2007 SCEC Final Report

Laboratory Experiments on Fault Shear Resistance Relevant to Coseismic Earthquake Slip

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Knowledge of shear resistance on faults during earthquakes is an important ingredient for attaining SCEC goals. To construct theoretical models of the earthquake process, we must understand how frictional resistance on faults changes during earthquakes. The magnitude of strong ground motion accelerations and the total slip during an earthquake depend critically on the dynamic shear resistance at the seismic source and the manner in which friction varies with slip and slip velocity, as well as with time following cessation of slip.

During the past several years, with funding from the USGS-NEHRP program and from SCEC, we have been investigating the frictional weakening behavior of rocks at slip velocities higher than those usually investigated in rock friction experiments, but lower than those occurring during earthquakes. This report is an update on what we have discovered since the beginning of this award year in February 2007 and our progress in laying the foundation for future work.

Our research efforts in the past several years have focused on understanding two dynamic fault weakening mechanisms – 1) flash heating/melting (*Goldsby and Tullis*, in preparation), and 2) weakening due to the formation of dynamically weak silica gels on the sliding surfaces of silicate rocks (*Goldsby and Tullis*, 2002; *Di Toro et al.*, 2004). Both mechanisms yield low values of the friction coefficient at seismic slip rates (< 0.2 in some cases), and each is characterized by distinct dependences of friction on sliding velocity, slip, and normal stress. Experiments have been conducted in two rotary shear apparatuses – an ambient-pressure apparatus limited to low normal stresses (5 MPa) but capable of slip rates as high as 0.4 m/s, and our high-pressure rotary-shear apparatus, capable of large normal stresses (up to ~500 MPa) but limited in normal operation to a slip rate of 10 mm/s.

Progress in understanding flash weakening. We have previously reported results of high-speed friction experiments on a variety of crustal rocks of similar initial surface roughness, with inferred contact dimensions on the order of those observed in typical rock friction experiments, about 1 to 10 μm. The experiments employ near-seismic slip velocities (up to ~0.4 m/s) over relatively small displacements (~0.045 m) and thus are conducive to activation and, importantly, isolation of flash-heating phenomena. Within this year, new experiments have been conducted to investigate the effects of varying surface roughness, and hence asperity contact size, on the dramatic weakening that results from flash heating. Theory (e.g., *Rice*, 1999; 2006; *Beeler et al.*, 2008) indicates that the weakening velocity V_w at the onset of extreme weakening due to flash heating varies inversely with contact size

$$V_w = (\pi \alpha / D) [\rho c (T_w - T_f) / \tau_c]^2 \quad (1)$$

where α is thermal diffusivity, D is contact size, ρ is density, c is heat capacity, τ_c is contact shear stress, T_w is the temperature at the onset of severe thermal weakening of contacts, and T_f is the average temperature of the slip surface. Thus, an increase in roughness, and therefore presumably contact size (e.g., *Okubo and Dieterich*, 1984), should yield predictable decreases in V_w. A positive correlation of predicted and observed values of V_w with changes in surface roughness (contact size) would be a strong validation of the theory and provide additional confirmation of the occurrence of flash-weakening phenomena in our experiments. The variation of macroscopic friction f with velocity due to flash heating is given by:

$$f = f_0 \; V_w / V \qquad (2)$$

where f_0 is the nominally constant value of friction at slow, quasistatic slip rates. Equation 1 follows on the assumption that contacts have negligible shear strength in their weakened state above V_w , i.e., that $f_w = 0$. *Beeler et al.* (2008) assumed that contacts have finite shear strength above V_w, i.e., $f_w > 0$, yielding a more gradual decrease in friction with increasing slip velocity.

$$f = f_w + (\, f_0 - \; f_w) \; V_w / V \qquad (3)$$

Representative values of $\alpha = 1.85\ (\text{mm})^2/\text{s}$, $\rho c = 3\ \text{MJ/m}^3\ \text{K}$, $D = 10$ mm, $T_w - T_f = 1000$ K and $\tau_c = 10$ GPa yields estimates of V_w of ~0.1 m/s for minerals like quartz and feldspar. Results for novaculite, a monomineralic quartz rock of metasedimentary origin, are shown in Figure 1.

