the rocks). In the past year, the end-member experiments, on 1) unsaturated, practically impermeable samples, and 2) fully saturated samples of high permeability, have been completed.

INTRODUCTION

This is a final technical report for USGS grant G10AP00067. The grant covers a one-year period, from May 1, 2010 to April 30, 2011. We have continued work to increase our understanding of flash weakening and thermal pressurization. The work is relevant to understanding dynamic resistance during earthquakes. We will discuss our progress in detail below.

PUBLICATION RESULTING FROM THIS GRANT

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Kohli, A. H., D. L. Goldsby, G. Hirth, and T. E. Tullis (2011), Flash weakening of serpentinite at near-seismic slip rates, *J. Geophys. Res.*, *116, B03202*, doi:10.1029/2010JB007833.

Goldsby, D. L., and T. E. Tullis (2011), Flash heating leads to low strength of faults during earthquakes, *Science*, *In review*.

RESULTS

Background

During the past several years, we have been investigating the frictional properties of rocks at seismic slip rates. Our experiments to date reveal that two distinct weakening mechanisms occur at sliding velocities above ~1 mm/s. First, a previously unknown mechanism, silica-gel weakening, operates above velocities of ~1 mm/s and requires hundreds of mm of slip to be activated. Second, flash weakening of asperity contacts operates above ~0.1 m/s (for many crustal silicate rocks) and requires only fractions of a mm of slip to be effective. Weakening via the gel mechanism is so extreme for quartz rocks that our data extrapolate to essentially zero strength at a coseismic slip rate of ~1 m/s [*Di Toro et al.*, 2004]. Complete recovery of strength occurs in 100 to 2000 s at low or zero slip rate after rapid sliding, suggesting that the gel is thixotropic. Weakening due to flash heating yields friction that is nearly purely velocity-dependent (i.e., is characterized by a characteristic weakening distance that is on the order of the contact size, since the contact temperature, and therefore frictional strength, adjust to values appropriate to the ambient slip rate over slip distances on the order of the contact size [*Blok*, 1937]), with extrapolated values of the friction coefficient at a slip rate of 1 m/s of ~0.2. Weakening due to gel lubrication is not likely to be conducive to slip-pulse rupture, as the healing times cited above are long compared to the rupture duration in most cases. Flash weakening, in contrast, amply provides the velocity-weakening friction and essentially instantaneous healing with decreasing slip rate that are required for propagation of dynamic ruptures as slip pulses.

In the past two years, through exhaustive analysis and additional machine testing, we have eliminated our prior concerns about machine artifacts in our experimental data and produced a robust demonstration of flash weakening for a wide variety of rocks. Those efforts have resulted in two papers – one on flash heating of serpentine [*Kohli et al.*, 2011] and one on flash heating of a variety of crustal rocks submitted to *Science* [*Goldsby and Tullis*, 2011]. (Note: Arjun Kohli, the lead author on the *JGR* serpentine paper, was a Brown undergraduate, now a grad student at

Stanford). With these accomplishments in hand, during this year we have conducted extensive new experiments on flash heating to study the influence of elevated fault temperature on the weakening velocity for flash heating/melting, V_w. Experiments were conducted in our workhorse Instron testing machine using a newly designed and constructed heating stage. Our expectation from flash-heating theory (*Rice*, 2006; *Beeler et al*., 2008) was that an increase in the average fault temperature T_f from 25 to 300 ºC, a value appropriate for the base of the seismogenic zone, would shift V_w to lower slip rates by a factor of ~2 (see below), making it a viable weakening mechanism at slip rates as low as 40 mm/s, depending on the sample material. As detailed below, these experiments reveal essentially no or very modest increases or decreases in V_w at 300 ºC compared to samples at room temperature (except for serpentine). While at first glance these data might appear surprising, a detailed analysis of the theoretical expression for V_w, and the covariation of various thermodynamic and materials parameters in that equation with increasing temperature, indicates that little-to-no variation in V_w with increasing temperature is *fully consistent* with theoretical expectations. The results of these experiments are currently in preparation for submission to *Geophysical Research Letters [Passelegue et al., 2011]*.

