FINAL TECHNICAL REPORT FOR GRANT NUMBER: 08-HQGR0067

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.

During this year we have continued working on the gel weakening mechanism, flash heating/melting, and thermal pressurization weakening. We have gained a better understanding of why it has been so difficult to reproduce an earlier gel weakening experiment that showed reversal of weakening when the water content was changed, as well as how to overcome the problems. For gel weakening, our results, coupled with theoretical estimates of flash temperature, are consistent with flash melting at a sliding speed of 100 mm/s or higher. Constitutive equations for this mechanism are being used in theoretical dynamic rupture models, so it is important that we verify that this mechanism is in fact responsible for the weakening observed in experiments. We now have several sample assemblies and much of our work has focused on exploring the role of some details of the sample grips that have surprising effects on the experimental results. Last year we reported that using our then-new high temperature assembly we did not see the weakening at high slip speeds that we universally had seen with our then-standard room temperature assembly. We believe we now understand the reasons for the differences and it appears that the high-temperature assembly was giving erroneous results and that the weakening seen in the older assembly is in fact correct. We need to know whether this conclusion holds up to further study and whether this weakening mechanism is likely to operate on faults during earthquakes. If so, it would cause large stress drops over very small amounts of slip, and healing would be essentially instantaneous. In our planned study of thermal pressurization weakening, another mechanism being used in dynamic rupture models but that has no experimental verification, we are making progress in getting suitable sample materials to use in a planned suite of experiments.

INTRODUCTION

This is a final technical report for USGS grant 08-HQGR0067. The grant covers a one-year period, from March 1, 2008 to February 28, 2009. We have continued work to increase our understanding of flash weakening. The work is relevant to understanding dynamic resistance during earthquakes. We will discuss our progress in detail below.

PUBLICATION RESULTING FROM THIS GRANT

Beeler, N. M., T.E. Tullis, D. L. Goldsby (2008) Constitutive relationships and physical basis of fault strength due to flash-heating, *J. Geophysical Res.*, *113*, B01401, doi:10.1029/2007JB004988.

RESULTS

Background

During the past several years, we have been investigating frictional properties of rocks at nearly seismic slip velocities. Our experiments show that two distinct weakening mechanisms occur at velocities above ~1 mm/s. One of these is a previously unknown mechanism, gel weakening, which operates above 1 mm/s and requires hundreds of mm of slip to be effective. The other mechanism, flash heating of asperity contacts, only operates above 100 mm/s (for many crustal silicate rocks) and only requires fractions of a mm of slip to be effective. Weakening due to thermal pressurization of pore fluids is predicted, but no experiments relevant to this mechanism have been done in spite of our early efforts [*Goldsby and Tullis*, 1997].

Weakening via the gel 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]. 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 layer explains our observations, further knowledge is required to better understand this mechanism and its applicability to earthquakes, including a better understanding of the roles of water and temperature. During this year we have reexamined the several different novalulites that we have used as sample material in the past and believe we understand better why we have been unable to duplicate the stunning results from one previous experiment. We believe we also have resolved a discrepancy we reported a year ago in which once sample assembly showed high speed weakening due to the flash mechanism and another did not.

Recent results and insights from high-speed friction experiments

Introduction. Our research efforts of the past year have focused on further understanding and quantifying the frictional behavior of crustal rocks at near-seismic slip rates. We have worked on obtaining a better understanding of dynamic fault weakening due to gel weakening, flash heating of asperity contacts, and thermal pressurization. Most of our efforts have been on flash heating and further delineating the conditions for which this mechanism is expected to control fault strength. In order to study these problems in more detail, we have been using a variety of sample grips, some newly designed, and some new measurement technology in order to understand some of the surprising effects that seemingly modest changes in the experimental

configuration in the Instron testing machine have on the experimental results. We will also soon begin to use other established methods for studying flash heating, such as the pin-on-disk (POD) apparatus, that will compliment the results obtained using the Instron apparatus. We have made progress in obtaining suitable material for thermal pressurization experiments.