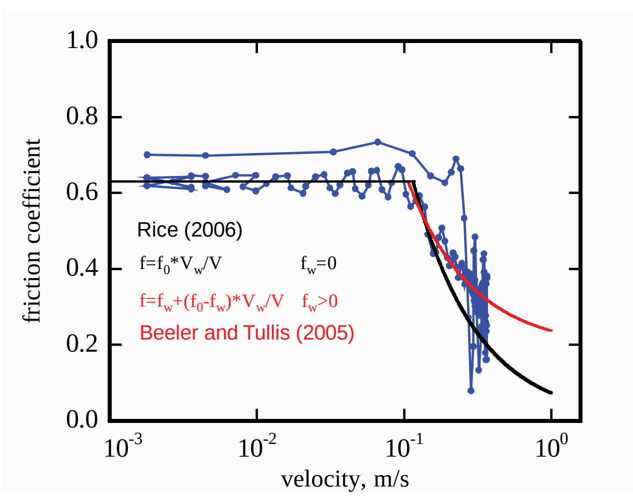

Figure 1 – Plot of friction coefficient vs. slip velocity data from flash heating experiments on novaculite samples.

New experiments - Here we report results of tests on samples with larger initial roughness than we have investigated previously. The experiments yield unexpected results - a disappearance of the flash-weakening behavior observed in otherwise identical experiments on smoother samples – i.e., an *increase* in the weakening velocity with *increasing* contact size, contrary to theoretical expectations. The experiments highlight critical issues affecting the occurrence of flash weakening in nature, like the size of asperity contacts in natural fault gouge and the degree of slip localization on faults. Such issues were the focus of the just-completed SCEC workshop on Dynamic Faulting Parameters in Pomona, California, on March 11, 2008, in which one of us (DLG) participated.

Experiments to investigate flash-heating phenomena are performed in our workhorse Instron compression-torsion apparatus in the Prince Engineering Labs at Brown University. In these experiments, a sample consists of an upper annulus of rock mounted in a steel sample grip, slid against a lower flat circular plate of the same rock mounted on a stainless steel platen. Normal stress is held constant with a servo-controlled hydraulic ram, typically at 5 MPa. The apparatus allows for ~0.045 m of slip in rotary shear at slip rates up to 0.4 m/s, conditions conducive to extreme flash heating of asperity contacts, but insignificant heating of the entire fault surface due

