FINAL TECHNICAL REPORT FOR GRANT NUMBER: 06-HQGR0068
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 made progress beyond last year's results to better understand the gel weakening phenomenon we discovered, in particular to understand the interaction between the thickness of the silica gel layer and the roughness of the sliding surfaces.

We have also continued experiments investigating flash heating and flash melting. These experiments are conducted at sliding velocities of ~400-700 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. 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.

INTRODUCTION

This is a final technical report for USGS grant 06-HQGR0068. The grant covers a one-year period, from March 1, 2006 to February 28, 2007. 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.

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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. In

order to study these problems in more detail, we have developed a new heating stage for the Instron apparatus in which we do our highest slip-speed experiments. We briefly describe the apparatus below before discussing our recent results.

New elevated temperature assembly for conducting high-speed friction experiments. In the past year, we have designed, constructed, and begun to use an elevated temperature assembly for the Instron apparatus; we have used the apparatus previously to conduct many room-temperature, high-speed friction experiments. The ability to elevate the ambient temperature in our

a. b.

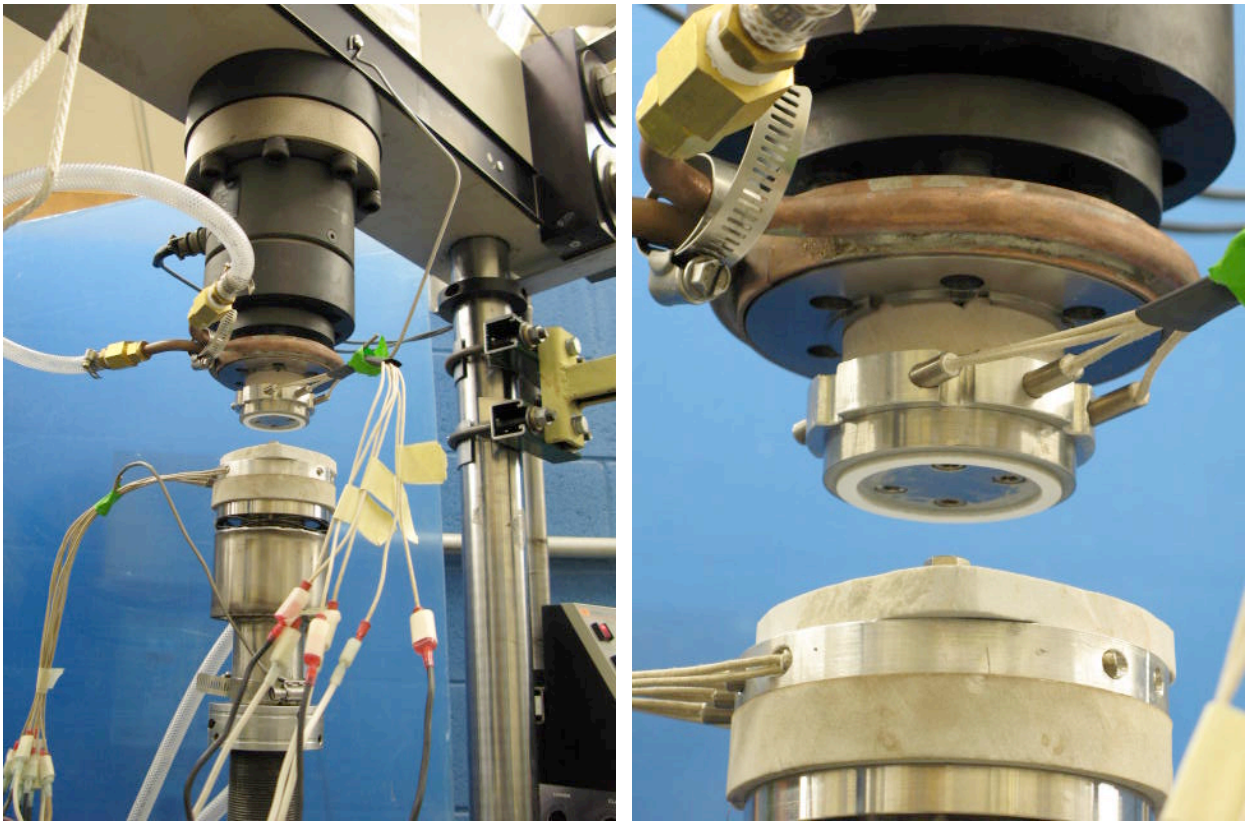

Fig. 1 - New high temperature sample assembly for the Instron 1-atm rotary shear apparatus. a) Overview perspective showing Instron loading frame, heater leads, and cooling tubes that prevent overheating of the load/torque cell at top and the fixture at the bottom that contains low-melting-point metal used to align sample. b) Close-up showing the upper sample grip with three cartridge heaters inserted into an aluminum heating block and the similar five-cartridge heater block located below the lower sample. Pyrophyllite and rock insulating blocks separate the aluminum heater blocks from the water-cooled mounting hardware. The assembly is shown with the ring-shaped novaculite sample separated from the lower novaculite sample plate, prior to bringing them into contact for an experiment. Temperatures of 300 ^{o}C have been achieved at only 50% of the available power.

