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LABORATORY EXPERIMENTS ON ROCK FRICTION FOCUSED ON UNDERSTANDING EARTHQUAKE MECHANICS

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TECHNICAL ABSTRACT

For the past several years we have been investigating a surprising weakening that occurs during frictional sliding of quartz and other silicate rocks to displacements of several meters and at slip speeds up to 3 to 100 mm/s. Previously we have been unable to identify the weakening mechanism and have only succeeded in eliminating a variety of potential mechanisms. During this grant period we have obtained results that suggest the weakening is due to the production of a layer of weak silica gel on the sliding surface. The results leading us to this conclusion are two-fold. First, the weakening is absent in extremely dry samples and can be alternately caused and eliminated by alternately adding and removing atmospheric humidity to/from the sample. Second, SEM micrographs of the weak samples show clear textural evidence for the existence of a material that has flowed from a continuous layer on the sliding surface into small pre-existing depressions on the surface. Although further evidence supporting or eliminating this gel-weakening hypothesis are needed, it seems likely that it will withstand further investigation. We hypothesize that this material behaves in a thixotropic manner, in which a time-dependent tendency to strengthen competes with a strain-dependent tendency to weaken. Although is too early to say if the mechanism might operate during earthquakes, some lines of suggest this is plausible. If it is important in some or many earthquakes, the co-seismic dynamic strength might be essentially zero. Thus, if the tectonic stresses are high, then very high accelerations and very strong ground motions would be expected.

INTRODUCTION

This is a final technical report for USGS grant 01-HQGR0127. The grant covers a one year period, from March 1, 2001 to February 28, 2002. We have focussed our efforts on understanding the physical mechanism causing the dramatic frictional weakening of unknown origin that we have discovered during previous grant periods. The work is relevant to understanding dynamic resistance during earthquakes. We will discuss our progress in detail below.

PUBLICATIONS RESULTING FROM THIS GRANT

.Goldsby, D.L., and T.E. Tullis, Low frictional strength of quartz rocks at subseismic slip rates, *2001 Southern California Earthquake Center Annual Meeting Proceedings and Abstracts*, 77-78, 2001.

Tullis, T.E. and D. Goldsby, The influence of fault friction on earthquake stress transfer and fault interaction, *Eos. Trans. Am. Geophys. Union, 82*(47), Fall Meeting Suppl., Abstract S11C-06, 2001.

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Titone, B., K. Sayre, G. Di Toro, D. Goldsby, and T.E. Tullis, The role of water in the extraordinary frictional weakening of quartz rocks during rapid sustained slip, *Eos. Trans. Am. Geophys. Union, 82*(47), Fall Meeting Suppl., Abstract T12G-03, 2001.

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Di Toro, G., D. Goldsby, and T.E. Tullis, Low friction at seismic slip rates?, *in preparation* for Science, 2002.

RESULTS

Background

During previous grant periods we have discovered dramatic frictional weakening by a process that does not seem to be any of those on that have previously been considered. For example, our results cannot be explained by shear melting [*Spray*, 1987; *Tsutsumi and Shimamoto*, 1997], because, as shown by calculations and direct measurements, the temperature in our experiments are too low. They cannot be due to thermal pressurization of pore water [*Lachenbruch*, 1980; *Mase and Smith*, 1984; *Mase and Smith*, 1987] because the effect is equally important if our rock is saturated with water under pressure or if the only water is that adsorbed from the atmosphere, and it is equally important for low and high permeability rock. Instead, the weakening mechanism appears to be due to formation of a layer of silica gel on the sliding surface. In this report we will describe the results that lead us to this conclusion and then we will discuss briefly the possible geophysical significance of this mechanism. There are implications for the magnitude of dynamic stress drops and thus for peak seismic accelerations expected during earthquakes and the amplitude of strong ground shaking.

Recent results and insights from controlled humidity tests

Introduction. As we have reported previously, at rapid to dynamic slip rates of 3 mm/s to 100 mm/s at room humidity, the friction coefficient for quartz rocks decreases in some cases by a factor of 8. Though we have not previously identified the mechanism responsible for this extraordinary decrease in friction, we have, through temperature measurements and calculations, determined that this weakening must occur in the absence of melting [*Di Toro et al.*, 2001; *Di Toro et al.*, 2002; *Goldsby and Tullis*, 2002]. Nor is the weakening caused solely by elevated temperatures on the sliding surface. New insights into the nature of the weakening mechanism have emerged from controlled humidity experiments.