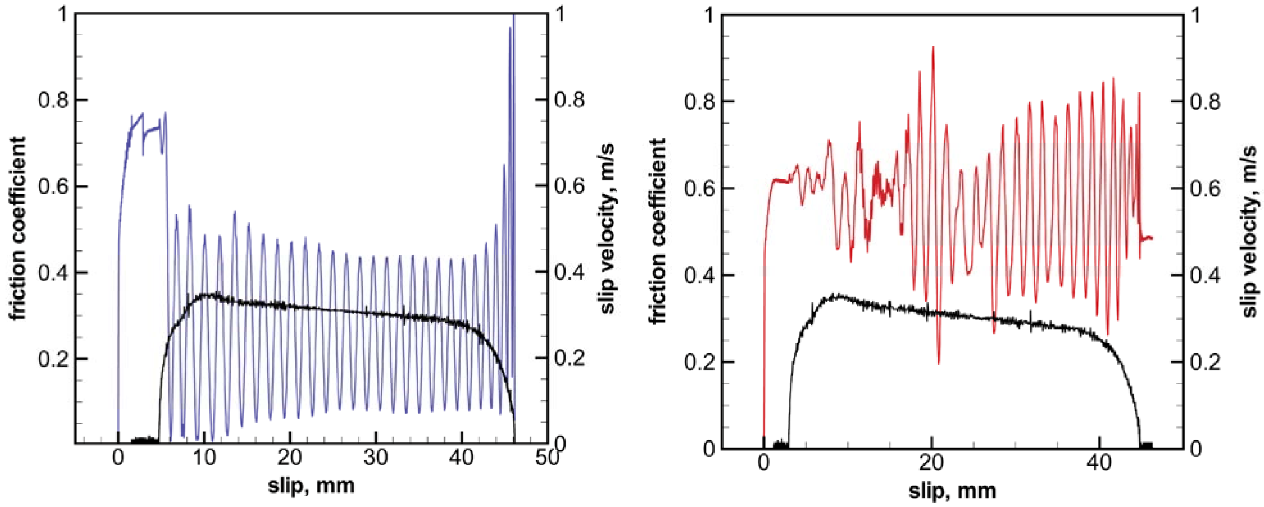

Figure 2 – High-speed friction data for experiments on monominerallic quartz rocks of varying wear resistance and surface roughness. **LEFT –** Friction coefficient (in blue) and slip velocity (black trace) plotted against slip in millimeters, from an experiment on more wear resistant quartzite. Note the dramatic decrease in frictional strength at slip rates above 100 mm/s, and the increase in friction as slip velocity falls below ~100 mm/s at the end of the tests. **RIGHT** - Friction coefficient (in red) and slip velocity (black trace) plotted against slip in millimeters, from an experiment on comparatively less wear resistant novaculite. Note the lack of any significant weakening in the data from the tests on novaculite. Microstructural observations indicate relatively little generated gouge for the quartzite sample, and much thicker (>100 μm) in the case of the novaculite.

to the small accrued slip. All tests begin with 2-3 mm of slip at V=10 μm/s to establish a low-speed value of the friction, then sustained slip at rates up to 0.36 m/s over the remaining 0.04 m of slip. As we have shown previously, such experiments typically yield data which exhibit a 1/V decrease in friction coefficient with increasing V for V > 0.1 m/s, to an extrapolated value at seismic slip rates of ~0.2. Furthermore, friction is nearly independent of slip in these tests, i.e., is nearly a pure function of V, above V=0.1 m/s. Friction vs. velocity data are well fit by the theoretical model of *Beeler et al.* (2008), a variant of the Rice model (*Rice*, 1999; 2006) (see Figure 1). The results strongly suggest that macroscopic friction in these experiments is controlled by severe transient heating (or, in the extreme case, melting) of microscopic contacts and subsequent degradation of their strength.

In our new experiments, we conducted tests on two types of sample – smoother, more wear-resistant quartzite samples roughened with #60 grit alumina prior to testing, and rougher, less wear-resistant novaculite samples roughened with #24 grit alumina. In all other respects, these experiments are identical to the previous flash-heating experiments described above.

Data from friction experiments and associated deformation microstructures for smoother, more wear-resistant quartzite samples and for the rougher, less wear-resistant novaculite samples are shown in Fig. 2. Tests on the quartzite generate very little gouge, which is absent or present in thicknesses of only a few microns, and yield the extreme weakening behavior we have observed in previous experiments on samples prepared with #60 or #120 grits, as shown in Fig. 2. The large, regular oscillations in these data result from the interaction of the strongly velocity weakening frictional behavior and the relatively compliant apparatus. Modeling of the data using a spring-block model that incorporates a constitutive law for flash weakening suggests that these oscillations represent stick-slip cycles (N. Beeler, unpublished data). In contrast, tests on the initially rougher, less wear-resistant novaculite generate much more gouge (at least 100 μm in thickness) than tests on quartzite, and yield no dramatic decrease in friction during the tests, as shown in Fig. 2. Technical difficulties prevented us from epoxying the ring and plate together after sliding in the case of the rough sample, which requires that the sample be epoxied under constant servo-controlled load. Because of this, we were unable to assess the degree of shear localization in the gouge. New techniques for epoxying our experimental faults *in situ* will allow us to assess the degree of shear localization in future experiments.