During the past two years, we modified our high-pressure rotary-shear apparatus and collected and had machined the sample materials that have allowed us to conduct experiments on weakening due to thermal pressurization of pore fluids. For these experiments, we wish to employ the fastest available slip rates in our high-pressure apparatus. With the addition of a new pump for our hydraulic power supply, and with modifications to the C program that controls the apparatus, we upped our available slip speed to ~0.01 m/s, a value that theory (e.g., *Mase and Smith*, 1987) indicates will yield profound shear weakening due to thermal pressurization. In the past year, we conducted numerous calibration tests to determine what the physical limits are to the maximum available speed, to prevent damage to our electro-hydraulic stepping motor. As explained below, we ascertained that the best material for the fluid-pressurization experiments is a fine-grained diabase. Diabase does not undergo weakening at large slip displacements and high slip rates as do other silicate rocks of higher silica content [*Roig Silva et al*., 2004a; b], and does not weaken due to flash heating at the modest (sub-0.1 m/s) slip rates of the proposed tests [*Goldsby and Tullis*, 2011]. Any observed weakening due to thermal pore-fluid pressurization will therefore not be convolved with that due to other known mechanisms. (As detailed below, our first tests on dry samples of essential zero permeability, and saturated samples of relatively high permeability, confirm these expectations.) We have collected large suitable samples of Frederick Diabase from near its type locality east of Frederick, Maryland, had the blocks slabbed at a stonecutter in preparation for coring, made thin sections of the material for microstructural characterization, and conducted our first experiments. We will continue to use this material to explore thermal pressurization, a mechanism which theory indicates should be readily accessible in experiments on saturated diabase samples in our high-pressure apparatus.

Recent results and insights from high-speed friction experiments at elevated temperature

Introduction. Our research efforts of the past year have focused on further understanding and quantifying the frictional behavior of crustal rocks at seismic slip rates. We have focused on better understanding dynamic fault weakening due to flash heating of asperity contacts, and on thermal pore-fluid pressurization. Flash-heating tests in the Instron apparatus have recently employed a sample grip less compliant and more massive than the grip used in previous tests; this more massive grip leads to better data with fewer oscillations. We therefore modified it for high-temperature use. Using this modified high-temperature grip results in reduced oscillations

in shear stress due to machine resonance compared to our earlier more compliant high-temperature grip (see below).

Dynamic weakening due to flash heating/melting. At seismic slip rates, high temperatures can be generated at the microscopic contacts on a fault surface, which may thermally degrade the solid-state strength of or even melt frictional contacts, yielding dramatic reductions in fault strength. This 'flash-weakening' mechanism is reasonably well understood theoretically, and quantitative predictions of macroscopic frictional strength due to flash heating using available constitutive laws [*Beeler and Tullis*, 2003; *Beeler et al*., 2008; *Rice*, 1999; 2006], employing appropriate physical properties of earth materials and laboratory-like contact dimensions, are apparently in good agreement with data from some high-speed friction experiments on rocks, including those from our laboratory [*Goldsby and Tullis*, 2003; 2011; *Tullis and Goldsby*, 2003], Vikas Prakash's lab at Case Western University [*Prakash and Yuan*, 2004; *Yuan and Prakash*, 2005], and Toshi Shimamoto's lab [*Hirose*, 2002; *Hirose and Shimamoto*, 2005; *Tsutsumi and Shimamoto*, 1997].

The influence of average fault-surface temperature on flash-heating behavior. We surmised that an experimentally testable prediction of flash-heating theory [e.g., *Rice*, 2006] is that the weakening velocity V_w should decrease with increasing average temperature T_f of the fault surface. Theory [e.g., *Rice*, 2006] predicts that

$$V_w = \frac{\pi\alpha}{D}\left[\frac{\rho C(T_w - T_f)}{\tau_c}\right]^2$$

Here α is thermal diffusivity, D contact size, ρC thermal capacity (where ρ is density and C is heat capacity), T_w the weakening temperature, T_f the slowly evolving average temperature of the fault surface, and τ_c the contact shear stress. From the expression above, an increase in temperature T_f from 25 to 300 °C would be expected, neglecting variations in other parameters in the expression for V_w, to cause a decrease in V_w by a factor of ~2 assuming a weakening temperature of 1000 °C. Such a change in V_w should be discernible in our friction data.

