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Laboratory Experiments on Fault Shear Resistance Relevant to Coseismic Earthquake Slip

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Knowledge of the 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 an earthquake. 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, we have been investigating frictional weakening behavior of rocks at slip velocities higher than those usually investigated in rock friction experiments, but lower than slip velocities during earthquakes. This is an update on what we have discovered since the beginning of this award year on February 1, 2005 and on what progress we have made in laying the foundation for future work.

Our previous efforts have focused on understanding two dynamic fault weakening mechanisms – 1) coseismic fault weakening due to silica gel formation on the sliding surfaces of silicate rocks [*Di Toro et al.*, 2004; *Goldsby and Tullis*, 2002], and 2) flash heating/melting (*Goldsby and Tullis*, in preparation). Both mechanisms lead to low values of the friction coefficient at seismic slip rates (< 0.2 in some cases), and each is characterized by very different 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 0.36 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 4.8 mm/s.

Progress in understanding the gel weakening mechanism. Two important aspects of the gel weakening mechanism that are relevant to how this mechanism might affect earthquake behavior are 1) the slip distance required for weakening and 2) the time required for restrengthening following high speed slip. We have some new data that bears on both of these issues. We have collected some new data that provide a better understanding of the slip weakening distance for gel lubrication, whereas in the second case we have some interesting systematic data that we are puzzled by.

We have shown [*Di Toro et al.*, 2004] that the slip displacement needed to attain a steady-state slip resistance when gel lubrication is active is on the order of 1 m. It is important to understand what gives rise to this slip weakening distance. We believe it is the amount of slip needed to generate a layer of gel that provides lubrication, and we have several new results to present that support this interpretation. In one set of experiments using an albite feldspar rock, we in some cases removed the 75-100 μm thick layer of wear debris (gouge flakes) off the sliding surface between successive sliding episodes on the same samples, and, in other cases,