The stark contrast in behavior of comparatively smooth and rough samples may result from increased interpenetration and grinding off of asperities for the rough samples, which results in a thicker layer of gouge. The lack of weakening in the case of the thicker gouge suggests it sheared uniformly rather than in a localized fashion over the relatively small slips in these tests, ~4 cm. If gouge deformation was distributed, then the contact-scale slip velocity was less than the far-field velocity by a factor N, the number of gouge particles across the gouge layer; equivalently, V_w was increased by a factor N. Distributed shear of a 100 μm-thick quartz gouge, with an estimated gouge particle size of ~20 μm or less (both values consistent with layer thickness and particle sizes estimated from microstructural analyses of the novaculite sample) and lab-like contact dimensions of 10 μm would shift V_w to ~0.5 m/s, above the highest velocity we can obtain in the Instron apparatus. Distributed shearing of natural gouge layers with thicknesses >100 μm, and/or smaller particle sizes, might shift V_w to in excess of seismic slip rates, i.e., >1 m/s. This scenario does not take into account 1) The tendency for gouge particles to clump together due to cohesion, perhaps making effective larger particles with larger contact sizes that might weaken due to flash heating (J. Rice, personal communication), nor 2) The likelihood that slip in gouge becomes localized during high-speed slip. The strongly velocity weakening behavior due to flash heating is expected to promote localization (*Scruggs and Tullis*, 1998).

In short, high-speed friction experiments designed to isolate flash-heating phenomena, on samples of comparatively large initial surface roughness, reveal no dramatic weakening, like that observed previously for smoother samples. The difference likely results from the development and subsequent distributed shearing of a relatively thick gouge layer. Our results emphasize the critical importance of slip localization and asperity contact size for determining whether flash heating occurs in nature. We will continue these important experiments in 2008 for a broader range of initial surface roughnesses. These experiments will be accompanied by more detailed microstructural analyses of deformed samples, with an eye toward characterizing gouge particle sizes, contact sizes, and the degree of slip localization as a function of slip.

Progress in developing experimental techniques for conducting high-speed friction experiments at elevated temperatures. In the past year, we designed and constructed an elevated temperature assembly for the Instron apparatus described above. The ability to elevate ambient temperature in our experiments will allow us to make another critical test of flash heating/weakening in our experiments, since an increase in ambient temperature yields predictable decreases in the V_w (see

