FINAL TECHNICAL REPORT FOR GRANT NUMBER: 03-HQGR0077

LABORATORY EXPERIMENTS ON ROCK FRICTION FOCUSED ON UNDERSTANDING EARTHQUAKE MECHANICS

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TECHNICAL 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. Among the results of our work is a better understanding of the variability in dynamic shear resistance among relevant crustal rock types. Such variability may control the dimensions of an earthquake rupture and thus determine which earthquakes grow to become major damaging events.

We have made significant progress since last year. We have conducted additional controlled-humidity tests to better understand the gel-weakening phenomenon we discovered, to characterize the gel on the sliding surface, and to better understand and characterize the situations in which gel weakening can occur.

We have also continued an exciting suite of experiments investigating flash heating and flash melting. These experiments are conducted at very high sliding velocities of nearly ~400 mm/s over displacements too short for ultracomminution and hence gel formation to be significant. Our results, coupled with theoretical estimates of flash temperature, are consistent with flash melting at a sliding speed of 300 mm/s or higher.

INTRODUCTION

This is a final technical report for USGS grant 03-HQGR0077. The grant covers a one-year period, from March 1, 2003 to February 28, 2004. We have focused our efforts in two areas. One is to gain further understanding of the physical mechanism causing the dramatic frictional weakening that we attribute to the development of a layer of lubricating thixotropic silica gel on the sliding surface that we discovered during previous grant periods. The other is a series of experiments on so-called 'flash heating' that occurs at highly stressed asperity contacts and that also causes dramatic weakening. The work is relevant to understanding dynamic resistance during earthquakes. We will discuss our progress in detail below.

PUBLICATIONS RESULTING FROM THIS GRANT

Di Toro, G., D. L. Goldsby, and T. E. Tullis, Friction falls to zero at seismic slip rates, *Eos. Trans. Am. Geophys. Union, 84 (46)*, Fall Meeting Suppl., Abstract S41B-02, 2003.

Di Toro, G., D.L. Goldsby, and T.E. Tullis, Friction falls toward zero in quartz rock as slip velocity approaches seismic rates, *Nature*, *427*, 436-439, 2004.

Tullis, T. E., and D. L. Goldsby, Flash melting of crustal rocks at almost seismic slip rates, *Eos. Trans. Am. Geophys. Union, 84 (46)*, Fall Meeting Suppl., Abstract S51B-05, 2003.

RESULTS

Background

During the past several years, we have been investigating previously unknown frictional properties of rocks at nearly seismic slip velocities. Our experiments demonstrate that extraordinary weakening of silicate rocks occurs at slip rates between 3 and 100 mm/s, over sliding displacements and normal stresses characteristic of earthquakes. In some cases, we have measured values of the friction coefficient of <0.1. Weakening is likely caused by the formation of a layer of a weak, silica gel-like material on the sliding surface. Although this is a newly discovered weakening mechanism, comparison with fault surfaces in nature suggests that this mechanism could be operative during dynamic earthquake slip. Weakening via this mechanism is so extreme for quartz rocks that our data extrapolate to a strength of essentially zero at a coseismic slip rate of ~1 m/s [*Di Toro et al.*, 2004]. A combination of large displacement and rapid slip speed is required for weakening to occur, and complete strength recovery at low or zero slip rate after rapid sliding occurs over times of 100 to 2000 s, suggesting that the gel is thixotropic. Although the formation of a silica gel-like layer appears to explain our observations, further knowledge is required to better understand this mechanism, including better characterization of the gel, and an understanding of the roles of water and temperature. This proposal addresses these outstanding problems.

We have completed an extensive series of experiments investigating another dynamic fault weakening mechanism, 'flash heating,' which occurs during the very short (milliseconds) time of contact of microscopic asperities on a fault surface. At sufficiently high velocities, flash heating can lead to melting of the asperities and a reduction in the friction coefficient, even though the average temperature of the sliding surface is too low for the entire fault surface to be melted.

Theory suggests that flash melting should occur readily for silicate rocks at seismic slip rates; results of our experiments appear to be in good agreement with theory, suggesting that *all silicate rocks slide with low friction at seismic slip rates*.