experiments allows us to investigate a number of important aspects of high-speed sliding behavior for several dynamic weakening mechanisms. For the flash heating/weakening mechanism we can determine whether shifts in the weakening velocity with increasing temperature occur as predicted by theory. For the silica gel weakening mechanism, we can evaluate the effect of water on silica gel behavior, the temperature dependence of gel strength, and the effect that elevated temperatures have on healing of the gel.

The elevated temperature assembly is shown in Fig. 1. The assembly consists of two

aluminum heater blocks located adjacent to the friction samples. A 'sample' consists of a ring of rock epoxied into a steel grip, which is slid against a flat, roughly circular plate of the same material. The aluminum blocks are heated with cartridge heaters inserted into holes drilled in the heater blocks, three cartridges for the upper block and five for the larger lower block. Because of the relatively long time constant of the system, we presently use two variable AC power supplies (Variacs), one for each sample grip, to manually adjust the power to attain the desired temperature on the samples as measured by thermocouples. A temperature controller may be added to the system for even more precise temperature control, as needed.

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*, 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?

Flash heating experiments on serpentine. We have extended our investigations to include high-speed friction experiments on antigorite serpentine rocks at sliding velocities approaching seismic slip rates. Previous laboratory experiments on the frictional behavior of serpentine exhibit velocity strengthening behavior at low sliding velocities (<0.03 μm/s), providing a possible explanation for the modest seismicity rate in serpentinized regions (e.g., *Reinen et al*., 1994; *Moore et al*., 1997; *Boettcher and Jordan,* 2004). Experiments on serpentinite also show a transition, at about 0.03 μm/s, from velocity strengthening at lower sliding velocities to velocity weakening at higher sliding velocities in the range 0.03 to 10 μm/s, suggesting that ruptures that propagate into serpentinized regions could trigger seismicity (*Reinen et al.*, 1994). However, these sliding velocities are orders of magnitude lower than experienced during earthquakes. Our experiments were conducted in a 1-atm rotary shear apparatus at a fixed normal stress of 3 MPa. Two types of test were conducted, one to study the long-displacement, steady-state velocity dependence of friction at intermediate velocities, and one to determine whether flash heating occurs at even higher velocities. In the first type of test, samples were subjected to repeated reciprocating oscillations of the sliding direction over ~4 m of cumulative slip (Fig. 2a). In the second type, samples were slid more rapidly in only one direction over ~40 mm of slip (Fig 2b). Reciprocating slip tests were begun by sliding at 10 μm/s for several mm of slip, then at V up to 100 mm/s over the remaining 4.5 m of slip. Unidirectional slip tests were begun by sliding at 10 μm/s for several mm of slip, then at V up to 360 mm/s over the remaining 4 cm of slip. Reciprocating tests, over the V range 10 μm/s to 30 mm/s, yield a value of the friction coefficient of ~0.83, whereas at 100 mm/s a value of ~0.6 is observed. Unidirectional slip experiments