During this grant period, we have made important breakthroughs in identifying and understanding the physical mechanism by which quartz rocks weaken so dramatically at rapid slip rates [*Titone et al.*, 2001; *Titone et al.*, 2002]. Our progress stems in part from experiments designed to investigate the role of water in the weakening mechanism. We demonstrate below that water is a critical ingredient for weakening to occur, such that removal of water results in high frictional strengths even at rapid slip rates. Our mechanical data, coupled with microstructural observations of the sliding surface and estimates of temperature, strongly suggest that intense comminution in the presence of water results in the formation of a silica gel layer on the sliding surface. This gel layer apparently lubricates the sliding surface.

We briefly describe below the experimental method for these new tests and detail the remarkable new experimental results. Finally, we discuss possible implications of gel lubrication for faulting in the Earth.

Experimental methods and mechanical results. Sliding experiments were conducted on Arkansas novaculite, a >99% quartz rock with a fine grain size (<10 μm). 'Room dry' samples were prepared 'as-is', with no attempts made to remove water from the sample. So-called 'dry' samples were baked in a 1-atm furnace for 24 h at 850^{o} C prior to sliding to remove intercrystalline and intracrystalline water from the samples. The fine grain size of the novaculite allows for efficient removal of intracrystalline water, for example water in fluid inclusions, from the sample via volume diffusion through the quartz grains, then more rapid grain boundary diffusion to the exterior of the sample [*Farver and Yund*, 1992].

Sliding experiments were conducted in an Instron compression/torsion apparatus which allows unidirectional sliding over ~90 degrees of rotation. To achieve large cumulative displacements, in some cases >60 m (Fig. 1), the rotation direction was periodically reversed. The absolute value of the frictional resistance is plotted in Fig. 1 (allowing long-term trends in the data to be observed without offsets in the data due to reversals of sign of the friction coefficient). Samples could only be slid continuously for ~4 m of displacement, due to data acquisition constraints. In between these 4 m segments, sliding was paused for ~5 minutes to download and store the raw data. At the beginning of each segment the sample was slid at a velocity of 1 μm/s for 2 mm of slip before increasing sliding velocity to 3.2 mm/s.

In several experiments, 'room dry' samples were slid at room humidity, which varied between approximately 50% and 80%, to total displacements of ~30 m. Representative data from one such control experiment (shown in gray in Fig. 1) show a large decrease in friction coefficient with increasing displacement at a slip rate of 3.2 mm/s, from values of ~0.7 to less than 0.2 in ~25 m of displacement. In some cases, the friction coefficient measured at high speed in the beginning of one ~4 m sliding segment was higher than the value measured at high speed at the end of the previous segment – some restrengthening occurred in the ~5 minute pauses between segments.

In contrast, a 'dry' sample remains strong even at high sliding speeds if it is kept dry during the experiment. Furthermore, the sample can be reversibly weakened and strengthened by subsequently wetting and drying it, respectively. This remarkable behavior is illustrated in Fig. 1 by the data in red, green, and blue. The experimental procedure, and the resulting frictional response illustrated in Fig. 1, is as follows: The 'dry' sample was first placed inside a sealed plastic bag around the sample assembly. Dry nitrogen was allowed to fill and slightly pressurize the inside of the chamber for a period of ~24 hours prior to sliding. The relative humidity inside the bag was much less than one percent. Sliding was then begun with the sample in dry nitrogen and continued for ~24 m of slip. During this time, the strength remained high as shown by the data in red in Fig. 1. This behavior is in marked contrast to that for the room dry sample slid at room humidity, shown in gray. After sliding in dry nitrogen for ~24 m of displacement, a beaker of water was placed inside the sealed sample chamber, and the 'dry' sample was slid for an additional displacement of ~8 m. The sample remained strong during this time as shown by the data in green in Fig. 1. At this point, after ~34 m of total slip, the sample was held at zero sliding velocity for ~12 h inside the sample chamber containing the beaker of water. The sample was then exposed to room humidity and slid for a displacement of ~12 m. The behavior is shown by the data in blue in Fig.1. Initially the friction coefficient μ increased, to a maximum of ~0.9, and then a remarkable weakening occurred over a slip distance of about 2 m, to μ ~0.1. After sliding at room humidity, the sample was exposed again to the dry nitrogen and slid for 12 m, during which time μ almost immediately rose to a value of ~0.8 (second group of data shown in red in Fig. 1). Finally, when the sample was slid again in humid room air, μ very rapidly weakened to ~0.1 (second group of data shown in blue in Fig 1). Note that in addition to the remarkable reversibility in strength with changes in ambient humidity, μ is always 0.7 or higher at low speed (1 μm/s), as shown at the start of each ~4 m segment for both the 'as is' and 'dry' samples, regardless of the value of the ambient humidity.

