FINAL TECHNICAL REPORT FOR GRANT NUMBER: 05-HQGR0087
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.

We have continued experiments investigating flash heating and flash weakening. These experiments are conducted at sliding velocities of ~100-350 mm/s. 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 already being used in theoretical models of dynamic rupture, so it is important that we verify that this mechanism is in fact responsible for the weakening, as the agreement with theoretical predictions suggests. Our work this year has focused on three topics: 1) understanding the apparently higher weakening velocity on velocity speedups than slowdowns, 2) behavior in the presence of gouge, and 3) the role of surface roughness. Although more work in needed on all three topics, it appears that the correct weakening velocity is the one seen on slowdowns, the one on speedups appearing higher due to inertial effects in the measuring system. Gouge seems to behave similarly to initially bare surfaces. There may be some effect of roughness of the surface on the weakening velocity, but it is not yet clear if it matches theoretical predictions.

We have also made progress beyond last year's results to better understand the gel weakening phenomenon we discovered, in particular to understand the thickness of the silica gel layer responsible for the weakening. The thickness seems to be about 60 μm, greater than the 3 μm we had previously thought.

INTRODUCTION

This is a final technical report for USGS grant 05-HQGR0087. The grant covers a one-year period, from March 1, 2005 to February 28, 2006. We have continued work to increase our understanding of both gel weakening and flash weakening. The work is relevant to understanding dynamic resistance during earthquakes. We will discuss our progress in detail below.

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 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 conducted new gel tests and also new experiments on flash heating/melting. Our results on flash melting and their agreement with theory suggest that *all silicate rocks slide with a low friction coefficient, ~0.2 or less, at seismic slip rates*. Due to the importance of this conclusion we need to confirm that flash heating is definitely the mechanism responsible for the small-displacement, highest-velocity weakening we observe, and to determine whether situations exist for which the mechanism might not operate during earthquakes.

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 focused primarily on two goals – 1) obtaining a better understanding of dynamic fault weakening due to flash heating of asperity contacts and further delineating the conditions for which this mechanism is expected to control fault strength, and 2) gaining a better understanding of dynamic fault weakening due to the formation of silica gel during sliding of silica-rich rocks.

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 material properties for earth materials with laboratory-like contact dimensions, are in good agreement with data from some high-speed friction experiments on rocks [*Rice*, 2006], 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 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 bulk shear rather than localized slip at earthquake slip rates? Do clay minerals, a common fault zone constituent, undergo significant weakening due to flash heating? With these and other questions in mind, we have conducted new high-speed friction experiments on simulated quartz gouge and on samples of variable surface roughness and surface character, detailed below.

In addition to these scientific questions, we have also been addressing several technological issues (e.g., inertial effects in our apparatus) that may give rise to a marked hysteresis in friction vs. velocity data acquired during 'speed-up' and 'slow-down' in the flash melting tests. Sorting out these issues is crucial to understanding the complex interplay between the highly velocity weakening constitutive behavior due to flash weakening and the mechanical response of the Instron machine we have used to conduct our experiments. These efforts also provide insight into the ways in which results of our proposed flash weakening experiments in our gas apparatus are expected to differ from those obtained in the Instron apparatus, which will aid in the design of, and the interpretation of data from, our proposed experiments.

Hysteresis in data from flash heating experiments. We have continued to investigate flash heating in experiments on both initially bare surfaces and on gouge layers (see below). Aside from the deviations of the new data from previously acquired data discussed below, our experiments essentially duplicate the results of our previous tests. One aspect of the data common to all flash heating experiments we have conducted to date is the marked hysteresis of the friction vs. velocity data during speed up and slow down of the sliding rate. That is, the onset of weakening occurs at a higher velocity during speed up than on slow down, and the eventual negative dependence of friction on velocity during speed up is much greater than during slowdown (as shown below in Fig. 1, for example). In fact, the speed-up weakening trend is usually steeper than the $1/V$ dependence of friction on velocity expected from theoretical treatments of flash heating [*Beeler and Tullis*, 2003; *Rice*, 1999; *Rice*, 2006]. We think that understanding the nature of this hysteresis is essential before we submit our otherwise completed manuscript on flash heating for publication.