Recent results and insights from tests at rapid slip rates

Introduction. We have made significant progress in our stated scientific goals for this year to conduct additional controlled-humidity tests to better understand gel weakening phenomena, to characterize the gel on the sliding surface, and to better characterize the situations in which gel weakening can occur. In addition, we have completed new experiments investigating flash melting as a dynamic fault weakening mechanism and progressed in the modification of our rotary shear apparatus to allow high pressure experiments at coseismic slip speeds. These efforts are described below. During the past year we published a paper in *Nature* [*Di Toro et al.*, 2004] on results that document the velocity and displacement dependence of gel weakening at speeds up to 0.1 m/s.

Investigation of the gel-weakening hypothesis via controlled humidity tests. We have made four new attempts to duplicate our previous results under conditions of controlled low humidity. We observed previously that the the weakening due to gel formation was completely absent for a novaculite sample dried at 800 ^{o}C in air and slid in a dry nitrogen environment [*Titone et al.*, 2001]. Furthermore, the friction coefficient was larger at both low and high speeds (~0.8) in the dry environment than is typical for undried novaculite slid at low speeds in room humid air (~0.6). On admission of humid air to the sample chamber, however, the friction coefficient at high speed (3.2 mm/s) was observed to drop to values <0.2. Readmission of dry nitrogen to the sample caused friction to increase again to values >0.8; readmitting humid air into the chamber caused friction to drop again to values <0.2. We surmised that this astounding result - the ability to go between a friction coefficient of 0.8 to 0.2 at high velocities simply by varying humidity - resulted from the role of water in the formation of a gel-like material on the sliding surface. Our efforts to duplicate this amazing experiment have not yet been successful. We surmise that the difficulty in replicating our results stems from the notorious difficulty of removing water from the surfaces of silicates. In tests completed this year, we made a number of improvements in equipment and technique in the hopes of eliminating water from our system, including obtaining analytical grade < 5 ppm dry nitrogen, a hotter heat gun to dry out the surface of the sample prior to sealing it in dry nitrogen, baking out novaculite samples for longer times, honing our technique for drying and mounting the sample, and measuring the low test chamber humidity.

Our inability to duplicate the results of the dry experiment does not detract from our primary observation that quartz rocks are weak at high slip speeds and large displacements, and may suggest that the role of water is more complicated than we thought. Furthermore, textural observations of material that exhibits flow features from experiments in humid conditions [*Hinkle et al.*, in preparation] support the idea that a silica gel-like layer is responsible for the weakening.

Characterization of the silica gel layer. We had previously tried to use FTIR spectroscopy to measure the water content of the 3-4 μm thick silica gel layer, but it is too thin allow water detection in either reflected or transmitted mode. Irwin Singer, a tribologist at the Naval Research Laboratory, suggested we should instead try X-Ray Photoelectron Spectroscopy (XPS, also known as Auger Spectroscopy). XPS is commonly used for thin film analysis whereby the surface of a sample is bombarded with monoenergetic soft X-rays, causing electrons to be ejected. The identities of the elements in the sample (not including hydrogen) can be determined

from the kinetic energies of the emitted photoelectrons. The chemical state of the elements can be detected from small variations in the observed kinetic energies of the emitted electrons [*Strausser*, 1992]. We anticipated that such variations related to the presence of water which might change the character of, for example, Si-O bonding. We located an XPS facility at the University of Rhode Island and performed preliminary analyses using a portion of the frictional sliding surface of a sample containing silica gel, a virgin quartz surface, and a pellet of cold-pressed commercial silica gel powder. The shifts in the Si and O peaks that might be due to the presence of water were too small to be useful.

We have also tried to determine water content of the gel with an electron microprobe. The probe cannot determine hydrogen or water content directly, so we measured Si and O contents and compared with Si and O counts from a quartz standard; if there were a significant amount of water in the sample, Si and O counts would be lower in the gel than in the standard, as is the case with hydrated silicate glasses. However, the variability and uncertainty in count rate from several locations on the fault surface and standard were sufficiently high that no conclusion could be drawn concerning the water content of the gel.