Dynamic weakening due to silica-gel lubrication - As we have reported earlier, one of the most interesting experiments we have conducted that shows weakening due to the production of silica gel was conducted by two visiting undergraduate students [*Titone et al*., 2001]. They found that at a slip velocity of 3.2 mm/s, too slow for flash weakening, the weakening that we have observed under ambient humidity conditions in many experiments [*Di Toro et al*., 2004; *Goldsby and Tullis*, 2002] could be eliminated by conducting the experiment under very dry conditions (obtained by drying the samples at high temperature and conducting the tests in dry nitrogen). In fact they could alternate between very high friction (>0.8) and very low friction (<0.2) simply by alternating the environment between dry nitrogen and room-humidity air, respectively. Although we can think of no reason to doubt these results, since the weakening/strengthening behavior was reproducible in this one sample, we have been unable to reproduce this behavior in subsequent attempts. We attribute this lack of reproducibility to the notorious difficulty of removing water from the surfaces of silicate minerals, as Jim Dieterich and John Conrad encountered in their dry experiments on quartzite [*Dieterich and Conrad*, 1984]. During the past year we reexamined the various blocks of novaculite, a quartz rock of ~5 μm grain size, that we have used in various friction experiments. We discovered that the sample material used by *Titone et al*. [2001] is significantly harder than most of our other novaculite samples on which the subsequent experiments were done. The hardness was determined semi-quantitatively by dragging a dead-weight-loaded carbide tip across the surface of each rock. The increased hardness seems to be due to better cementation of the ~5 μm quartz grains comprising the aggregate. This harder novaculite used in the Titone et al. experiment produces very little wear debris (gouge) and does not show a topographically lower wear track (in spite of tens of meters of accumulated slip in the test), unlike the novaculite we have used in subsequent tests, which shows a comparatively deep wear groove for much smaller slips. We speculate that for this harder novaculite, slip is occurring on a very flat, bare surface (rather than in a gouge layer), which may make it easier to dry out the surface and change the friction by alternating the humidity. This suggests that future attempts at replicating this extraordinary experiment should employ harder samples as well as an elevated temperature assembly. Even though the experiments may be done at room temperature, drying the samples at high temperature in the experimental apparatus means that remotely dried samples are never exposed to moist air during transfer to the testing apparatus.

Another development in terms of gel weakening is that we have been contacted by Harry Stel from the Free University of Amsterdam who believes that he and coworkers have evidence for gel having existed in natural fault zones [*Stel*, 1981; *Stel and Lankreyer*, 1994]. He states that "It appears that the role of gels and colloids on faulting is larger than hitherto thought." We are initiating an interaction with him and hope it may lead to ways of recognizing in subsequently crystallized silica-rich fault layers that unstable silica gel was formerly present and consequently to a better understanding of the role that silica gel may play in fault weakening.

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

contact strengths or melt the contacts, yielding dramatic reductions in fault strength. This 'flash weakening' mechanism is reasonably well understood theoretically, and predictions of macroscopic frictional strength due to flash heating, employing appropriate physical properties of earth materials with laboratory-like contact dimensions, are apparently in good agreement with data from some high-speed friction experiments on rocks [*Rice*, 2006a], including those from our laboratory [*Goldsby and Tullis*, 2003; *Goldsby and Tullis*, 2006; *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*, 2004; *Tsutsumi and Shimamoto*, 1997]. However, several questions arise with regard to the operation of this mechanism on natural faults. Is flash weakening important at seismic slip rates for highly comminuted fault gouge, which may have contact dimensions much smaller than lab dimensions? Does flash weakening occur for gouge samples undergoing distributed shear rather than localized slip at earthquake slip rates? Do clay minerals, common fault zone constituents, undergo significant weakening due to flash heating?

Progress on understanding flash weakening. At the time last year's report was submitted we had resolved some of the technical problems that had arisen previously, namely that the Instron testing apparatus in the Engineering Division at Brown had been out of commission due to a problem with one of the large electronic cards in the control panel which controls the rotary actuator and hence sliding of our samples. However, the experiments we had managed to do with our new high-temperature grips showed some surprising contrasts with all of the results we had previously obtained with what we call our 'standard' grips. The difference was that novaculite samples showed no or very little weakening with the high-temperature grips although they showed substantial weakening with the standard grips. The questions are therefore - which set of grips is better and which result is correct?