To that end, we conducted during the past year a more rigorous mechanical analysis of our experiments that includes the possible effects of inertia and other parameters on the observed data. In short, we believe we have had a breakthrough in our understanding of the observed hysteresis, detailed below.

The apparent explanation of the hysteresis is that it is caused by inertial effects in the machine components. The relatively large moment of inertia of the apparatus components between the sample and the torque cell, which is on the opposite side of the sample from the load-point, prevents sufficiently rapid response of the torque cell to real reductions in shear stress on the sliding surface. This results in an apparent friction coefficient that is temporarily higher than on the sliding surface, and would appear as an increase in weakening velocity on speed up, as is observed. To test this idea, we calculated the moment of inertia of the mass between the sample and the torque cell and determined the torque that would be required to change the rotation rate of this mass, assuming it is an rigid mass with a torsional spring between it and the torque cell. We find that the torque required to accelerate this mass by the amount that occurs during the rapid increase in speed at the beginning of the tests is about a factor of 10 larger than the torque due to the shear strength of the sample in its unweakened state. Although more detailed analyses are required to account for the torsional spring being the mass that is being partially accelerated, the result of our current calculation suggests that compared to the slow-down, the apparently higher weakening velocity followed by a more rapid decrease of torque on speed-up are indeed a result of machine inertia. The rate of deceleration during slow-down is low enough that the slow-down data are probably little affected by inertia. We believe this explains the observed hysteresis, but plan a more elaborate analysis to better understand the machine–sample interactions.

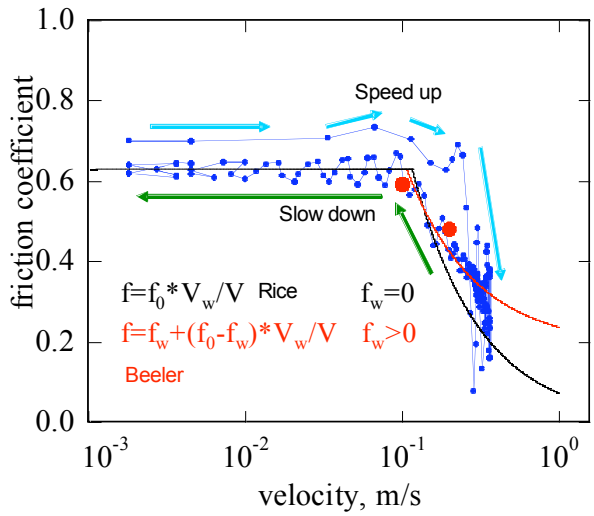

Fig. 1 – Plot of friction coefficient vs. velocity for a flash heating experiment on novaculite. Note hysteresis in the data on speed-up and slow-down. Steady state friction data from constant velocity tests at 100 mm/s and 200 mm/s are shown (red data points) for comparison (see text for details). Slow-down data are in good agreement with the $1/V$ dependence of friction expected from the flash heating theory of *Rice* [1999] in black and *Beeler and Tullis* [2003] in red.

Finally, we note that when 'steady-state' values of friction from flash heating tests conducted at constant velocities of 100 and 200 mm/s are plotted with friction vs. velocity data from the variable velocity tests, the data from these constant velocity tests agree well with the slow-down data from the variable velocity tests, as shown in Fig. 1. These experimental data and our analysis of inertial effects therefore strongly suggest that the hysteresis in the flash heating data is caused by inertial effects, and that the slow-down data are a more reliable indicator of the frictional strength than the speed-up data. This conclusion is bolstered as well by the $1/V$ trend of the slow-down data, in accord with theory.