Experiments to characterize situations in which gel weakening occurs. We have conducted new experiments to further test our hypotheses about dynamic frictional weakening due to silica gel formation. The experiments were conducted by Dr. Giulio DiToro in the Engineering Department at Brown. Tests were conducted on a variety of rock types listed below:

Rock type	Modal composition of quartz	Weight percent silica
Calcite	0	0
Tanco feldspar	0	68.59
Westerly granite	0.39	69.22
Aplite	0.66	87.67
Novaculite	1.0	100

Modal compositions were determined using optical microscopy, backscattered SEM images and energy dispersive x-ray analyses by Dr. DiToro. Weight percent silica was calculated from modal compositions. One goal of these experiments was to explore the role of quartz and/or silica content in the development of weak silica gel layers during high speed sliding. Experiments were conducted in the Instron Torsion/Compression apparatus described in detail in [*Di Toro et al.*, 2004].

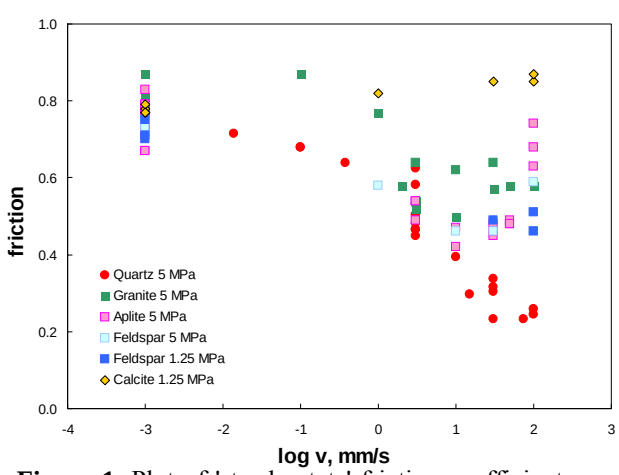

Figure 1. Plot of 'steady state' friction coefficient vs. log velocity for tests on the rocks listed in Table 1. Note the increase in friction at the highest velocities for Tanco feldspar and aplite.

The results are shown in the plot of 'steady state' friction coefficient vs. log velocity in Fig. 1. The plot shows data for novaculite, aplite, granite, Tanco feldspar, and marble. As shown in Fig. 1, tests on all of the rocks except calcite show decreasing friction with increasing slip velocity. Furthermore, the data reveal decreasing friction at a given velocity, in order from highest to lowest friction, for calcite, granite, aplite, Tanco feldspar, and

novaculite. Examination of the table above suggests that the degree of weakening depends not on the amount of quartz present, but rather on silica content (since Tanco feldspar contains no quartz and would show no weakening if the weakening mechanism depended on the amount of quartz present). Interestingly, data for aplite and Tanco feldspar reveal *increasing* friction for $V > \sim 10$ mm/s. A similar increase in friction may occur for novaculite ('quartz' in the figure) at a higher velocity of ~30 mm/s, in contrast to the extrapolation to essentially zero strength at ~1 m/s as we proposed in [*Di Toro et al.*, 2004].

An intriguing explanation for the transition from decreasing to increasing friction is that friction increases when the temperature of the sliding surface is high enough (>100 ^{o}C) to drive off water, in agreement with previous temperature measurements and finite element modeling calculations that indicate temperatures of ~100 ^{o}C or higher at V>10 mm/s for comparable values of friction coefficient and displacement [*Goldsby and Tullis*, 2002; *DiToro et al.,* 2004]. This hypothesis is also supported by the shift toward higher sliding velocities of the transition between decreasing and increasing friction with decreasing values of the friction coefficient (e.g., compare the progression from granite to aplite to novaculite), since heat input on the sliding surface is proportional to the friction coefficient.

If true, this hypothesis has important implications for dynamic fault weakening in the Earth, since it suggests that the decreasing friction with velocity trend observed at velocities less than the transition velocity might continue up to seismic slip rates in the Earth [*Di Toro et al.*, 2004], where faults are saturated with water and pore pressure prevents water from being driven from the sliding surface by heating. Since many faults in the Earth are enriched in silica, this would mean that the gel weakening mechanism might operate during many earthquakes, resulting in total stress drops. Total stress drops imply larger accelerations than typically are observed, unless the initial tectonic stress is relatively low. Such implications for stress magnitudes illustrate the importance of these data.