To test this hypothesis, we modified the design of our existing, so-called "massive grip", shown in Fig. 1, to accommodate an aluminum heating-block containing resistive heating

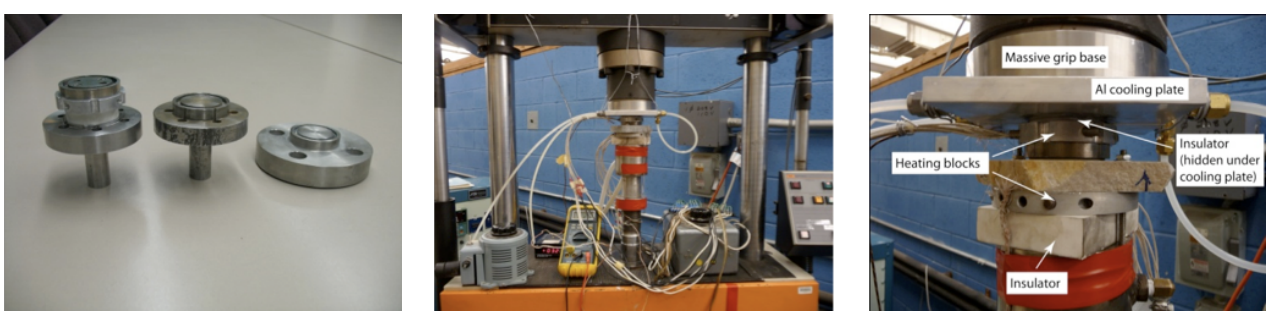


Figure 1 – LEFT - Photograph of various upper sample grips used in the study of flash heating behavior in the Instron apparatus. The left-most is the compliant high-T grip, the middle is the compliant room-T grip, and the right-most is the room-T massive grip. CENTER – Photograph of the Instron set up for high-temperature experiments. RIGHT – Detail photo showing the modifications to the sample assembly required for the high-temperature experiments, with our new massive grip base at the top. White hoses in the RIGHT photo carry cooling water to and from the upper cooling plate and the lower sample grip.

elements that allows samples to be heated to in excess of 300 ^{o}C. Unlike the previous, much more compliant version of our upper sample grip (both the room-temperature and elevated-temperature versions are shown in Fig. 1), the massive grip bolts directly to the load/torque cell of the apparatus with four large cap screws (see Fig. 1); the compliant grips, in contrast, are attached to a spacer that bolts to the load cell, and are held inside the spacer only through a compression fit on the 25.4 mm diameter shaft. The latter arrangement is much more compliant in compression and in shear than that of the massive grip, and this increased compliance, combined with the strongly velocity-weakening constitutive behavior of the fault due to flash heating, can yield large oscillations in friction (in a few cases, with oscillations large enough to completely unload the dynamic friction!). The massive grip results in fewer oscillations of lower amplitude, and thus was modified for high-temperature use. The straightforward modification of the grip design involved the insertion of a 'thermal break', i.e., an insulating element (Macor® glass ceramic), between the hot stage and the metal part of the grip attached to the load/torque cell. Water passing through aluminum cooling blocks (see Fig. 1), in conductive contact with the Macor thermal block and the massive metal base part of the grip, advected heat away from the load/torque cell. The lower high-temperature grip, unmodified from our previous design, is shown in Fig. 1; it also consists of an aluminum block containing heating elements, with an insulating block and a cooling element between the heating stage and the hydraulic ram. The temperature of upper and lower grips was controlled independently using variable ac power supplies (Variacs), with heating elements in each grip connected in parallel to their own Variac.

The testing procedure for the elevated-T experiments was as follows: Samples were brought into contact at room T and a nominal normal stress of 5 MPa was applied (and held constant throughout the test) with the hydraulic ram. In some cases, flash-heating tests were first conducted at room T, and subsequent tests (on the same sample) were conducted at progressively higher Ts. In other cases, samples were first heated to the highest T, ~300 ^{o}C, and a flash-heating test was conducted, and subsequent tests (on the same sample) were conducted at progressively lower Ts. To heat the samples, the ac voltages to the heating stages were slowly increased in ~10% (of 110 V) increments, with 10 to 15 minutes allowed between increases for T to increase and stabilize. Two K-type thermocouples were used to monitor T, one each for the upper and lower grips. One thermocouple was placed in contact with the side of the upper sample ring, as close to the fault surface as possible without touching the sample plate; the other was placed in contact with the surface of the sample plate, as close as possible to where the ring contacted the plate. We also used a handheld laser-pointed infrared (IR) T sensor to provide an additional measure of T. Moving the thermocouple and the IR laser spot around on the surface of the lower sample plate both revealed some variation of T with location; we estimate that the temperatures reported for the ring and plate are known to within 20 ^{o}C. The maximum T in the experiments is limited not by the heating stages but by the epoxy used to glue the rings in the upper sample grip, which burns at ~350 ^{o}C.