Flash heating tests on simulated quartz gouge. We have conducted a series of new flash heating experiments on simulated quartz gouge in the Instron torsion/compression apparatus. The 'gouge' in this case is a quartz powder with a particle size of 5 μm or less, in layers <0.5 mm in thickness placed between two bare surfaces of novaculite in our otherwise 'standard' sample geometry (an annulus of rock slid against a circular plate of rock). Flash heating

experiments were then carried out in the normal manner by sliding the samples at the highest possible rates (up to about 360 mm/s) over a sliding distance of about 40 mm. As we have detailed previously, these high-speed/small-slip conditions are ideal for isolating flash heating effects on friction from the effects of other weakening mechanisms activated at high speeds and larger displacements, such as melt lubrication, or the silica gel weakening mechanism.

Results of two tests on quartz gouge are shown in Fig. 2. The data show an even more pronounced hysteresis than exists for tests on initially bare surfaces. The samples remain strong during speed-up even for up to 1 cm of slip at 360 mm/s, following which, the shear strength plummets to the low values typically seen for bare surfaces. During slow down, however, data from gouge tests yield weakening velocities of ~100 mm/s, as are observed typically for bare surfaces. In accord with our discussion of inertial effects above, we conclude that the observed hysteresis is caused by inertia, such that the slow-down data represents the real frictional strength of the interface. The similar weakening velocities on slow-down for gouge and bare surfaces may indicate that the contact sizes are similar in both cases, due to extrusion of gouge from the sliding surface (the gouge is unconfined laterally). Alternatively, similarly sized contacts might be produced via comminution during sliding in both cases.

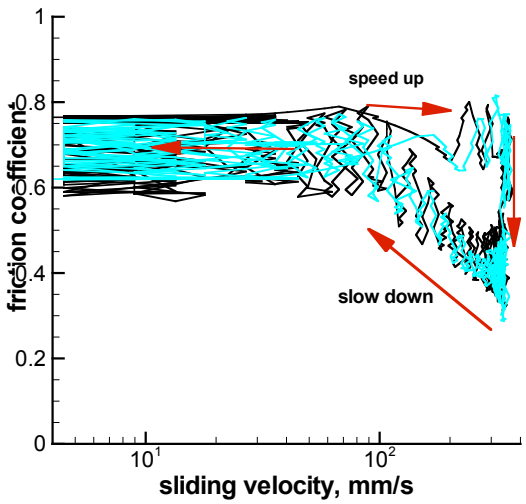

Fig. 2 – Plot of friction coefficient vs. velocity for two flash heating experiments on simulated quartz gouge. Note the strong hysteresis in the data on speed up and slow down. Slow-down data predict a weakening velocity of about 100 mm/s.

Flash heating tests on surfaces of varying roughness, character – We conducted flash heating tests on a novaculite sample and alternated them with sliding tests conducted for large displacements and sliding velocities of 100 mm/s or less. The flash heating tests were conducted as described above, at velocities up to ~360 mm/s over a sliding distance of ~40 mm. The long displacement tests between the flash heating tests were conducted at velocities of 10 or 30 mm/s over slips of ~4.5 m. The purpose of these experiments was to investigate how variations in surface roughness and the character of the material (e.g., amorphous vs. crystalline) on the sliding surface affect flash heating behavior. The sliding surface becomes progressively smoother with slip in these tests, particularly during the longer displacement tests, likely reducing the contact dimensions on the slip surface. Based on flash heating theory [*Beeler and Tullis,* 2003; *Rice*, 1999; *Rice*, 2006], the effect of decreasing contact size would be to shift the velocity at which the onset of flash weakening occurs to higher velocities. Also, the material on the slip surface likely becomes amorphous, based on previous transmission electron microscope (TEM) studies of laboratory samples of quartz rocks from long displacement friction experiments (hundreds of mm) conducted at low slip velocities (≤10 μm/s) [*Yund et al.*, 1990]. We surmise that in the long displacement, rapid slip tests done here, an amorphous layer of wear debris develops on the sliding surface. We anticipated that such changes should influence the contact stresses and hence the resulting flash heating behavior.