Alternatively, the increase in friction above the transition velocity may represent a change in the kinetics of bond formation and disruption in the gel layer due to the relative effect of temperature on these processes, with the result being an increase in the rate of bond formation relative to disruption at higher temperature. Such a competition between bond formation and disruption underlies thixotropy, a flow phenomenon exhibited by silica gels [*Serdobintseva and Kalinin*, 2001].

Flash melting experiments. Within the past year, we have completed 9 new experiments investigating the phenomenon of flash heating/melting during rapid sliding of a variety of crustal rocks. Flash melting occurs at highly stressed contacting asperities, due to the extremely high but short-lived input of heat into the contact. The experiments are conducted at ambient pressure at high slip speeds up to ~0.4 m/s and small displacements of ~40 mm; the high velocities but small displacements obtained in these tests insure that insufficient heat is generated to melt the entire or even significant areas of the fault surface, effectively isolating flash heating/melting phenomena from bulk melting effects. At these speeds, theory suggests temperatures well in excess of the melting temperature for quartz, feldspar, and pyroxene [*Rice*, 1999].

Experiments were performed by first sliding at a slow rate (1 or 10 μm/s), then at up to 0.4 m/s for displacements of ~40 mm. Data from a test on Tanco feldspar (a 100% albite rock) are shown in Fig. 2. Similar responses of friction to sliding velocity are observed for novaculite,

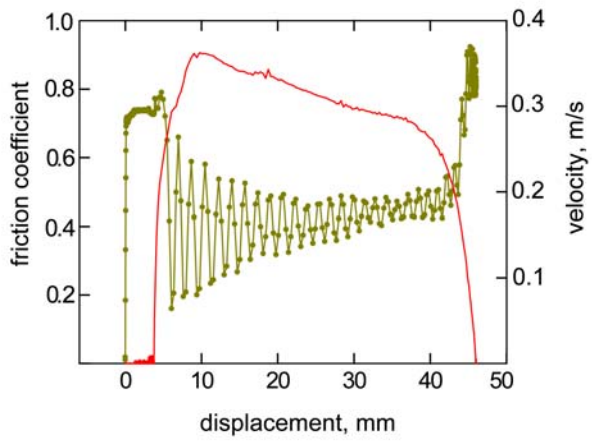

Figure 2. Plot of friction coefficient (in olive green) and sliding velocity (in red) vs. displacement in mm from an experiment on Tanco feldspar. Sliding at slow speeds (10 μm/s) yields a value of the friction coefficient of ~0.6; at higher speeds up to ~360 mm/s, the value of the friction coefficient decreases to an average value of ~0.3. As the sliding velocity decreases toward the end of the test, friction increases back to a value of ~0.6.

granite, and gabbro, as shown below. No weakening is observed for marble. The friction coefficient decreases dramatically with increasing velocity, obtaining values as low as 0.3 for Tanco feldspar at 360 mm/s, then increases as velocity decreases toward the end of the test, to the same values obtained at low speed at the start of the experiment. The oscillations in the data likely result from the interaction of the friction constitutive behavior on the sliding surface and the relatively compliant apparatus. A critical observation is that there is only a very small displacement dependence of friction, exactly as would be expected for flash melting. Data for four different crustal rocks are plotted in Fig. 3 on axes of friction coefficient vs. velocity. The data have been fitted with analytical expressions for the effect of flash heating/melting on macroscopic friction from [*Rice*, 1999] and *Beeler* [submitted manuscript]. Rice derived an expression for the effect on the macroscopic friction coefficient of flash heating $f = f_o V_w / V$, where f_o is the friction coefficient at low velocities, and the characteristic weakening velocity V_w, above which asperties are assumed to have negligible strength is $V_w = (\pi\alpha/D)\, \rho c\, [(T_w - T_f)/\tau_c]^2$, where ρ is density, c heat capacity, T_w the temperature above which asperities have negligible strength, T_f the gradually evolving average fault temperature and τ_c the shear strength of the contact. A key assumption in Rice's analysis is that above V_w asperities have essentially zero strength. Beeler modified the analysis by assuming that weakened asperities have finite strength, yielding $f = f_w - (f_o - f_w)\, V_w / V$.

