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LABORATORY EXPERIMENTS ON ROCK FRICTION FOCUSED ON UNDERSTANDING EARTHQUAKE MECHANICS

Terry E. Tullis

and

David L. Goldsby

Brown University
Department of Geological Sciences
Providence RI 02912-1846

Tele: (401) 863-3829
FAX: (401) 863-2058
Email: Terry_Tullis@brown.edu
Web Site. http://www.geo.brown.edu/faculty/ttullis/index.html

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TECHNICAL ABSTRACT

We have been investigating the frictional resistance of rocks at slip speeds much faster, to displacements much larger, than those in most laboratory experiments. We have discovered a dynamic weakening mechanism that causes extraordinary frictional weakening of silicate rocks even at slip rates two and half orders of magnitude slower than seismic slip rates; we attribute this weakening to the development of a silica gel-like layer on the sliding surface. While a key experiment conducted previously has suggested that presence of water is critical for the gel-weakening mechanism to operate, subsequent experiments have failed to duplicate those earlier results, which may suggest that the role of water in the gel weakening mechanism is more complicated than originally hypothesized.

We have also begun an exciting suite of experiments investigating flash heating and flash melting. These experiments are conducted at very high sliding velocities of nearly ~400 mm/s over displacements too short for ultracomminution and hence gel formation to be significant. Our first results, coupled with theoretical estimates of flash temperature, are consistent with flash melting at a sliding speed of 300 mm/s or higher.

During the past year, we have begun modifying the drive system of the apparatus to allow slip at 1 m/s or faster at high confining pressure. Developing this new capability will be a multi-year effort, but when complete will allow us to study shear melting as well as other potential weakening mechanisms that are not currently assessable by available experimental techniques.

INTRODUCTION

This is a final technical report for USGS grant 02-HQGR0070. The grant covers a one-year period, from March 1, 2002 to February 28, 2003. We have focused our efforts on further understanding the physical mechanism causing the dramatic frictional weakening that we attribute to the development of a layer of lubricating thixotropic silica gel on the sliding surface that we 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, *Geophys. Res., Lett., 29, 1844, doi:10.1029/2002GL015240*, 2002.

Goldsby, D.L., T.E. Tullis, G. DiToro, B. Titone, and K. Sayre, Frictional weakening of silica-bearing rocks at large displacement and high slip velocity, *2002 Southern California Earthquake Center Annual Meeting Proceedings and Abstracts*, 73-74, 2002.

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

RESULTS

Background

During the past several years, we have been investigating previously unknown frictional properties of rocks at nearly seismic slip velocities. Our experiments demonstrate that extraordinary weakening of quartz (and to a lesser extent feldspar) rocks occurs at slip rates between 3 and 100 mm/s, over sliding displacements and normal stresses characteristic of earthquakes. For quartz rocks, we have measured friction coefficients of less than 0.1. The weakening appears to be due to the formation of a weak layer of silica gel-like material on the sliding surface. Although this is a newly discovered weakening mechanism, comparison with fault surfaces in nature suggests that this mechanism could be operative during dynamic earthquake slip. We have a paper published detailing our findings [*Goldsby and Tullis*, 2002], a second paper in review at *Science* [*Di Toro et al.,* 2003], and another in preparation to be submitted to GRL. Weakening via this 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. A combination of large displacement and rapid slip speed is required for the silica gel layer to be weak, and complete recovery of strength at slow or zero slip rate after rapid sliding requires 100 to 2000 s, suggesting that the gel is thixotropic. Although the formation of a silica gel-like layer appears to explain our data, further knowledge is required to better understand this mechanism, including an understanding of the roles of water and temperature, and better characterization of the gel layer. Part of our proposed research is directed at these outstanding problems.

We have conducted a new series of experiments investigating another high-speed weakening mechanism, so-called 'flash heating,' which is the localized heating that occurs at rubbing asperity contacts. Due to the very large contact stresses, the temperatures generated at asperities can be much higher than the average temperature of the sliding surface. At sufficiently high velocities, flash heating can lead to melting of the asperities and a reduction in the friction

coefficient, even though the average temperature of the sliding surface is too low for the entire fault surface to be melted.

In this report we will describe our results and then we will discuss briefly the possible geophysical significance of these weakening mechanisms. 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 tests at rapid slip rates

Introduction. We have focused our ongoing effort to understand the dynamic frictional behavior of rocks on two problems: understanding the nature of the dramatic weakening mechanism we have discovered for quartz rocks [*Di Toro et al.*, 2003; *Goldsby and Tullis*, 2002]), and understanding flash heating and melting as a dynamic fault weakening mechanism. Both mechanisms have important implications for dynamic rupture initiation and propagation.