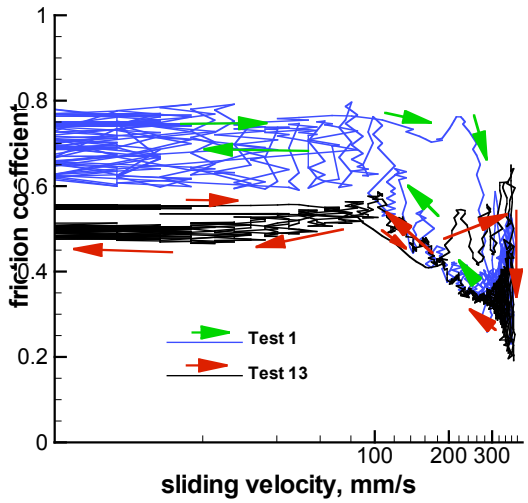

Fig. 3 – Plot of friction coefficient vs. sliding velocity for two flash heating experiments, one on a surface ground with #60 grit powder (Test 1 in blue), the other on the same sample after alternating flash heating and long displacement tests yielding 27.3 m of total slip. Arrows indicate whether data were acquired during acceleration or deceleration of the sample. Note the shift to higher velocity of the weakening velocity on speed up, but the good agreement in the weakening velocity during slow down (100 to 150 mm/s for both tests).

The series of tests involved 13 stages. The series began and ended with a flash heating test, and flash-heating tests alternated with long displacement tests. Since the displacement in each flash heating test is 45 mm and in each long displacement test is 4.5 m, the total displacement at the end of the series was 27.3 m. The sample remained in contact under a normal stress of 5 MPa throughout the entire sequence of tests, that is, no efforts were made to remove wear debris from the surface between the tests. To accomplish this, the ending angular position of the sample from a flash test was the same as the starting angular position of the following long displacement tests, and vice versa. Data from some of these flash heating tests are shown in Fig. 3. For clarity, we plot only the results of the first and last flash experiments. Results of the long displacement tests are nearly identical to our previous results for such tests (e.g, the 'silica gel' experiments of *Di Toro et al.* [2004]) and are not shown here.

As shown in Fig. 3, the effect of ~27 m of cumulative slip prior to the final flash heating experiment is to shift the onset of weakening at the beginning of the tests to higher sliding velocities; in the first test (blue data) the sample begins to weaken at ~200 mm/s, whereas in the thirteenth test (black data) the sample begins to weaken only at the peak velocity of ~360 mm/s. However, both experiments yield data displaying marked hysteresis (see above), and both tests show a weakening velocity during slow down of ~100-150 mm/s, suggesting that the true weakening velocity is not affected by the long history of sliding. It is not evident why the apparent weakening velocity on speed up is affected by the total slip and the true weakening velocity during slow down is not. It is surprising that there is no change in the presumed true weakening velocity, given the likely differences between contact dimensions and character of material on the sliding surfaces for a sample starting with a #60 grit roughness and one that has undergone 27 m of slip. It is evident that we need to study further the dependence of the weakening velocity on surface roughness and character.

Dynamic fault weakening due to silica gel - With regard to the silica gel weakening mechanism, we have conducted new experiments and made some rather intriguing observations concerning the occurrence of the weakening mechanism and the presence or absence of wear debris on the sliding surface of Tanco albite. These experiments point to the importance of ultracomminuted wear debris between the opposing sliding surfaces, as well as the thin layer of silica gel found on the bare sliding surfaces themselves, for operation of the gel weakening mechanism.