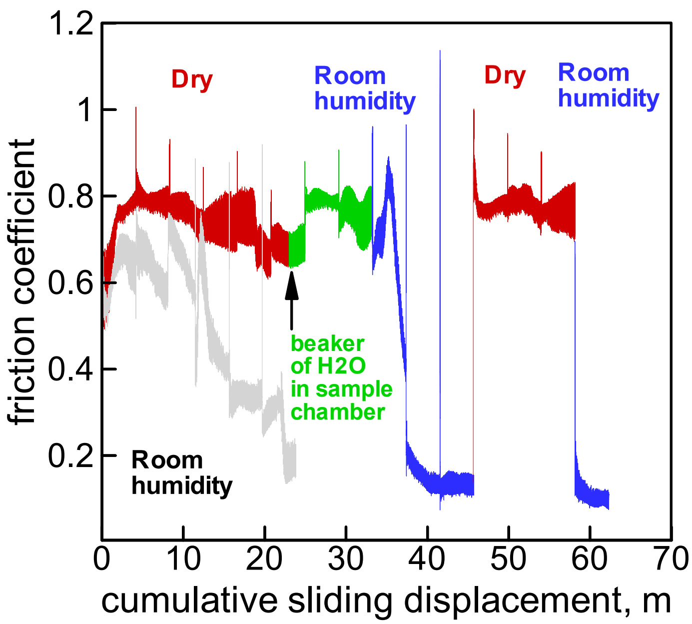

Fig. 1- Friction coefficient vs. displacement for unconfined samples slid at 5 MPa and 3.2 mm/s. Samples were slid in 'segments' of ~4 m of displacement. Each 'segment' consisted of a period of slow sliding at 1 μm/s for 2 mm of slip (represented by the long thin 'spikes' in the data), followed by rapid sliding at 3.2 mm/s. In one example, a 'room dry' novaculite sample was slid under room humidity conditions (data shown in gray). In another example, a 'dry' sample was slid under conditions that alternated from dry to humid to dry to humid. See text for further details.

Microstructural observations. In addition to the remarkable mechanical data from the ‘dry’ experiment, detailed observations were made of the sliding surfaces using transmitted and reflected light microscopy as well as scanning electron microscopy (SEM). A reflected light image of the 'dry' sample acquired after the controlled humidity test is shown in Fig. 2. The photograph was taken using only room light to illuminate the sliding surface. As shown in the photograph, the sliding surface is extremely smooth and reflective. Dark-colored spots on the sliding surface are pores in the novaculite.

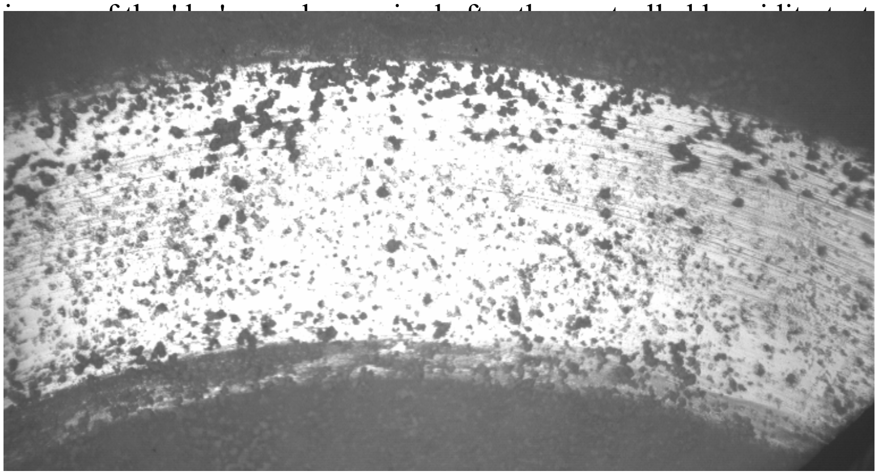

Fig. 2 – Reflected light image of the 'dry' sample of Fig. 1 (plate side of a ring-on-plate sample) after sliding under both dry and room humid conditions. The sliding surface is ~5 mm wide. Dark background is unreflective rock surface where no sliding occurred. Slickenline grooves on the sliding surface show the sliding direction