Investigation of the gel-weakening hypothesis. We have previously reported the results of an extensive series of experiments at rapid to nearly seismic slip rates on a variety of rocks. These results have demonstrated that frictional sliding of quartz rocks at room temperature and rapid slip rates activates a frictional weakening mechanism that causes an extraordinary decrease in the friction coefficient, to values as low as ~0.15 [*Di Toro et al*., 2003; *Goldsby and Tullis*, 2002]. We have proposed that this weakening results from the formation of silica-gel like material on the sliding surface. Much of our current work is focused on understanding in more detail the nature of this weakening mechanism.

One important factor which may yield critical insights into the nature of this mechanism is the role of water. We have previously reported the results of an intriguing experiment designed to investigate the role of water in the weakening observed for quartz rocks [*Titone et al.*, 2001]. In that experiment, intercrystalline and intracrystalline water was removed from a fine-grained quartz (novaculite) sample by baking it in air at a temperature of 800 ^{o}C. A frictional sliding experiment was then conducted in an Instron rotary shear apparatus in a dry nitrogen environment, at rapid slip rates of 3.2 mm/s. The apparatus is capable of a rotary shear displacement of only ~40 mm. Larger displacements (up to tens of meters) are accumulated by reversing the sliding direction.

We observed that the dried sample slid in a dry nitrogen environment was much stronger than undried samples slid in a room humid environment; the friction coefficient of the dried sample was ~0.8 compared to ~0.6 for undried samples in room humidity. Furthermore, when the dried sample was exposed to humid air, the friction decreased precipitously to a value less than 0.2. When the sample was re-exposed to dry nitrogen, the friction increased to ~0.8; re-exposure to humid air then caused another decrease in friction coefficient, back to a value less than 0.2. Thus, the friction of the quartz sample could be systematically varied from 0.8 to 0.2 simply by varying the humidity within the sample chamber.

Given the prominent role that water appears to play in the weakening of quartz rocks at high slip speeds and large sliding displacements, we have made four attempts within the past year to duplicate the results of this important experiment. Our first three attempts were unsuccessful; data for the dried samples slid in a dry environment were indistinguishable from undried samples slid at room humidity. We believe the difficulty of repeating these measurements is related to the difficulty of removing water from the system. We have identified three factors that may have contributed to this problem. For example, since our first experiment, Brown University has

changed gas vendors, and the nitrogen gas acquired from the new vendor may have higher water content than that from the previous vendor. Another contributing factor may have been that the heat gun used to dry the surface of the sample in the earlier test just prior to encasing the sample in the dry nitrogen tent was capable of generating much higher temperatures than the one used in subsequent tests. Finally, the flow rate of nitrogen through the tent around the sample may have been higher in our initial test than in subsequent experiments.

To test these hypotheses, we have just completed another experiment in which 1) an ultra high purity grade of nitrogen was used (with an advertised water content of < 5 ppm), 2) a heat gun with a much larger heat input than used in the previous three attempts was employed, and 3) a higher flow rate than in the previous three experiments was used.

To our astonishment, this experiment has also failed to reproduce the results of our successful dry test, even though one half of the sample assembly was baked out at 900 ^{o}C for over two weeks (!) and the other half was baked out for over 48 hours. Furthermore, the experiment produced some very puzzling results that we still do not understand. With the dried sample in the dry nitrogen environment, the sample weakened more dramatically than an undried sample slid at room humidity over a displacement of ~4 m, obtaining a value of the friction coefficient of ~0.2. Then, when the sample was exposed to humid room air, the friction coefficient increased to a value of ~0.4, a value appropriate for an undried sample slid at room humidity to the same displacement.

These new puzzling results suggest that the role of water in the gel weakening mechanism may be more complicated than we have proposed previously, and warrants further investigation. These totally unexpected results do not detract from our primary obeservation that quartz rocks are weak at high slip speeds and large displacements, but simply mean that we have not yet rediscovered the combination of conditions that allowed them to be strong at high velocity in our earlier experiment. Furthermore, our textural observations of material that has clearly flowed in experiments in humid conditions [*Sayre et al.*, in preparation] strongly support the idea that silica gel is responsible for the weakening in the presence of water. We will continue to explore this intriguing problem in our proposed experiments.

Flash heating experiments. To investigate dynamic weakening due to flash heating and melting, we have conducted a suite of experiments using an Instron rotary shear loadframe. We have used this apparatus extensively to conduct large displacement sliding experiments, in which large displacements are accumulated by reversing the sliding direction [*Di Toro et al.*, 2003]. The highest velocities attainable in the apparatus in this oscillating-sliding-direction mode is ~100 mm/s. This highest attainable speed is limited by the available output of the hydraulic power supply to the rotary servo of the apparatus. By sliding in only one direction, however, higher speeds of ~360 mm/s (only a factor of three less than a seismic slip rate of 1 m/s) can be attained for a displacement up to ~40 mm. At these speeds, theoretical estimates of flash heating of quartz yield extremely high temperatures at the contacting asperities. For example, as shown below, using reasonable values for the contact size and the contact stress, theoretical predictions yield a flash temperature of ~3400 C at a sliding velocity of 360 mm/s. These temperatures are well in excess of the melting temperature for quartz, 1713 ^{o}C [*Deer et al.*, 1992].