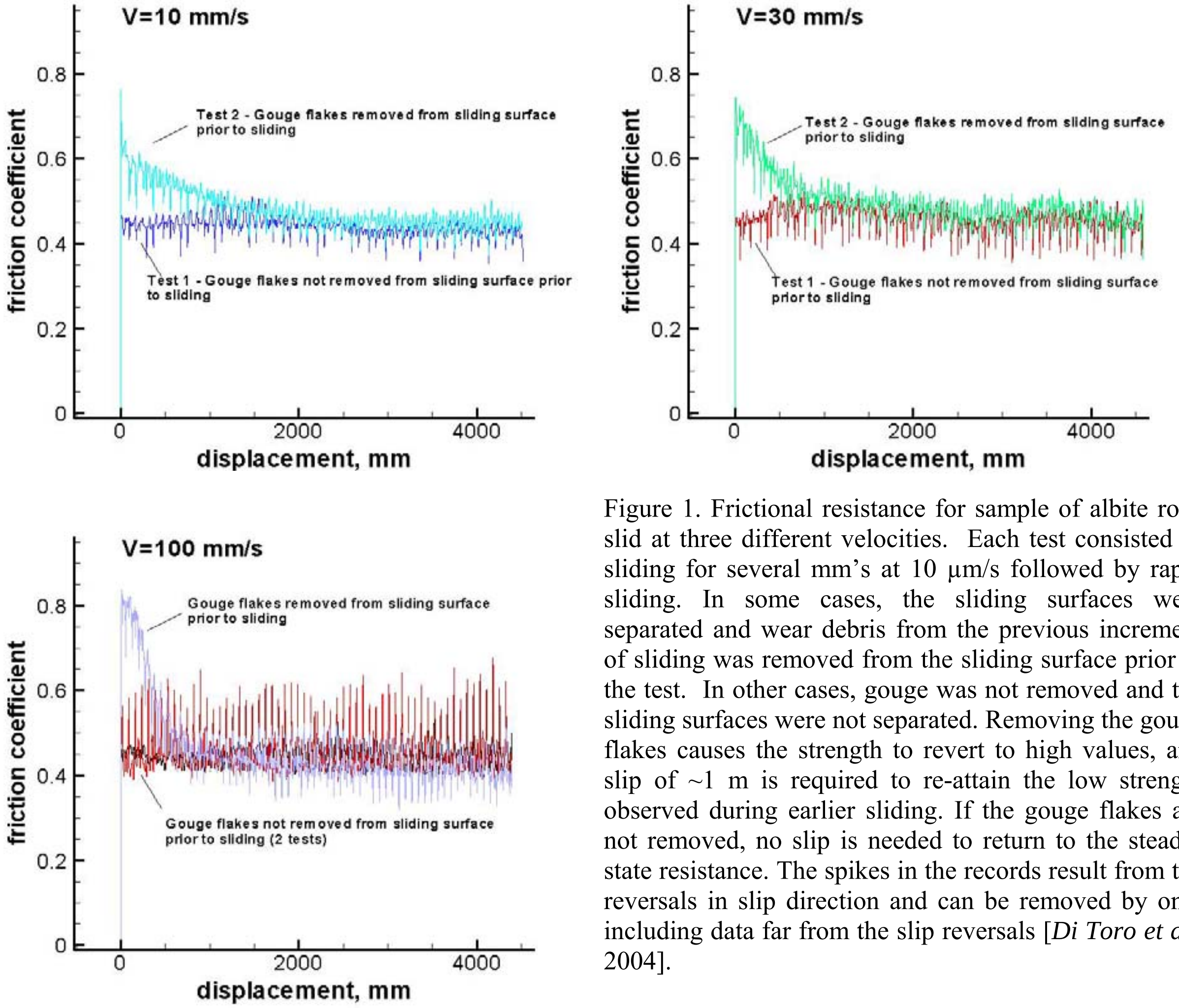

Figure 1. Frictional resistance for sample of albite rock slid at three different velocities. Each test consisted of sliding for several mm's at 10 μm/s followed by rapid sliding. In some cases, the sliding surfaces were separated and wear debris from the previous increment of sliding was removed from the sliding surface prior to the test. In other cases, gouge was not removed and the sliding surfaces were not separated. Removing the gouge flakes causes the strength to revert to high values, and slip of ~1 m is required to re-attain the low strength observed during earlier sliding. If the gouge flakes are not removed, no slip is needed to return to the steady-state resistance. The spikes in the records result from the reversals in slip direction and can be removed by only including data far from the slip reversals [*Di Toro et al.*, 2004].

resumed sliding after stopping sliding but did not otherwise disturb the wear debris on the sliding surface. Data from such tests are shown in Figure 1 for three different sliding velocities, 10, 30 and 100 mm/s. The data clearly show that if the surface is cleaned off between sliding episodes, values of friction return to the high levels characteristic of sliding at low slip rates, and a slip of ~1 m is required to return to the low value of friction obtained during earlier rapid sliding. In other words, the sample seems to be 'reset' to its original state by removing the gouge flakes. On the other hand, sliding resumed after a pause of <~180 s without brushing off the surfaces results in friction that is as low as it was prior to the pause of sliding, and there is no change in shear resistance with slip. We interpret this to mean that to attain low shear resistance it is necessary to develop a layer of silica gel on the slip surface, and if this layer is removed a significant amount of slip is needed to reform it and bring it back to a 'steady state' thickness.

Data we collected in 2004 that we have not reported previously are supportive of this interpretation, and they also address the issue of the time needed to restrengthen the surface after rapid sliding ceases. These data were obtained in our high pressure rotary shear apparatus and are shown in Fig. 2. There are several intervals of this experiment during which the sliding velocity was 1 mm/s or higher, as shown in Fig. 2a. For the first excursion to rapid slip rates (steps to 1