Four SEM images of the sliding surface of Fig. 2 are shown in Fig. 3. Portions of Fig. 3b and 3c show a smooth, almost featureless layer of material. At the edges of this smooth layer, near depressions on the sliding surface, numerous features are observed which strongly suggest flow of a viscous material. From the micrographs, we estimate a thickness of this layer on the order of 3-5 microns. The layer appears to blanket the smooth, featureless portions of the sliding surface. Viscous material appears to have flowed into the low spots on the sliding surface, resulting in the dramatic flow features in Fig. 3. This viscous layer is easily seen in transmitted light in thin sections cut normal to the plane of the sliding surface, at right angles to the sliding direction. Measurements of layer thickness from optical microscopy, 3-4 microns, are consistent with thickness estimates from SEM.

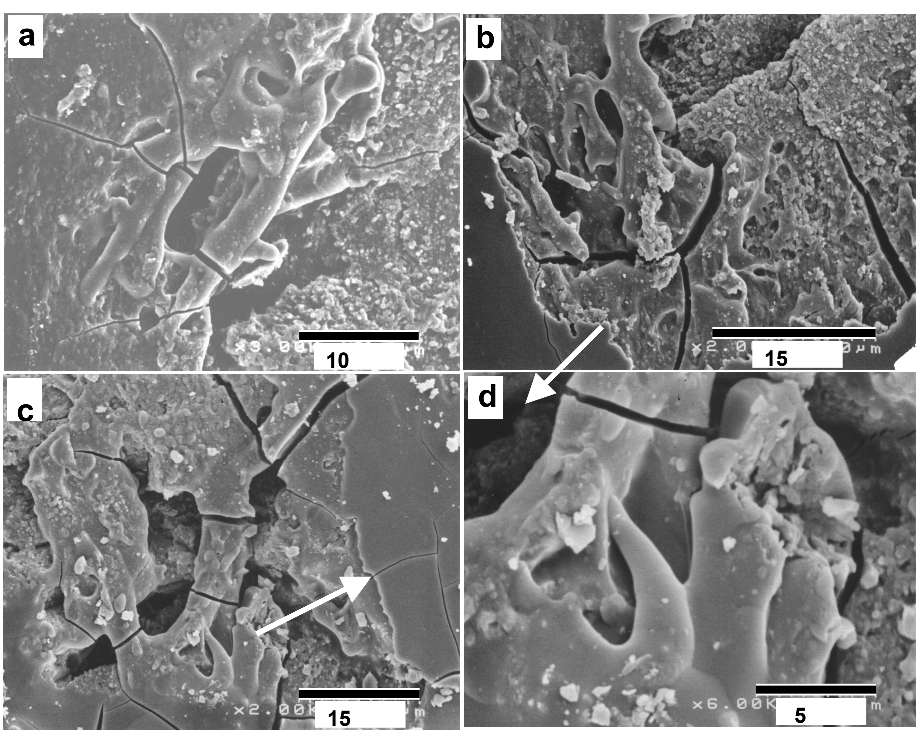

Fig. 3- SEM micrographs of the sliding surface shown in Fig. 2. Smooth, relatively featureless regions (arrows) are blanketed with a thin film of hydrated silica, and correspond to the flat, highly reflective parts of the sliding surface shown in Fig. 2. Viscous flow features are observed near depressions on the sliding surface, where silica gel has been dragged by sliding.

New insights from controlled humidity tests. Our frictional sliding experiments on quartz rocks at rapid slip rates activate a dramatic weakening mechanism that operates outside the range of displacements available in most rock friction apparatus. At first glance, the microstructural features observed in SEM (Fig. 3) might appear to be consistent with melting. However, the temperatures generated by sliding at 3 mm/s at a normal stress of 5 MPa are $<40^{o}$ C, much too low for melting [*Di Toro et al.*, 2001; *Di Toro et al.*, 2002; *Goldsby and Tullis*, 2002]. This is shown by FEM temperature calculations, calibrated against temperature measurements near the sliding surface, as described in our proposal last year.