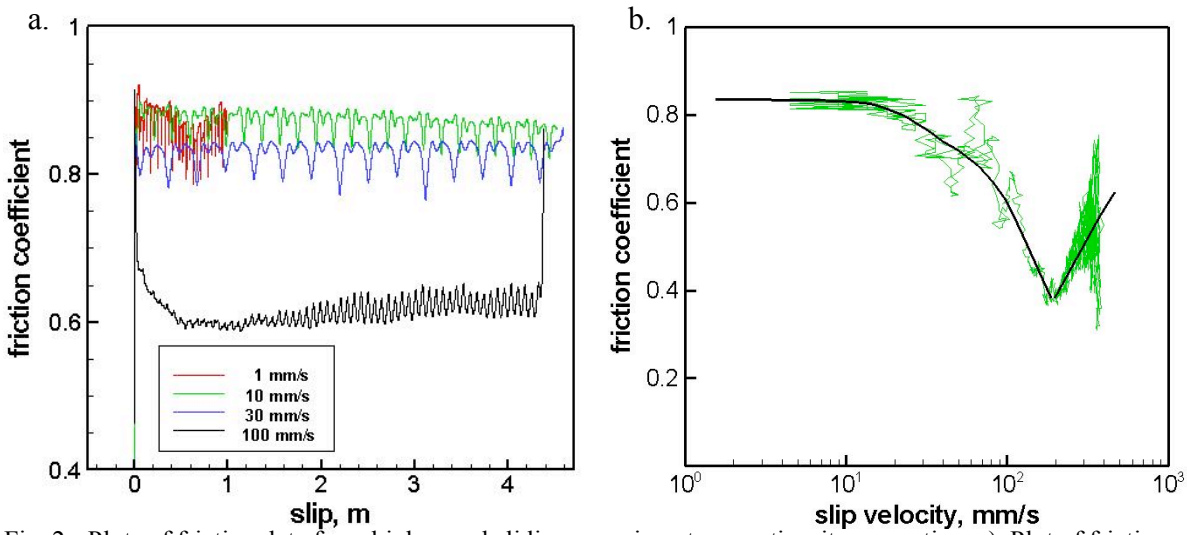

Fig. 2 - Plots of friction data from high-speed sliding experiments on antigorite serpentine. a) Plot of friction vs. slip from reciprocating sliding tests. Note the modest weakening at V=30 mm/s and the pronounced weakening at 100 mm/s. Note also that the strength for the V=100 mm/s test recovers nearly instantaneously as the velocity decreases to zero at the end of the test. b) Plot of friction vs. slip velocity for unidirectional sliding at up to ~400 mm/s. Note the weakening velocity of ~20 mm/s in these tests, compared with ~100mm/s for most other rocks.

reveal a 1/V decrease in friction coefficient with increasing V over the range 50 to 100 mm/s, to a value of 0.4 at 200 mm/s, followed by an increase in friction with increasing velocity for V > 200 mm/s. In both types of test, friction is nearly independent of slip, i.e., is nearly a pure function of V, above V=50 mm/s, although micron-scale evolution of strength with slip as expected for flash heating was not resolvable. The results suggest that macroscopic friction of serpentine is controlled by flash heating of microscopic asperities on the fault surface at relatively high slip velocities. In the highest V regime, the increase in friction with V may reflect dehydration reactions which may occur at flash-heated asperities.

Merging our new results with what was known previously, the overall behavior of antigorite serpentine at room temperature is velocity strengthening at fault creep rates, mildly velocity weakening at rates associated with earthquake nucleation, strongly velocity weakening at rates approaching seismic rates, and finally velocity strengthening at near-seismic slip rates. Our results suggest that ruptures which propagate into serpentinized regions - such as hypothesized for some regions of the San Andreas Fault, transform faults in the oceanic lithosphere, and altered lithosphere along the slab-wedge interface of subduction zones - may continue to propagate seismically, but only if sliding velocities are relatively low. Furthermore, propagation may be limited or terminated by serpentine's increase in resistance at velocities of a few hundred mm/s, namely at the transition to high-speed velocity strengthening behavior.

Progress in understanding weakening due to gel formation. We have used our high pressure rotary shear apparatus to further investigate the weakening caused by gel formation. In particular, we have investigated the gel weakening behavior for novaculite samples for larger slips (up to 10 m) than in previous tests. Data from such a test are shown in Fig. 4. The plot in Fig. 4 shows friction and sliding velocity plotted against slip in meters. The experiment was begun by sliding at a slow sliding velocity of 1 μm/s, during which a 'normal' value for the friction coefficient, ~0.6, was obtained. The velocity was then stepped up to 3.2 mm/s, after

which a dramatic decrease in friction was observed over a slip distance of about 0.5 m. The velocity was then stepped up to 4.8 mm/s, and a series of holds was conducted (holds are indicated by the long vertical spikes in the velocity data), during which time the load point velocity was set to zero. As shown in Fig. 4, the friction coefficient was quite noisy but averaged ~0.4 over slips of up to 5 m. These results are consistent with our previous high-speed sliding experiments on novaculite that were conducted to comparable slips. Above 5 m of slip, however, a dramatic increase in friction was observed, up to values of ~0.8, over the remaining 5 m of slip at 4.8 mm/s (interspersed with holds). Even over comparatively long sliding intervals (in excess of 1 m of slip in some increments), no weakening was observed back down to previous levels.