In most cases, the Beeler modification appears to provide a better fit to the data. The good agreement between theory and experiment in Fig. 3 suggests that weakening is due to flash heating and likely melting. More importantly, extrapolations to seismic slip rates indicate that the friction coefficient obtains values of <0.4 at seismic slip rates for all the silicate rocks tested.

These data potentially have profound implications for dynamic earthquake rupture, since they suggest that extreme weakening occurs for a variety of crustal rocks at seismic slip speeds. Before we publish our results, however, we would like to demonstrate that the behavior is not an artifact of the apparatus, due for example to loss of contact at the abrupt step in velocity. We have conducted tests in which we step from 10 μm/s to 100 mm/s and then 100 mm/s to 360 mm/s, decreasing the size of the step to 360 mm/s and thereby lessening the degree of possible interface separation. The results of that test are identical with results from 10 μm/s to 100 mm/s step tests, as shown in Fig. 3d, suggesting that interface separation does not occur.

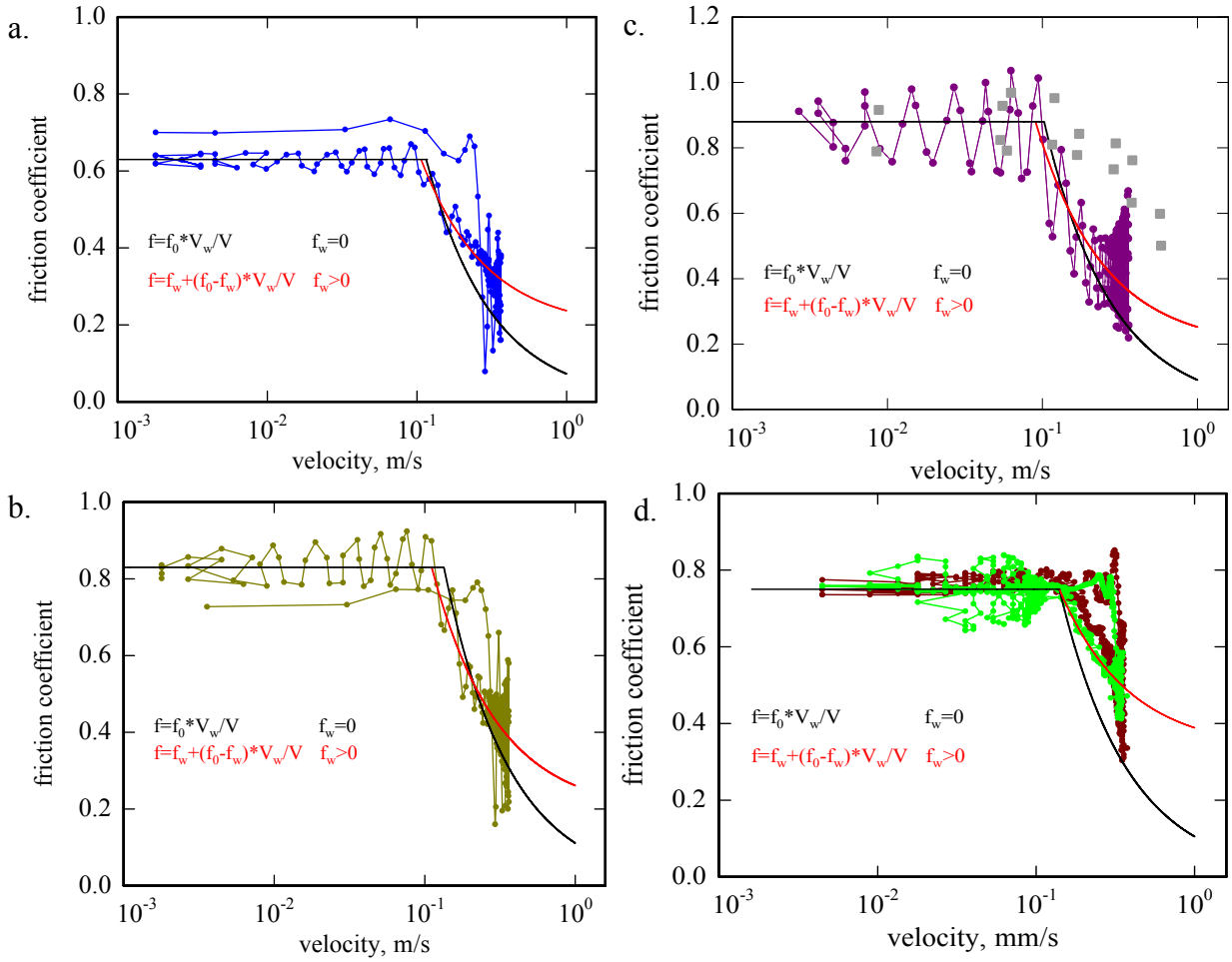

Fig. 3 - Plots of friction coefficient vs. velocity plotted on a logarithmic scale for a) novaculite, b) Westerly granite, c) gabbro and d) Tanco feldspar. Gray squares in c) are data from [*Tsutsumi and Shimamoto*, 1997] on the identical gabbro. Fits to the data are analytical solutions of Rice (1999) in black and Beeler (unpublished manuscript) in red (see text for details). Low speed data are removed from each data set for clarity. In d), data are from two experiments, one in which velocity was stepped from 10 μm/s to 100 mm/s to 360 mm/s (in green) to test for interface separation, and the other in which velocity was stepped from 10 μm/s to 360 mm/s.

Technical progress toward coseismic slip rates at high pressure.