Experimental results from high-temperature tests – Experiments were conducted on quartzite, gabbro, granite, calcite, and serpentine. Results of a series of tests on quartzite are shown in Fig. 2. (Note: In all plots of friction coefficient vs. slip rate presented here, we only plot friction from the peak slip rate to the friction at the end of the test, neglecting the data acquired during acceleration to the peak slip rate. We have shown previously that the data acquired during deceleration are a more reliable indicator of material behavior [*Goldsby and Tullis*, 2011; *Kohli et al.*, 2011]). As shown in Fig. 2, data acquired using the modified massive

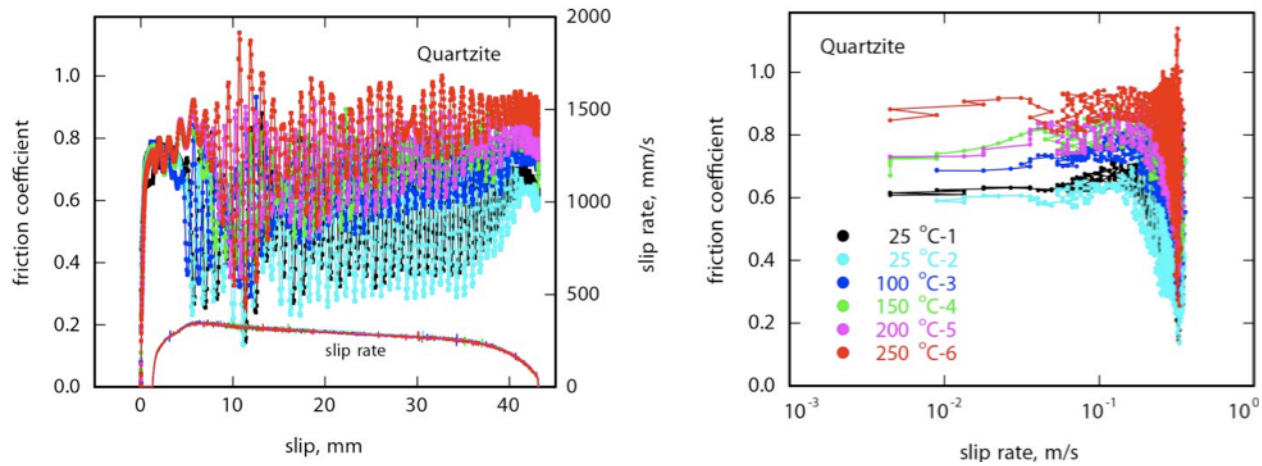


Figure 2 – Plots of a) friction coefficient and slip rate vs. slip and b) friction coefficient vs. velocity, for high-speed friction tests on quartzite. In both plots, data have not been smoothed using the FFT filter. Color scheme in the legend in b) corresponds to both plots. Numbers to the right of each run temperature in the legend indicate the sequence in which the data were acquired in multiple tests on the same sample.

grip still contain oscillations in friction of sufficiently large amplitude to make discerning between possible variations in V_w at the various temperatures somewhat difficult. (These oscillations presumably result from the addition of additional compliant elements in the upper sample grip). We therefore smoothed the data to make variations in V_w and frictional strength more discernible. (*Notes on smoothing*: Smoothing was accomplished using the equivalent of a Fast Fourier Transform (FFT) filter operation. See the Genplot Software manual - http://paros.princeton.edu/genplot.html - for details on the "smooth_FFT" data transformation. In Fig. 3 it can be seen that the smoothed data appear to represent a faithful average of the friction coefficient in plots of friction coefficient vs. slip (Fig. 3a) and vs. slip rate (Fig. 3b).