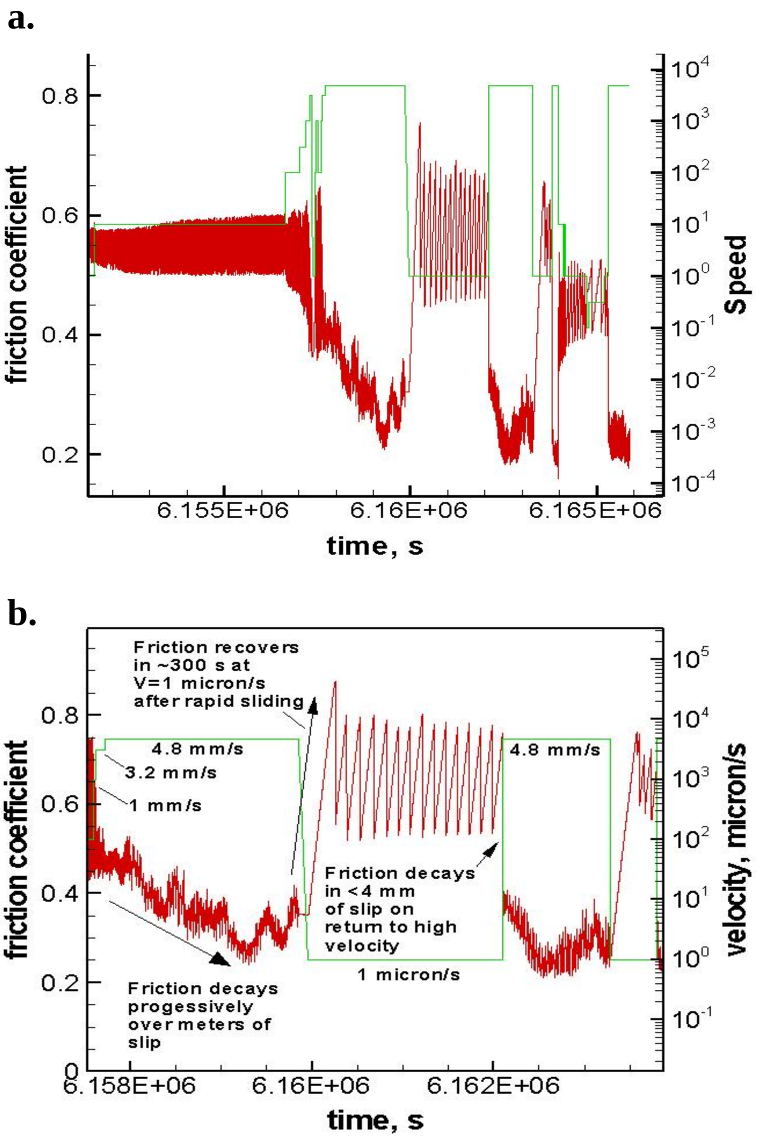

Figure 2. Plots of friction coefficient vs. time for a novaculite sample saturated with water, from an experiment conducted in our high pressure gas apparatus. a) Overview plot. b) Detail plot of Fig. 2a showing both the differences in the slip weakening distance for the initial rapid sliding sequence and subsequent steps to high (4.8 mm/s) sliding velocity, and the recovery of shear strength over shorter timescales (≤300 s) compared to similar tests with no fluids present. Because the time to reload is ~300 s, the recovery time could be shorter.

mm/s, 3 mm/s, then 4.8 mm/s), friction decreases slowly and reaches a 'steady state' over meters of slip, as shown in Fig. 2b. For subsequent steps to 4.8 mm/s, friction decayed rapidly over <4.8 mm of slip. We assume that the reason it took several meters of slip at the beginning of the experiment is that the initial surface roughness had to be smoothed in order to allow a layer of ultracomminuted, hydrated silica ('silica gel') to develop, whereas for subsequent intervals the surface was already smooth and the gel layer was already present: all that was required to weaken the gel again was rapid strain. This interpretation is consistent with our interpretation of the data in Fig. 1, and adds the idea that the smoothing of the initial roughness requires several meters of slip, but the recreation of a layer of silica gel on a smooth surface only requires about 1 m of slip

Another very interesting observation arises from the experiment which yielded the data in Fig. 2. Upon cessation of slip at 4.8 mm/s and resumption of slower slip, there is a finite period of time required for strengthening back to the level characteristic of slip at 1 μm/s. In this experiment this period of time is ≤300 s. This recovery time is consistent with what we observe in the 1-atm Instron apparatus where the sample is exposed to room humidity [*Di Toro et al.*, 2004]. What is surprising, and what we have been struggling to understand, is that the time for strength recovery in all of our previous experiments in the high pressure much longer than 300 s, namely ~2000 s. We do not currently know what causes the difference, but there is at least a possible correlation with the amount of water available in the surrounding environment. The experiment which yielded the data in Fig. 2 was conducted under water-saturated conditions, whereas our other high-pressure experiments were conducted in the absence of pore fluids; the fluid-free samples were thus effectively sealed from any reservoir of additional moisture. The unconfined experiments conducted under room humidity in the Instron and the high-pressure experiments on water-saturated samples therefore had a ‘reservoir’ of additional water available, whereas experiments on fluid-free samples have no such reservoir. If this interpretation is correct, it suggests that when water is freely available, the rate of strength recovery upon cessation of rapid slip is much more rapid than if it is not. However, the reason for this effect is not clear. We believe that strength recovery results from a time-dependent removal of water from interparticle contacts in the silica gel or a polymerization of the Si-O-Si networks in the silica component of the gel. If anything, we might have expected the recovery to be more rapid, not less rapid, in the dryer environment. This is because in the dry case, with no surrounding reservoir of water, the concentration gradient of H_2O from the wet gel to the dry surroundings should be higher than in the wet case and so the diffusion rate of H_2O out of the gel should be higher. The only counteracting effect we can envision is that perhaps the presence of water as a free phase, perhaps due to capillary condensation in the case of the atmospheric humidity experiments, enhances the movement of Si and so allows more rapid rearrangements that cause strengthening. In spite of our lack of understanding, our observations about the role apparently played by water availability in the rate of strength recovery may help us understand why we have observed different recovery rates in different experimental apparatuses, and determine which recovery rate is appropriate to the natural setting.