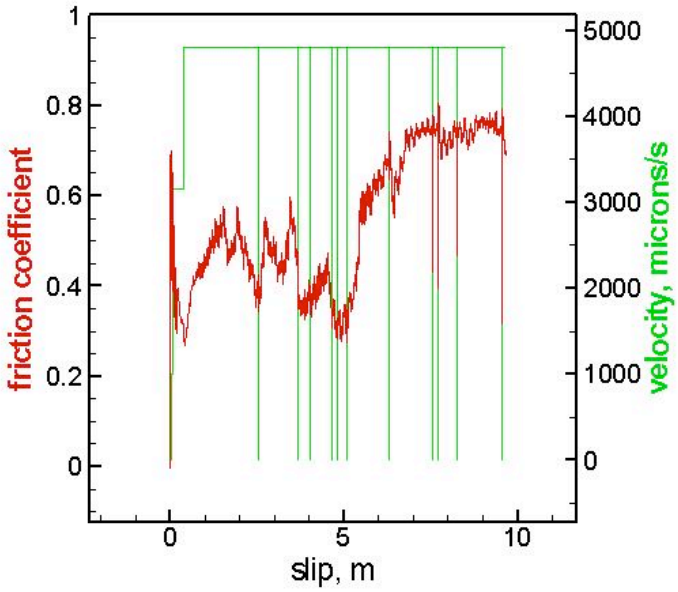

Fig. 4 - Plot of friction coefficient (in red) and slip velocity (in green) vs. slip for a high-speed friction experiment on novaculite. Normal stress was 25 MPa. Vertical spikes in the velocity data are holds, during which the load point velocity was set to zero. Note dramatic increase in friction above a slip of 5 m, attributable to cracking and roughening of the slip surface at large slips (see text).

Our microstructural observations of the sliding surface after the tests show that compared to novaculite samples slid to lower slips in previous experiments, the sample from this test had suffered much more fracture and crushing of the fault surface, such that the surface was quite irregular and only remnants of a discrete slip surface were observed. The roughness of the disrupted surface was considerably thicker than the ~60 μm thickness of the gel layer that is found on our typical samples from previous tests. These observations, coupled with the friction data, suggest the perhaps critical role played by surface roughness in gel weakening. Significant surface roughness due to fracture as in the current experiment may preclude the development of a surface that is sufficiently smooth to be lubricated by a gel layer.

Dynamic weakening due to thermal pressurization of pore fluids – We performed one experiment for preliminary evaluation of the usefulness of gabbro as the sample material for experiments on thermal pressurization. Our previous experiments designed to study this weakening mechanism were stymied by the discovery that weakening occurred due to the gel mechanism and so masked any possible weakening due to thermal pressurization. We later found that gabbro did not weaken by the gel mechanism due to its lower silica content [*Roig Silva et al.*, 2004a, 2004b], and so gabbro seemed suitable for a return to a study of thermal pore fluid pressurization. We realized that its permeability might be too low to allow us to saturate it with pore water on a practical timescale unless we thermally cracked it, and we have indeed found this to be the case. Previously we found that a permeability of about 10^{-19} m^2 was ideal for these experiments because it was low enough that fluid on the fault could become pressurized during the high-speed part of the experiment. In our experiments, we were unable to saturate the

uncracked gabbro by exposing it to high pressure water for one week. We measured its permeability and it is lower than 10^{-20} m^2. We nevertheless conducted an experiment on the unsaturated gabbro since it was already mounted in the sample grip, and found that at the 25 MPa normal stress of the experiment there was significant topography produced on the surface due to differential wear between the feldspar and the pyroxene grains. The topography may render these specimens unsuitable for the pore fluid pressurization tests, even when using thermally cracked gabbro, because there is too much opportunity for interlocking of the rough surfaces, given our sample dimensions. Consequently we have altered our plan and will use a rock of the same silica content (basalt) for which the wear will be on a scale more suitable to our sample size. We have collected a suitable dense basalt from the upper section of the Holyoke flow in the Tilcon Corporation quarry in North Branford, Connecticut. We plan to test this rock during our ongoing grant and hopefully use it as sample material in future thermal pressurization experiments.

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 involves the formation of a thin layer of lubricating silica gel. We have found that for this mechanism to operate it in necessary that the thickness of the lubricating layer of thixotropic silica gel be greater than the surface roughness so that shearing can occur in the layer without interlocking of the surfaces. We have also found that flash weakening occurs in serpentine as well as the other silicates tested, but that its behavior is more complex and included a strengthening at the highest slip velocities, a behavior that could limit the seismic slip rate on serpentinized faults. Whether either the gel or the flash weakening mechanisms 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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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.