In Fig. 4, the results of an extensive suite of experiments on quartzite, calcite, antigorite serpentine, India gabbro, and Westerly granite are presented. The observations can be summarized as follows: 1*) quartzite* – increasing friction is observed with increasing

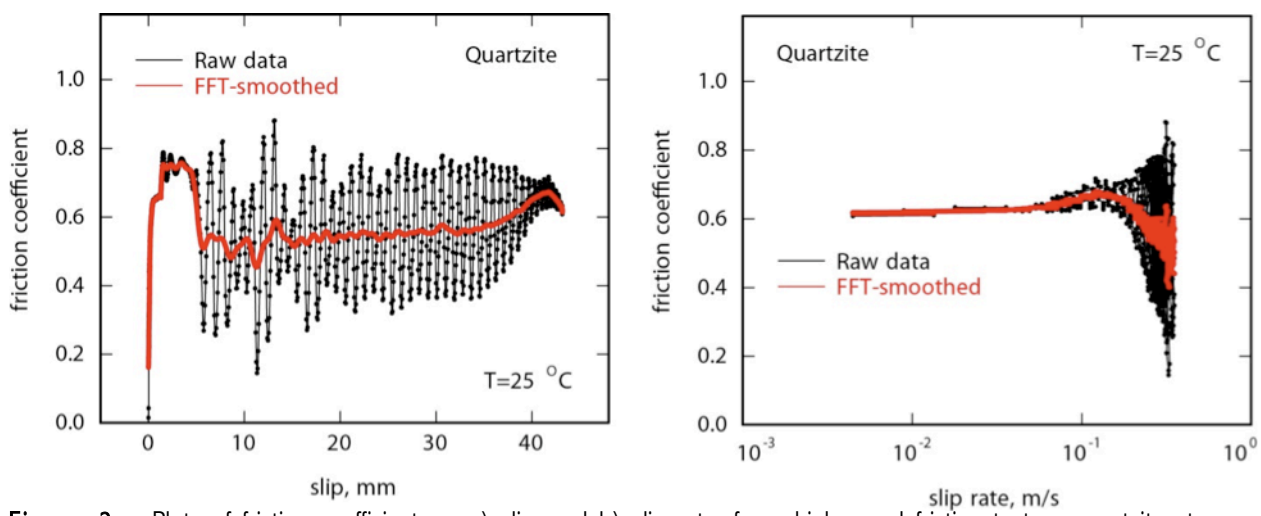
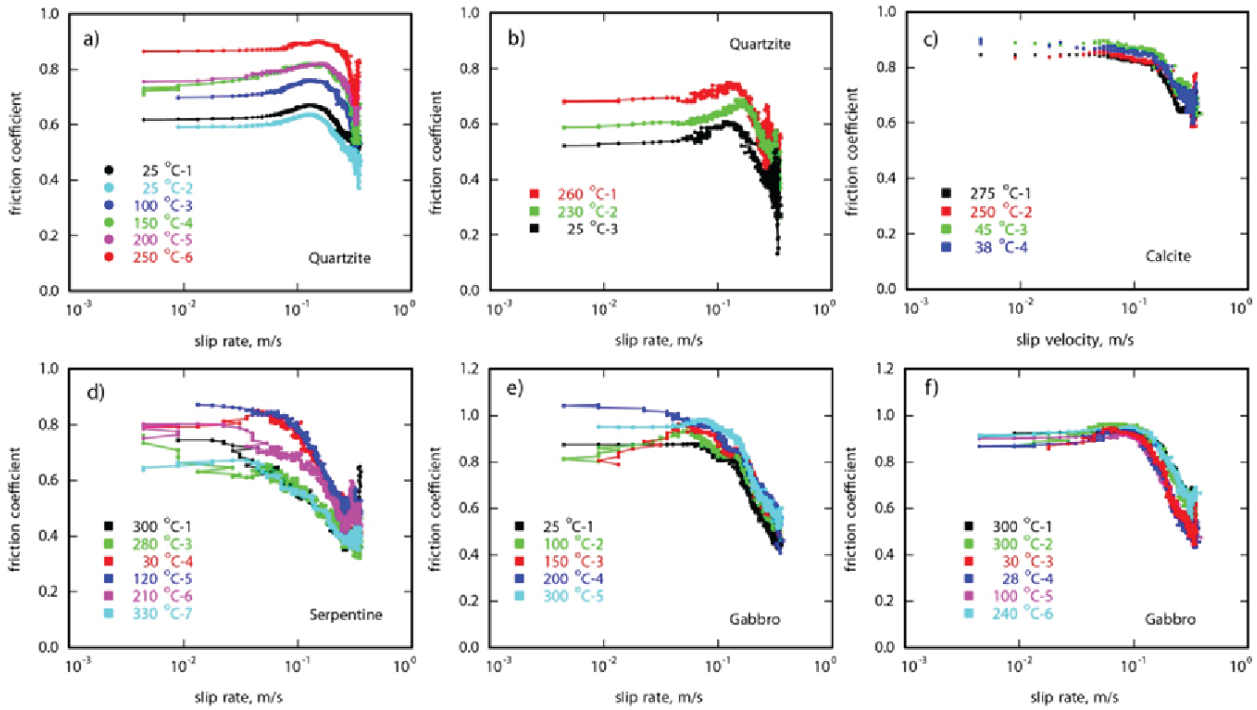