In order to resolve this we have been using some new transducers to measure normal displacement and normal and tangential accelerations, as well as a newly designed, more massive sample grip. The transducers are accelerometers mounted on both the upper and lower sample grips and a DCDT to measure the relative displacement between the upper and lower grips. These transducers are shown in Fig. 1. An 8-channel digital oscilloscope was used to acquire these data at sampling rates of 10 kHz. An example of some of the preliminary data obtained with this system is shown in Fig. 2. Although the accelerometer data are not yet calibrated against known standards, they indicate accelerations of both sample grips in the direction normal to the sliding surface during a flash-heating experiment and the DCDT shows oscillations in fault-normal opening. One of the more interesting results is that the fault-normal acceleration of the top, nominally stationary grip is larger than

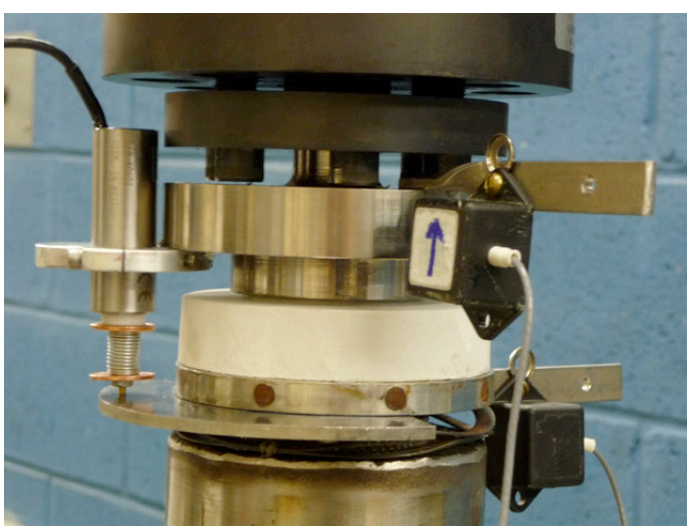

Figure 1. Standard grip instrumented with two vertically oriented accelerometers (black modules) and one DCDT (at left), whose core is spring loaded against a steel plate on the lower sample grip.

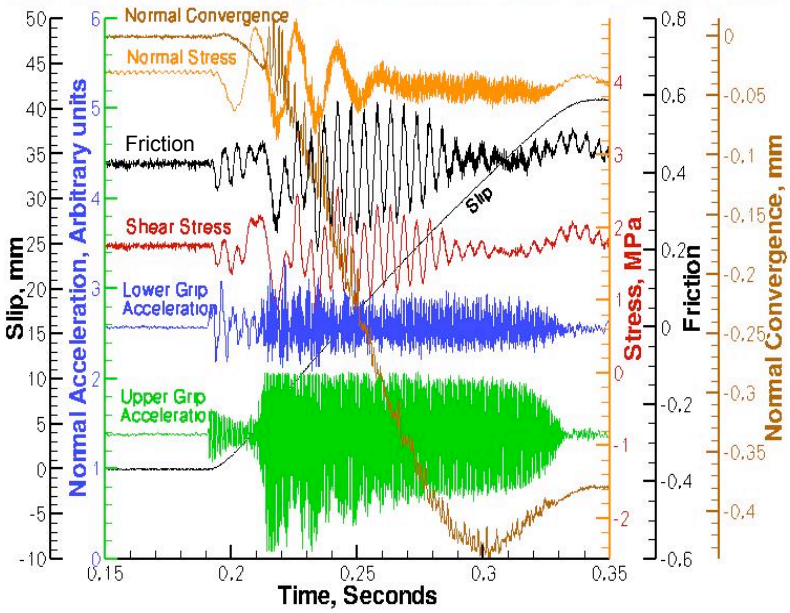

Figure 2. Data for instrumented standard grip of Fig. 1 showing accelerations of both the upper and lower sample grips normal to the fault surface, oscillatory normal convergence measured by the DCDT (the background trend in the brown line is due to the disk in Fig. 1 not being perfectly planar or normal to rotation axis) and oscillations in both normal and shear stress.