In the past year we have made progress in overcoming two hurdles which limit our ability to slide at seismic slip rates at high confining pressure: Implementing a drive system with enough horsepower and speed to rotate our samples at ≥1 m/s, and incorporating new materials into our sliding jacket assembly which can withstand high temperatures generated at high slip speeds. We have most of the parts we need for our BMW motorcycle engine drive system including the engine, right angle gear box, brake/clutch assembly, harmonic drive speed reducer and the sprockets and drive belts. The conceptual design is complete and the detailed CAD design is 75 percent complete. Previously we envisioned that the engine and drive system would hang off the side of the moving middle platen of the gas rig. However, the overhanging weight could cause the platen, which is attached to the ram which provides the normal force to the sample, to bind on the tie bars. A new design has the BMW engine and most of the drive system mounted on the floor and connected to the base of the hydraulic ram. A ball spline now allows the drive system to remain stationary while transmitting torque to the piston (which moves with the middle platen)

as shown in Figure 4. We continue to progress in this complex task and plan on beginning installation of the drive system this summer.

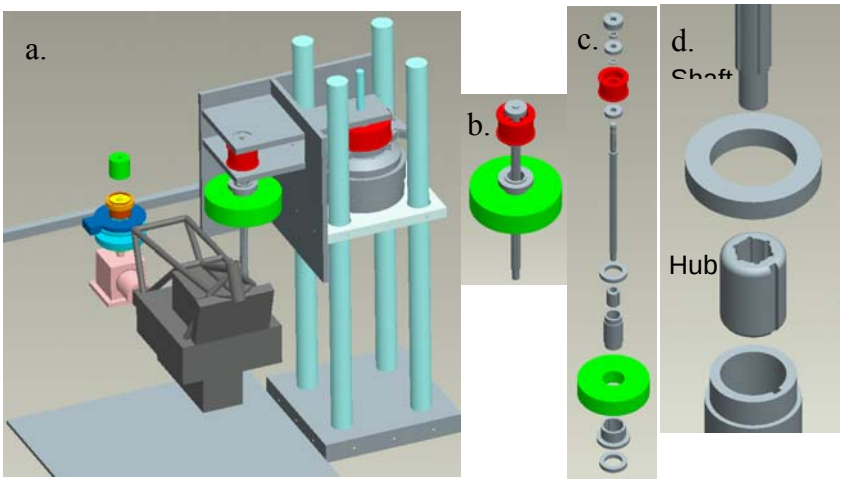

Figure 4. BMW engine drive assembly. **a.** Entire assembly. Engine, right-angle gearbox, brake/clutch, harmonic drive, and green sprockets are stationary, as is lower platen and tie bars of press. Red sprockets and middle platen move vertically via hydraulic ram (not shown) sitting on lower platen. **b.** and **c.** Normal and exploded views of ball spline assembly that allows red sprocket to move with its ball spline shaft while green sprocket and its ball hub are fixed vertically. **d.** Detail of ball spline hub and shaft.