Figure 3 – Plots of friction coefficient vs. a) slip, and b) slip rate, for a high-speed friction test on quartzite at room temperature. In both plots, the FFT-filtered data are shown by the red trace.



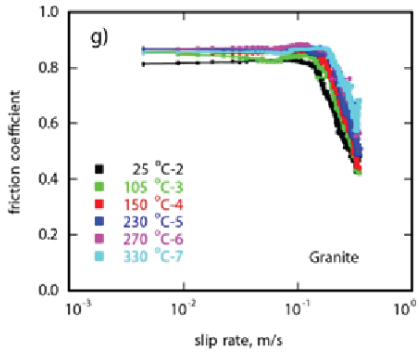


Figure 4 – Plots of friction coefficient vs. slip rate for a) quartzite, b) quartzite (same rock type but different specimen than in a), c) calcite, d) serpentine, e) gabbro, f) gabbro (same rock type but different specimen than in e), and g) Westerly granite. All data have been smoothed using an FFT-filter to allow the trends in the data, including V_w, to be determined. Numbers to the right of the temperatures in the legend indicate the sequence in which the data were acquired.

temperature, accompanied perhaps by a slight increase in V_w, 2) *calcite* - a slight decrease in friction in overall friction is observed with increasing temperature, with essentially no change in V_w, 3) *serpentine* – though the data are somewhat scattered, they appear to indicate a decrease in both friction and V_w with increasing temperature, 4) *gabbro* – friction increases with increasing temperature, with little to no change in V_w,, and 5) *granite* – friction and V_w increase with increasing temperature.

Variations in V_w (or the lack thereof) with increasing temperature – As noted above, an increase in the ambient temperature of the sliding surface in our experiments, to values appropriate for the base of the seismogenic zone, ~300 °C, yields modest to zero changes in the values of V_w. In some cases, the value of V_w *increases,* counter to expectations based on the theoretical relationship between V_w and T_f, i.e., $V_w \propto (T_w - T_f)^2$. However, our expectation was somewhat simplified in that it ignored concomitant variations in other parameters besides T_f in the equation for V_w, namely the thermal conductivity (and therefore thermal diffusivity), contact size, contact shear stress, and heat capacity. These variations turn out in most cases to nearly counteract the effect that would be expected from changes in T_f if these variations were ignored. It is straightforward to show from the equation for V_w above that V_w can be scaled from 25 to 300 °C with the following scaling relationship:

$$\frac{V_{w,300}}{V_{w,25}} \propto \frac{k_{300}}{k_{25}} \frac{C_{300}}{C_{25}} \frac{D_{25}}{D_{300}} \left[\left(\frac{\tau_{c,25}}{\tau_{c,300}} \right) \left(\frac{T_w - 300}{T_w - 25} \right) \right]^2$$