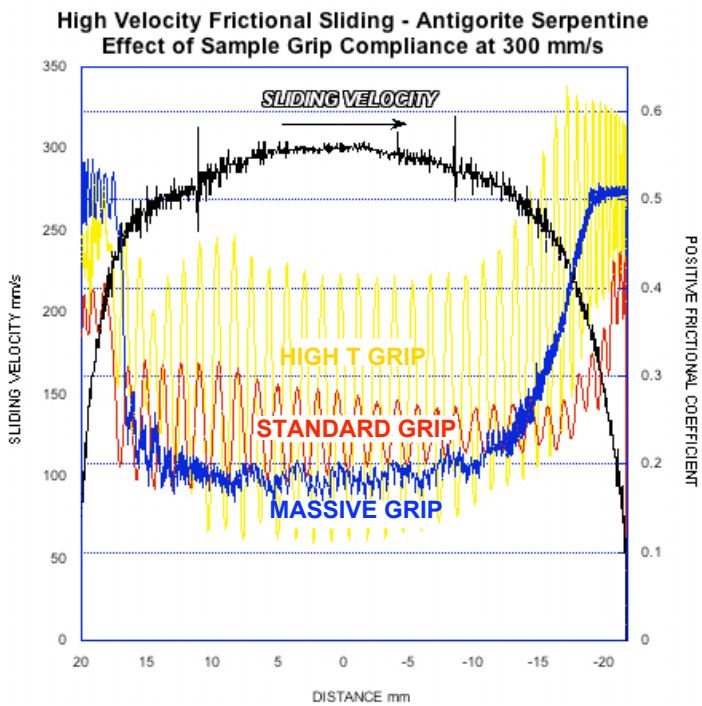

Figure 3. Illustration of much greater stability of system using massive grip. Standard grip is intermediate in behavior and high temperature grip is the least stable. Photos of these three grips are shown in Fig. 4. Clearly the massive grip has less machine-sample instability. For this serpentine sample, unlike the case for some novaculite samples, weakening is seen even with the high-temperature grip.

the acceleration of the bottom rotating grip. One goal of using the accelerometers is to double integrate the acceleration data to obtain fault-normal displacement, and to compare that result with the DCDT measurements of the same.

We presently have three sample grips; arranged in order of increasing stiffness these are the high-temperature sample grips, the 'standard' sample grips and a new stiff, more massive upper grip (see Fig. 4 below). The high-temperature grips are similar to our standard grips, but contain additional elements in each, namely a heating block and insulating block on each of the lower and upper grips, that increase their length compared to the upper and lower standard grips. Although we do not yet have accelerometer measurements and DCDT data for the high-temperature sample grips or the massive upper grip, we have made interesting comparisons of the overall behavior obtained using the three grips, shown in Fig. 3. For these comparisons, we used the same lower sample grip in each test (the 'standard' grip configuration) and only the upper sample grip was varied. Two features are particularly noteworthy in Fig. 3. First, the oscillations which have characterized our experimental results for several years when the standard grips were used are absent when the massive, stiff upper grip is used. Second, these oscillations are even worse with the high-temperature upper grip than with the standard upper grip. This