Our new results strongly suggest that weakening of quartz rocks at intermediate slip speeds results from silica gel formation. We believe gel forms as the result of amorphization of quartz in the presence of water. Solid state amorphization of quartz occurs during ball milling (see review of [*Lin et al.*, 1975]); in hydrostatic compression (diamond anvil) experiments [*Kingma et al.*, 1993]; and in shock experiments [*Di Carli and Jamieson*, 1959; *Langenhorst et al.*, 1992]. Amorphization during frictional sliding may occur at asperities, where contact stresses approach the hydrostatic pressures in diamond anvil tests, or result from comminution, as occurs during ball milling. Transmission electron microscope (TEM) analyses of quartz samples from our earlier low speed experiments to relatively large displacements demonstrate the existence of amorphous material [*Yund et al.*, 1990]. In controlled humidity tests, sliding of 'dry' samples in dry nitrogen likely results in comminution and amorphization of quartz, but no gel formation. Hence, values of the friction coefficient remain high under dry conditions at both low and high slip rates. The introduction of water into the sample chamber after sliding at dry conditions results in wetting of the comminuted material on the fault surface via adsorption and absorption, leading to gel formation. Readmission of dry nitrogen into the sample chamber results in drying of and increased interparticle bonding in the gel, and therefore increased strength. Rewetting of the gel by readmission of humid air into the sample chamber results in decreased strength.

The extraordinary weakening due to gel formation at rapid slip rates may be caused by: 1) thixotropy of the gel layer or 2) hydrodynamic lubrication via the gel layer. One might initially suppose that the explanation could be that higher temperatures generated at faster slip rates decrease the viscosity of a gel. Several lines of evidence from our experiments, however, suggest that the weakening is not due to the temperature dependence of gel viscosity. For example, the average fault surface temperature is only $\sim 35^{o}$ C at a slip rate of 3 mm/s and normal stress of 5 MPa, implying a large temperature dependence of viscosity. Furthermore, the friction coefficient increases after rapid sliding over characteristic times much longer than the decay in temperature [*Goldsby and Tullis*, 2002].

Alternatively, decreased shear resistance at higher slip rates could be caused by thixotropy, the time-dependent analogue to shear-thinning behavior [*Shaw*, 1980]. When a thixotropic fluid at rest is then sheared at a constant rate, the viscosity of the fluid decreases [*Ferguson and Kemblowski*, 1991]. When a previously sheared thixotropic fluid is maintained at rest, its viscosity increases with time due to reformation of structural elements in the fluid. For silica gel, these structural elements are interparticle bonds between silica particles [*Iler*, 1979]. Thus, weakening at higher velocities could be caused by the breakdown of interparticle bonds within a gel layer. Fig. 4 on the next page shows an almost instantaneous change in shear strength for an a 'dry' sample slip under humid conditions when velocity is stepped between 1 μm/s and 3 mm/s. This dramatic drop in shear resistance, which occurs in 1 s and a displacement of only 3 mm, is consistent with the thixotropic hypothesis, since the shear strain of the thin gel layer is large even for small displacements. Using the measured gel thickness of 3 μm yields a shear strain of 1000 for a displacement of 3 mm.

Weakening at higher slip velocity may also be caused by an increasing contribution from hydrodynamic lubrication by the gel as velocity increases. When a frictional surface with contacting asperities has a viscous fluid in the space between the asperities, the average pressure of the fluid can increase as the velocity increases due to the viscosity of the fluid. This pressurized fluid can reduce the effective stress, and so reduce the shear resistance, as an increasing part of the normal load is born by the fluid [*Brodsky and Kanamori*, 2001]. With pure hydrodynamic lubrication all of the resistance is due to viscous shearing of the fluid, and the resistance increases with increasing velocity. However, because the fluid resistance in the purely hydrodynamic regime is much less than the solid-to-solid resistance that occurs in the purely frictional regime, the transition from the frictional regime to the hydrodynamic regime can be marked by a decrease in shear resistance. Our experiments at slip velocities above 1 mm/s may be in this transitional regime. Although this might seem like an attractive mechanism to explain