Progress on developing experimental techniques for conducting rapid slip at high confining pressure. In order to understand several high speed weakening mechanisms, such as that due to thermal pressurization of pore fluids or lubrication by a layer of melt as occurs to form pseudotachylytes, it is important to perform experiments at elevated confining pressure. High pressure with a jacketed sample is desirable in the case of thermal pore pressurization in order that any pore pressure developed can be contained within the sample rather than leak along the fault surface to the 1-atm surroundings of an unconfined experiment. Such escape of fluid along the fault plane may be easier than perpendicular to the fault plane, since the fault zone permeability may be much higher along the fault [*Zhang et al.*, 1999; *Zhang and Tullis*, 1998]. In the case of generation of a melt layer by frictional heating, shear resistance may be due to viscous shearing of the melt layer, and consequently the resistance may be relatively insensitive to normal stress or confining pressure. The existing data [*Hirose and Shimamoto*, 2004; *Tsutsumi and Shimamoto*, 1997] have all been collected in unconfined tests in which the melt is able to escape, and consequently high melt pressures cannot develop. Expressed as a coefficient of friction, the shear resistance due to melting in the Shimamoto experiments appears to be high due to division of the shear stress by a low normal stress. Nevertheless, melt lubrication may be an important weakening mechanism at elevated pressures (i.e., at depth), assuming that the shear stresses involved do not increase with depth. Experiments need to be undertaken to explore weakening behavior due to melting at more geologically realistic conditions.

We are still making extensive modifications needed to slide indefinitely at slip speeds of about 1 m/s that involve adapting a 100 HP motorcycle engine to the drive system of our high pressure rotary shear apparatus. Although progress is being made, it is a major undertaking and is not close to completion. Consequently we have been investigating some alternative approaches that we might be able to follow in the short term. One of these involves using our existing rotary hydraulic actuator built several years ago as part of our rotary servo system,. It is designed to artificially stiffen the apparatus by making rapid corrections to the external drive system in response to a feedback signal generated by a measurement of slip made very near the sample's slip surface. This high speed rotary drive system is only able to rotate up to 9 degrees, corresponding to 4 mm of slip for our standard sample size. The fastest rate at which it can actually move, either for one short burst or for sustained oscillations, is something that we are presently measuring, since that was not part of its original design specifications. Our present calculations suggest that we will be able to slide at several hundred mm/s in at least the short single burst mode, which would be adequate to provide some useful new data for both flash heating and thermal pressurization.

When we decided that we might be able to perform rapid single shot or oscillatory sliding with the rotary servo drive system we realized that a commercial rotary actuator of either the vane or the rack-and-pinion type might be able to provide much larger displacements at high slip rates. Purchasing such an actuator and adapting it to our high pressure rotary shear machine would be a much simpler job than adapting the motorcycle engine, so we spent some time during this grant period investigating commercial rotary actuators that might be temporarily called into service. Unfortunately, this solution proved to be impractical. Vane-type actuators will not fit into the space available within the apparatus, and they provide at most about 270 degrees of rotation. Rack-and-pinion types, although they can provide up to one revolution of the sample share with the vane-type actuators the property that a large volume of oil is needed to provide the required torque and amount of rotation. With any practical hydraulic power supply, it is not possible to attain the flow rates needed to rotate much faster than the 4.8 mm/s slip rate we can now attain with our current continuous drive system powered by an electrohydraulic stepping motor. Our custom-designed rotary actuator used in the rotary servo system is a better temporary solution to the problem of attaining high slip rates while we continue to implement the more complicated motorcycle powered drive system.

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