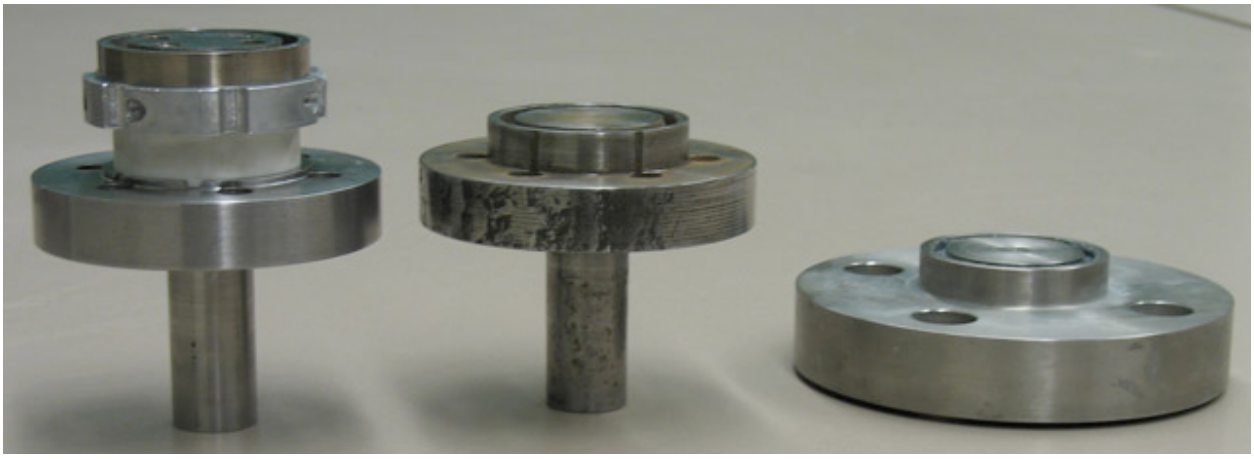

Figure 4. Upper sample grips discussed in text. From left to right these are a) the high temperature grip, b) the standard grip and c) the massive grip. They are oriented upside down for the photo. In use, the sample faces down, and the long one-inch-diameter neck for the left two fits into a collet-like holder (see Fig. 1). The sample is epoxied into the annular groove visible at the top of each grip.

comparison suggests that the massive grip is giving results that are not contaminated by undesirable sample behavior-machine interactions, and that the high temperature upper grip has the greatest undesirable interactions.

What the standard upper grip and the high temperature grip have in common is that the connection to the top stationary crosshead of the Instron and its load/torque cell is made with a one-inch diameter appendage (Fig. 4a and b) that is held in the crosshead with a tapered collet-like arrangement. This is not a stiff configuration in torsion, compression, or bending, although it is the standard method that Instron uses for attaching grips to the crosshead. The massive upper grip (Fig. 4c) is of our own design and manufacture and bolts directly to the crosshead assembly with four large bolts; it is much stiffer in torsion, compression, and bending. The difference between the high-temperature upper grip and the standard upper grip can be seen in Fig. 4. The high temperature grip is longer and consequently it is more compliant in all three modes. With the high-temperature grip we have noted by observing the grips closely during a run that samples run out of alignment laterally, and that when the normal load is removed at the end of a run the samples shift back into alignment. Thus we suspect that results obtained with the high-temperature grips are unreliable.

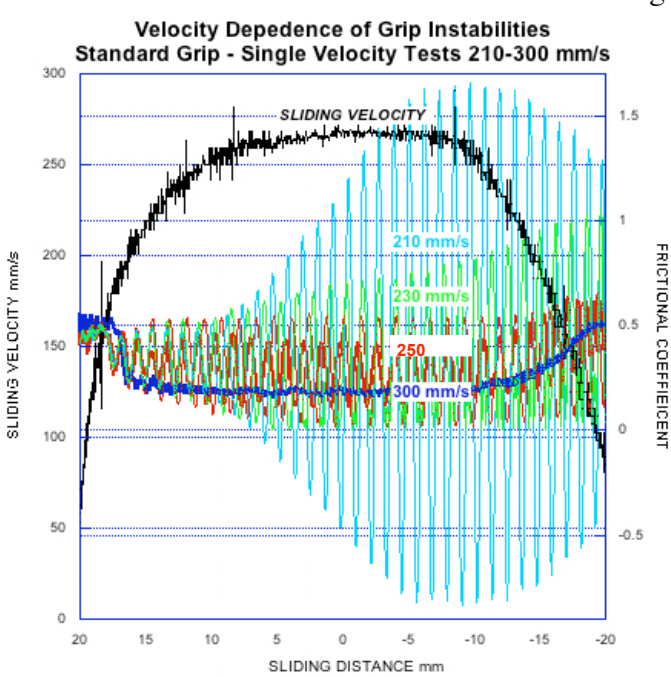

Figure 5. Illustration that the oscillations in friction using the standard grip are larger at 210 mm/s and diminish at higher slip speed, showing that they represent some kind of resonance.