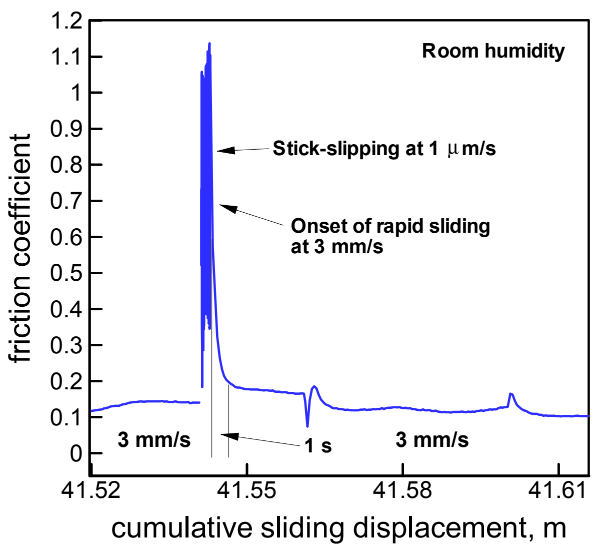

Fig. 4 - Data from a portion of Fig. 1, for a 'dry' sample slid under humid conditions, plotted over a much shorter displacement range. Plot isolates data from a portion of the experiment in which velocity is changed from 3.2 mm/s to 1 µm/s (after a 5 minute pause to reset the data recorder) and then back to 3.2 mm/s. At low speed, friction oscillates (stick-slips) about a high value near 0.9. With an increase in velocity to 3.2 mm/s, friction decreases in ~1 s, over a displacement of ~3 mm, to a value near 0.1. 'Bumps' in the data beyond 41.55 m of displacement are artifacts from changing the sliding direction.

our results, the mechanism cannot explain the fact that upon cessation of rapid sliding the strength remains low even when slid is done at a slow speed where the samples were previously strong. Strength recovery seems to be controlled by a time constant of about 3000 s. Thus, during this 3000 s, the samples are weak, even at slow slip speeds. Hydrodynamic lubrication cannot explain this result – it only predicts a low strength while sliding is rapid because rapid shearing is needed to maintain the pressure in the viscous fluid.

G*eophysical implications.* If the weakening we observe experimentally also occurs on natural faults, then dramatic weakening occurs at conditions much less severe than those required for melting and occurs at slip rates lower than 1 m/s. It is not yet clear how much SiO_2 must exist in a rock for this silica gel mechanism to cause weakening; furthermore, we don't know what the tendency is for other silicate minerals to form gel layers during prolonged sliding. We have previously reported intermediate-speed weakening that occurs in a pure feldspar rock and to a lesser extent in granite. In the case of the feldspar rock, weakening was much less severe than in quartz rocks. In the case of granite, weakening only occurs at the highest normal stresses (~100 MPa). However, it is notable that many fault zones are mineralized with quartz, even though the country rock may not contain much quartz. Some of the textures seen in such fault zones are difficult to understand and may involve a stage of precipitation of chalcedony, opal or other silica polymorphs [*Power and Tullis*, 1989]. Some of these fine-grained varieties of silica have similarities to silica gel [*Graetsch*, 1994; *Knauth*, 1994], making it plausible that silica gel might form in many fault zones. Another interesting observation is that pseudotachylites are never observed in pure quartz rocks [*G. Di Toro, personal communication*, 2001], perhaps because friction on such faults is low as a result of the silica gel weakening mechanism such that the frictional heating is insufficient to cause melting.

Many rocks will likely not weaken via this gel mechanism, but may weaken at sufficiently high slip velocities due to frictional-heating induced melting. This may result in even lower values of the coefficient of friction. Different rock types along a fault zone may weaken via different mechanisms and to different degrees. This variability could result in heterogeneity in rupture velocity and stress drop that could be responsible for some of the complexities inferred in source inversions from strong motion data [*Archuleta*, 1982].Clearly we need to better understand dynamic fault weakening mechanisms. We intend to further that understanding by conducting friction experiments over a wide range of slip velocities to large displacements at conditions relevant for earthquakes.

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 frictional melting. The weakening mechanism appears to be that of production of a weak layer of silica gel on the sliding surface. Whether this proposed 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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NON-TECHNICAL ABSTRACT

Our recent experiments have shown that frictional sliding of rocks at speeds approaching those of earthquake slip makes them much weaker than in slower conventional experiments, but the reason for this has been unclear. We find that water is needed for this weakening and examination of the sliding surfaces shows material exhibiting flowage features. This suggests the weakening is due to the production of a weak layer of silica gel, a mixture of silica and water.. If weakening also occurs during earthquakes, faults could be so weak that the size of damaging ground motions might be larger than usually expected.