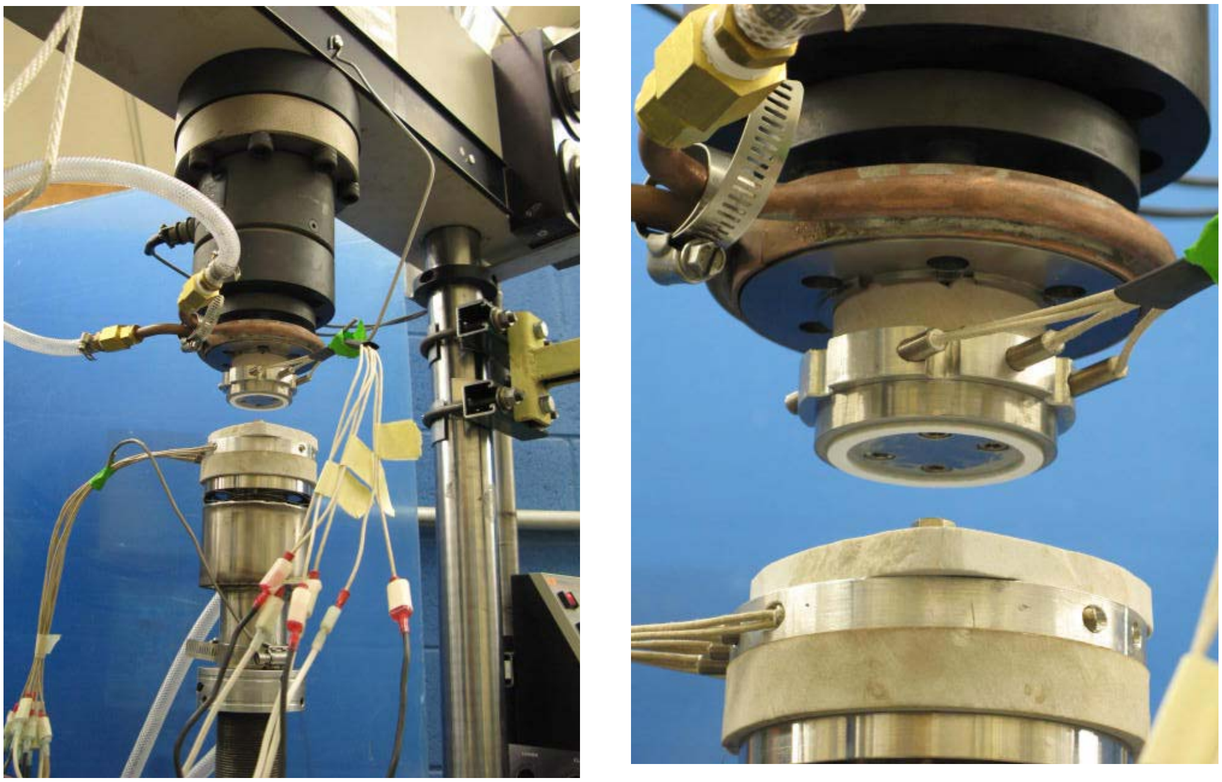

Figure 3 – Photographs of the high temperature sample assembly mounted in the Instron torsion/compression load frame. Aluminum blocks above the upper sample ring and the lower sample plate (novaculite sample shown) are heated with cartridge-type resistance heaters. Temperatures will be monitored with thermocouples embedded in the sample surface. Copper cooling jacket on upper sample grip, with flowing water inside the jacket, protect the load and torque cell from overheating. Preliminary tests indicate that temperatures in excess of 300 ^{o}C are easily obtained.

Equation 1). In addition, we will be able to investigate a number of different aspects of the high-speed sliding behavior of silica gel, including the effect of water, the activation energy for the gel mechanism, and the effects that elevated temperatures have on the thixotropic behavior and healing of the gel. The assembly has been tested and is ready to use, and the Instron apparatus, which was unavailable for about six months in 2007 due to a major malfunction in its electronics and a delay in the procurement of funds for its repair, has been upgraded and repaired, and is fully functional.

The elevated-temperature assembly is shown in Fig. 3. The assembly consists of two aluminum heater blocks that are adjacent to the friction samples. The upper sample ring is epoxied into a steel grip mounted against an aluminum heating block, which is slid against a flat, roughly circular plate of the same material mounted against another aluminum heating block. The blocks are heated with cartridge heaters inserted into holes drilled in the blocks, three cartridges for the upper block and five for the lower block. The cartridges in a single block are all connected in parallel to a variable AC power supply (Variac). Our shakedown testing of the assembly shows that it is quite easy at less than 50% power from the Variac to obtain a temperature of 300 ^{o}C at the sample surface.

Critically, with this system in place, we will be able to revisit our earlier silica gel experiments (*Titone et al.*, 2001) in which we demonstrated that removal of water from novaculite samples and their surrounding atmosphere during friction experiments causes a disappearance of the gel weakening phenomenon. We have never been able to duplicate these astounding results, a fact we attribute to the notorious difficulty of removing water from the surface of quartz and other silicates. With our new sample stage, we will be able to heat samples *in situ* in a dry environment to aid in the removal of water from the sliding surface. The heating assembly will also allow us to vary temperature in our experiments and obtain activation parameters for gel 'rheology', as well as investigate the effects of temperature on healing of the gel. Finally, we will be able to provide a robust test of our interpretation of the results of our high-speed, small-slip experiments as being due to flash-heating phenomena by raising the ambient temperature and determining whether expected downward shifts in the weakening velocity are observed.

Progress in understanding weakening due to gel formation. Most of our efforts in 2007 were focused on improving our understanding of the flash weakening mechanism, surmounting numerous technical problems associated with the Instron apparatus used in those experiments, and implementing the high-temperature system in the Instron. The Instron apparatus is now in full working order, which with our new high temperature capabilities will allow us to investigate gel-weakening phenomena in much more detail. In spite of the experimental evidence to suggest that weakening due to thixotropy of silica rich, gel-like material on slip surfaces is an important dynamic weakening mechanism for a variety of important crustal rocks (*Goldsby and Tullis*, 2002; *DiToro et al*., 2004; *Roig Silva et al.*, 2004), many aspects of this mechanism remain poorly understood. What is the precise physical basis for the mechanism? What is the temperature dependence of gel thixotropy? What is the effect of surface roughness on operation of this mechanism? Is operation of this mechanism dependent upon the very smooth surfaces that exist in laboratory samples? (a question raised at the just-completed SCEC workshop on Dynamic Faulting Parameters in Pomona, California, on March 11, 2008). We will continue to investigate the silica gel weakening mechanism via careful experiments and microstructural analyses.

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