We have gained some additional

insight into the behavior of the standard grip by running experiments at a range of high velocities. Our highest attainable velocity is ~360 mm/s and at this velocity the oscillations with the standard grip are appreciable, as we have noted for years (and is shown in Fig. 3). However, as is shown in Fig. 5, the oscillations are even larger at 200 mm/s, and then not so large at higher velocities. Thus, it appears that the oscillations are due to a resonance with the machine using the standard grip, and at a velocity of ~200 mm/s the resonance is the greatest. Fortunately, as shown in Fig. 3, this problem can be avoided by using the massive upper grip.

Another insight confirming our previous interpretation of our data has been gained by conducting velocity-stepping tests at high velocity. The issue these data address is how to interpret the fact that during one of our typical high speed tests, in which the velocity increases rapidly, stays constant for less than 0.1 seconds, and then decreases, we find that there is hysteresis in the friction. That is, the friction is higher, and the data have a higher slope on a plot of friction vs. velocity, during the increasing-velocity portion of the test than during the slowdown portion. As reported in a previous annual report, we have determined that the slowdown portion is the 'correct' behavior and the speedup part is 'incorrect', because during speedup the inertia of the mass between the sample and the torque cell prevented the torque cell from immediately detecting the decrease in torque. The velocity-stepping test results shown in Fig. 6 confirm this interpretation. Although the displacement at each velocity in such tests is small, an approximately steady-state friction level is attained at each velocity. Superimposing these friction vs. velocity data points on our friction vs. log velocity plots of data obtained in