We have been investigating the possibility of replacing the Teflon we now use in our sliding jacket assembly with a high temperature thermoplastic. The most encouraging material to date is Vespel®, made by Dupont, which depending on its grade has friction coefficients from 0.12 to 0.29 and can be used continously up to 300 ºC and for brief periods up to 540 ºC. Since the jacket only needs to survive for one to a few seconds in these fast experiments, these capabilities seem adequate. We have not yet obtained any of this material because it is extremely expensive and the nominal stock sizes available require machining away much of the material. We have budgeted for this product for testing purposes, but will not purchase significant quantities until we can ascertian its suitability.

Geophysical implications

The gel-induced weakening mechanism suggests large, up to near-total, stress drops during dynamic rupture if this mechanism is operative in the Earth. It is notable that many fault zones are mineralized with silica, even though the country rock may not contain much quartz. Some textures seen in such fault zones are difficult to understand and may involve a stage of precipitation of chalcedony, opal or other silica polymorphs [*Power and Tullis*, 1989]. Some of these fine-grained varieties of silica have similarities to silica gel [*Graetsch*, 1994; *Knauth*, 1994], making it plausible that silica gel might form in many fault zones. Another interesting observation is that pseudotachylites are never observed in pure quartz rocks [*Killick*, 1994] perhaps because friction on such faults is too low (as a result of the silica gel weakening mechanism) to cause melting.

Some rocks of low silica content will not weaken via this gel mechanism, but may weaken at high slip velocities due to shear melting. Melting can occur at either the asperity scale, i.e., flash melting, or over the entire fault surface. In contrast to the gel mechanism, which may only occur in certain rock types of sufficient silica content, or along fault zones mineralized with quartz, flash melting has been shown to occur for a variety of crustal silicate rocks. Both flash and bulk melting may result in dramatic decreases in the friction coefficient. Different rock types along a fault zone may weaken via different mechanisms and to different degrees. This variability could result in heterogeneity in rupture velocity and stress drop that could be responsible for some of the complexities inferred in source inversions from strong motion data [*Archuleta*, 1982]. We

intend to further understanding of dynamic fault weakening by continuing our investigation of the frictional behavior of rocks at high slip velocities over at conditions relevant for earthquakes.

Summary

Our experiments show that substantial reductions in shear stress can occur at slip rates faster than those usually attained in laboratory experiments, even at rates slower than typical of earthquakes and even without frictional melting. Two weakening mechanisms have been identified and studies, weakening due to generation of a lubricating layer of thixotropic silica gel and weakening due to local heating at short lived highly stressed asperity contacts. Whether these weakening mechanisms are important for earthquakes is still unclear, but it is certainly plausible. If the large reductions in shear stress seen our experiments are characteristic of earthquakes, it implies that dynamic stress drops may be nearly complete and that, unless the initial stress is also small, accelerations and strong ground motions should be quite large. Thus, there are linked implications for the magnitudes of tectonic stress and of earthquake shaking – if one is high the other is likely to be high as well.

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NON-TECHNICAL ABSTRACT

Our recent experiments have shown that frictional sliding of rocks at speeds approaching those of earthquake slip makes them much weaker than in slower conventional experiments. We have continued to study one weakening mechanism we discovered earlier that could operate during earthquakes, the production of a lubricating layer of silica gel on the sliding surface. We have also investigated another weakening mechanism involving generation of high temperatures at small sliding contact junctions due to frictional heating. If weakening also occurs during earthquakes, faults could be so weak that the size of damaging ground motions might be larger than usually expected.