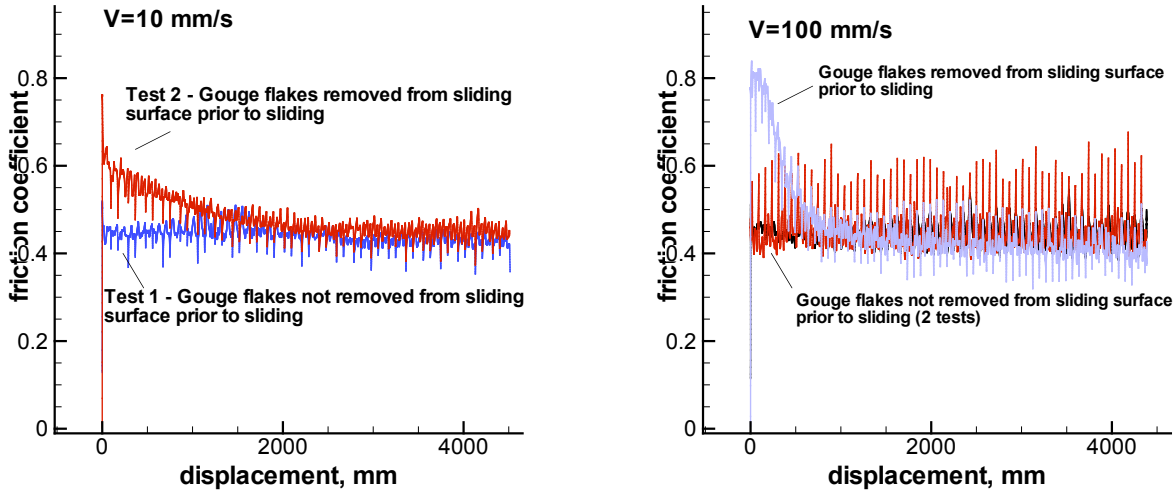

Fig. 4 – Plots showing the effect of gouge removal on friction coefficient vs. displacement data from long displacement tests on Tanco albite rock at a) 10 mm/s and b) 100 mm/s.

Tests were conducted on a Tanco albite rock at a series of progressively higher sliding velocities in the range 1 mm/s to 30 mm/s. Results for two sliding velocities, 10 mm/s and 100 mm/s, are shown in Fig. 4 a and b, respectively. For these tests, we either left the gouge layer (that is about 60 μm thick and which forms during sliding) intact after the previous test (without separating the ring and plate) prior to sliding, or separated the ring and plate and brushed off the gouge layer left over from the previous test prior to sliding. These procedures yielded two very different behaviors. When the gouge layer was not removed prior to sliding, frictional strength was lower at the beginning of the test, and remained constant during sliding. When the gouge layer was removed, however, frictional strength recovered to quasi-static values, and a sliding displacement of 0.5 m or larger at high velocity was required to regenerate the gouge layer and reduce the frictional strength to the same values as obtained in the intact-gouge tests. The presence of the gouge clearly lowers the shear strength. We have previously observed ~3 μm thick coatings of material containing 'flow structures' on the surfaces of novaculite samples from large displacement tests, and have attributed low shear strengths in these tests to flow of this 'silica gel'-like material on the sliding surface. However, our new tests suggest that silica gel may also comprise the ~60-μm-thick gouge layer, and the presence of this additional thickness of gel influences the strength of our samples.

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 can be important, not only for practical matters related to predicting strong ground motions, but also for answering many of the "big" questions, for example the strength of the San Andreas fault / 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 apparently involves flash heating of asperity contacts and occurs in experiments involving a layer of gouge as well as initially bare surfaces. The weakening velocity for gouge seems similar to that for bare surfaces, but additional investigation is required to understand the distribution of the deformation within the gouge. For bare surfaces the weakening velocity seems to depend somewhat on surface roughness, but it is not clear what this dependence is or whether it matches predictions from theory. Reduction in friction due to the gel weakening mechanism seems to depend on the thickness of the layer of gouge generated by sliding and, contrary to our previous indications, the active layer may be closer to 60 μm than the 3 μm as we earlier concluded. Whether either the flash weakening or the gel weakening mechanism is 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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Program Element III - Understanding Earthquake Processes

Key Words: Laboratory studies, Source characteristics, Fault dynamics, Strong ground motion

NON-TECHNICAL ABSTRACT

Our continued 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 been studying two weakening mechanisms, the production of a lubricating layer of silica gel on the sliding surface and the generation of high temperatures at small sliding contact junctions due to frictional heating. The weakening is either due to thermal softening or to local melting. If weakening also occurs during earthquakes, stress reduction during earthquakes could be so large that the size of damaging ground motions might be larger than usually expected.