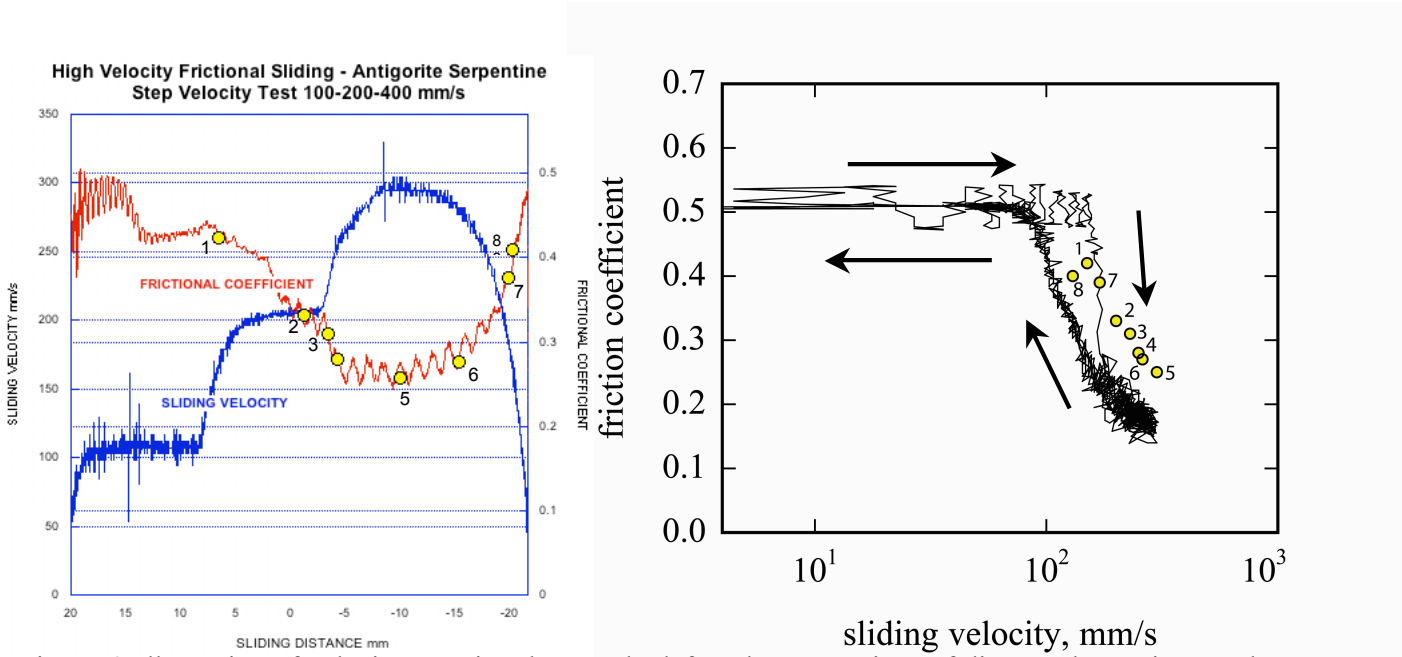

Figure 6. Illustration of velocity-stepping data on the left and a comparison of discrete data points on the left with results of continuously varying velocity tests on the right. The data collected during the speed-up part of the continuously varying velocity tests are biased due to the inertia of the mass between the sample and the torque cell. The numbered yellow dots on the left correspond to those on the right showing the sequence in which the data were collected. The black arrows on the right show the direction of speed up and slow down in the test. Although the magnitudes of the friction for the discrete data points from the stepping test are higher than for the test in which velocity is varied continuously, due to differences in total displacement for the two data sets, the slope of the data from the two tests is nearly identical.

tests with smoothly varying velocity, as shown in Fig. 6, indicates that for the same sample the data points fall along a trend parallel to the slowdown portion of the curve, supporting our hypothesis that the slowdown data represent the better measurement. The fact that the theoretical prediction of a $1/V$ dependence of friction on velocity [*Beeler et al*., 2008; *Rice*, 1999; *Rice*, 2006b] matches the slowdown part of the experiment further supports this conclusion and at the same time lends support to our conclusion that the weakening shown with the standard and massive grips are valid measurements, uncontaminated by experimental artifacts.

Dynamic weakening due to thermal pressurization of pore fluids – As we have stated previously, we have settled on a mafic rock as the best material to use for studying thermal pore fluid pressurization, a mechanism being used extensively in theoretical models of dynamic earthquake slip, because the silica content is low enough that weakening does not occur by the silica gel mechanism [*Roig Silva et al*., 2004a; *Roig Silva et al*., 2004b]. As we explained last year, the gabbro samples that we tried a fluid-pressurization test on turned out to be too coarse-grained for our sample size because it developed a grain-scale topography due to hardness differences between the phases, and the diabase sample we collected from the Holyoke flow in the Tilcon Corporation quarry in North Branford, Connecticut contained too many fractures, making it difficult to core intact samples. We have since focused on obtaining samples of a diabase from Fredrick Maryland, a fine-grained coherent material that has been used by experimentalists for many years after it was originally selected for experimental studies by Francis Birch. However, none of the labs that have used it in the past possess any remaining material, and the outcrops of the original material no longer exist due to later construction and development. We have contacted a geologist, Randy Weingart, of the Luck Stone Corporation who has searched for fine-grained samples in their Leesburg, VA, quarry and is shipping samples to us. If the grain size of these rocks turns out to be too coarse, we plan to take a trip to MD to collect samples from natural outcrops that may have diabase similar to the original material obtained by Birch.

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 is 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, even at rates slower than typical of earthquakes and even without wholesale frictional melting. One weakening mechanism involves the formation of a thin layer of lubricating silica gel and there are reasons to believe that this mechanism may operate on natural faults as well as in our experiments. The weakening that we have attributed to flash weakening is seen in some sample assemblies and not in others. It appears that the sample assemblies that do not show the weakening are giving unreliable results and that the weakening is real and not an experimental artifact. However, more experiments are needed to verify this conclusion. Whether either the gel or the flash weakening mechanisms is important for earthquakes is still unclear, but they are certainly plausible candidates. If the large reductions in shear stress seen in 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.

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