where k is thermal conductivity. As an example, we estimate this ratio for quartz. Increasing T_f from 25 to 300 °C yields a value of k_{300}/k_{25} of ~0.5 [*Clauser and Huenges*, 1995], and C_{300}/C_{25} of 68/49 [*Hemingway*, 1987]. D_{25}/D_{300} is estimated from the assumption that the indentation hardness H, equal to P/A, where P is the contact load and A the contact area, is proportional to the yield stress, and D is equal to the diameter of circular contacts; changes in D are thus derived from changes in hardness with temperature (H_{300}/H_{25} ~ 0.7) [*Evans*, 1984]; this gives D_{25}/D_{300} of ~ $\sqrt{0.7}$. The ratio $\tau_{c,25}/\tau_{c,300}$, ~10/7, assumes that the contact shear stress is proportional to the yield stress, estimated from indentation hardness data for quartz at 25 and 300 °C [*Evans*, 1984]. Assuming a weakening temperature T_w of 1000 °C yields a ratio of (Tw-300/T_w-25) of 0.7. Substituting these various ratios into the scaling relationship yields a value of ~0.6, that is, a decrease in V_w by a factor of ~0.6 with an increase in T from 25 to 300 °C. This decrease in V_w contrasts with the essentially zero change in V_w with increasing T shown in Fig. 4a,b. This discrepancy may indicate that the assumed weakening temperature is too small; adopting the melting temperature of cristobalite (the high-temperature, low-pressure phase of quartz), 1710 °C, yields a ratio of $V_{w,300}/V_{w,25}$ of 0.82, closer to the observed factor of about 1. Adopting the likely more appropriate melting temperature of coesite for T_w, ~2800 °C, the equilibrium phase at the high pressures of experienced by asperities in contact, yields a value of $V_{w,300}/V_{w,25}$ of ~0.96. Given the levels of uncertainty in the values of the materials parameters, and the relative simplicity of the Rice model, the agreement between the prediction and the observations is good. We are currently searching the literature for all of the materials parameters at low and elevated temperatures for calcite, gabbro and granite that will allow us to further test the above scaling relationship for interpreting our data.

As another example, serpentine, in contrast to quartz, shows a distinct decrease in V_w with increasing temperature. As shown in Fig. 4d, although there is some scatter in the data, values of V_w at elevated temperatures are in the range 18-35 mm/s, whereas at room temperature values of V_w of ~75 mm/s were obtained, giving ratios of $V_{w,300}/V_{w,25}$ in the range of 0.24 to 0.47. This dramatic difference compared to the other materials can be interpreted using the scaling relationship above. Increasing T_f from 25 to 300 °C yields a value of k_{300}/k_{25} of ~2.5/2.8 and C_{300}/C_{25} of ~1.5 [*Osaka et al.*, 2010]. The ratio D_{25}/D_{300} is estimated in a similar manner as for quartz, yielding a value of 1/1.4. The ratio $\tau_{c,25}/\tau_{c,300}$ is estimated from the Peierl's law of [*Hilairet et al.*, 2007] to be no larger than 1.2 (close to perfect plasticity). Finally, the weakening temperature T_w is assumed to correspond with the temperature of the onset of the serpentine=olivine+talc+water reaction (*Kohli et al.*, 2011), ~600 °C. Substitution of these ratios into the scaling relationship yields a value of 0.49, close to the upper bound of the observed ratio of $V_{w,300}/V_{w,25}$.

In general, it appears that variations in the weakening velocity for flash heating with temperature can be understood in terms of the simple model of *Rice* [2006]. A broad conclusion that can be drawn from our experiments is that over a temperature range that spans those within the seismogenic zone, changes in V_w with temperature are modest at best. This fact strengthens the rationale for applying existing constitutive models for flash weakening to the Earth. The remaining questions that must be addressed before flash-weakening 'laws' can be extrapolated

with full confidence to faults in the Earth concern the influence of localized/distributed shearing and comminution on flash-weakening behavior, and the degree to which the presence of weak phases like clays affect the onset of flash weakening.

Dynamic weakening due to thermal pressurization of pore fluids

In the past year, we have conducted our first tests on thermal pore-fluid pressurization, a mechanism being incorporated extensively in theoretical models of dynamic earthquake slip [*Lapusta and Rice*, 2004a; b; *Noda*, 2008; *Noda and Shimamoto*, 2005; *Noda et al.*, 2009; *Rice*, 2006; *Rice et al.*, 2010; *Schmitt and Segall*, 2009; *Segall and Rice*, 2006]. Thermal pressurization of pore fluids occurs when frictional heating along a slip surface results in thermal expansion, and therefore pressurization, of pore fluid within the fault zone. The operation of this mechanism depends critically on the permeability of the rocks adjacent to the slipping zone; if permeability is sufficiently high, thermal expansion of pore fluids can quickly drive fluid flow away from the heating zone, and there is no significant rise in fluid pressure. We have conducted two end-member experiments on Frederick diabase – one on an unsaturated sample (no pore fluids present), and one on a saturated sample of relatively high permeability (~7×10^{-18} m^2). Our experiment on the unsaturated sample confirm our expectation that the Frederick diabase samples have low-enough silica content that they are not weakened by the formation of silica gel-like materials on the slip surface, even after slip at rapid slip rates over meters of displacement, unlike quartz and other more silica-rich rocks [*Di Toro et al.*, 2004; *Goldsby and Tullis*, 2002; *Roig Silva et al.*, 2004a; b]. (Frederick diabase is a useful material in that experimentalists have been using it for 80 years due to its fine grain size and lack of alteration [*Adams and Gibson*, 1929; *Brace*, 1965; *Caristan*, 1982; *Kronenberg and Shelton*, 1980; *Mackwell et al.*, 1998], such that its various material properties are well characterized). The experiment on the saturated sample demonstrated the utility of thermal cracking as a means of varying the permeability of our samples. We subjected the sample in this experiment to a temperature excursion from room T to 1000 ^{o}C prior to the friction experiment. The sample was then 1) glued into the sample grips, 2) saturated while it was inside the gas apparatus under confining pressure, using our flow-through pore pressure system to control the externally applied pore pressure at a constant value, 3) taken out of the apparatus to remove the flow-through tubing (which is incompatible with large sliding displacements) and install a plug in the lower pore-pressure port, and 4) placed back in the apparatus and pressurized to the desired confining pressure and pore pressure. During the experiment, pore pressure was servo-controlled at a constant value. The saturation stage yielded a value of the permeability for the 1000-^{o}C thermal-cracking treatment of 7×10^{-18} m^2, which contrasts with uncracked samples that are impermeable on a practical laboratory timescale. When this sample was sheared at high slip rates, it exhibited a modest but significant weakening at the highest slip rates (nearly 1 cm/s), by ~10-20% compared to sliding at slow slip rates <0.1 mm/s). We also observed very rapid recovery of strength immediately after sliding at 10 mm/s, much more rapid than has been observed for weakening due to gel lubrication. While these data are provocative, and suggestive of fluid-pressurization effects, more experiments are required for us to more confidently map out this behavior and make comparisons of our data with theoretical predictions.

Geophysical implications

All of the weakening mechanisms that we are studying have profound implications for the magnitude of stress-drops during earthquakes and consequently for the magnitude of strong

ground shaking. The manner in which fault strength varies with displacement and rupture velocity, as well as the rate at which healing occurs as slip velocity drops behind the rupture tip, can control the mode of rupture propagation, i.e. as a crack or as a pulse. Furthermore, these data can be important for resolving questions concerning stress levels in the crust. If coseismic friction is low, and seismic data seem to constrain the magnitude of dynamic stress drops to modest values, then the tectonic stress levels must also be modest. We may have a strong crust that is nevertheless able to deform by faulting under modest tectonic stresses if the strength is overcome at earthquake nucleation sites by local stress concentrations and at other places along the fault by dynamic stress concentrations at the rupture front. Thus, understanding high speed friction is important not only for practical matters related to predicting strong ground motions and resulting damage, but also for answering major scientific questions receiving considerable attention and funding, e.g. the strength of the San Andreas fault / the heat-flow paradox, the question that ultimately was responsible for the SAFOD project.

Summary

Our experiments show that substantial reductions in shear stress can occur at slip rates faster than those usually attained in laboratory experiments. Our experiments show the operation of the weakening mechanism involving flash heating and reductions of shear strength at localized asperity contacts due to thermal weakening, phase transitions, or local melting. Our preliminary end-member experiments on another weakening mechanism, thermal pressurization, suggest that we should be able to detect it in our experiments. This is because Fredrick diabase does not show gel weakening and it's permeability can be altered by thermal cracking to produce permeabilities high enough saturate the rock, but low enough to prevent loss of fluid pressure during rapid sliding. If the low values of friction at high speed seen in our experiments are characteristic of earthquakes, it implies that dynamic stress drops may be nearly complete. This suggests that, because accelerations and ground motions do not appear to correspond to stress drops to nearly zero from peak values corresponding to a coefficient of friction of 0.6, initial shear stresses on many faults may be well below their static strengths.

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