Prior to sliding, the samples were prepared by grinding the sliding surface with a wet, diamond-impregnated wheel, then roughening the resulting surface with #60 grit alumina powder in water on a glass plate. The experiments were conducted by first sliding a distance of 1.2 mm at low speed (1 or 10 μm/s) to determine a baseline value for the friction coefficient. During the low speed portion of the test, data were sampled at a rate of 1 Hz. After sliding at low speeds, the samples were then subjected to a step change in load point velocity, up to a velocity of 30,

100, or the maximum attainable velocity, ~360 mm/s, and slid for a total displacement of ~45 mm. During this higher speed portion of the test, data were sampled at a rate of 1 kHz.

We estimated flash temperatures in our experiments using the flash temperature theory presented by [*Archard*, 1958]. The calculation assumes that circular contact junctions of average radius a slide on a flat surface and we assume that the average contact junction diameter is a typical value (10 μm) for the characteristic slip weakening distance D_c for a surface prepared in this way. It is also assumed that the asperities flow plastically (such that the contact stress is equal to the yield stress), which yields an upper bound for the flash temperature.

At low sliding velocities, there is time for the temperature distribution in the upper body (the asperity) to be established in the lower body (the flat surface). The flash temperature is then

$$\theta_m = \mu \frac{\pi a p_m}{8 K} V$$

where μ is the friction coefficient of a contact junction, a is the contact radius, p_m is the yield pressure of the material, K is thermal conductivity, and V is sliding velocity.

At higher sliding velocities, there is insufficient time for significant lateral flow of heat from the contacts, such that lateral flow can be neglected and a linear heat flow solution applies. The flash temperature is then

$$\theta_m = \mu \frac{1}{3.25} \frac{\pi \sqrt{a}\, p_m}{(K \rho\, c)^{\frac{1}{2}}} V^{\frac{1}{2}}$$

where ρ is density and c is specific heat.

The appropriateness of the low vs. high speed flash temperature solutions is determined by the value of the dimensionless Peclet number, given by $L=aV/(2X)$, where X is thermal diffusivity. The Peclet number is the ratio of the time over which heat is applied to the time required to diffuse it away. For $L < 0.1$, the low speed solution applies, whereas for $L > 10$, the high speed solution applies. At intermediate Peclet numbers between 0.1 and 10, the flash temperature is determined by interpolation between low and high speed solutions [*Archard*,

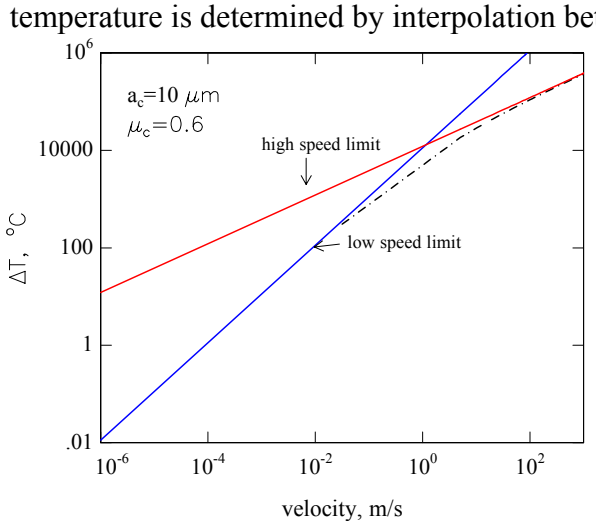

Figure 1- Low speed (in blue) and high speed (in red) solutions for the flash temperature vs. velocity from Archard (1958). Calculation assumes a contact diameter of 10 μm and a friction coefficient of the contact of 0.6. For velocities up to ~1 m/s, the low speed solution is appropriate for quartz.

1958]. The low and high speed equations from Archard's analysis are plotted in Figure 1.

Results from an experiment at a maximum sliding rate of ~360 mm/s are shown in Figure 2. After a sliding displacement of 1.2 mm at low speed (1 μm/s), the sample was then subjected to an abrupt change to a higher sliding velocity. The maximum possible sliding speed in the apparatus, ~360 mm/s, was obtained by setting a velocity for the rotary servo of the apparatus well above 360 mm/s and allowing the apparatus to rotate as fast as the output of the hydraulic power supply would allow. As shown in Figure 2, a sliding speed of ~300 mm/s results in a dramatic and nearly immediate decrease in the friction coefficient, to an average value near 0.2. As the velocity decreases toward zero near the end of the experiment, the friction increases dramatically, back to a value near 0.6.

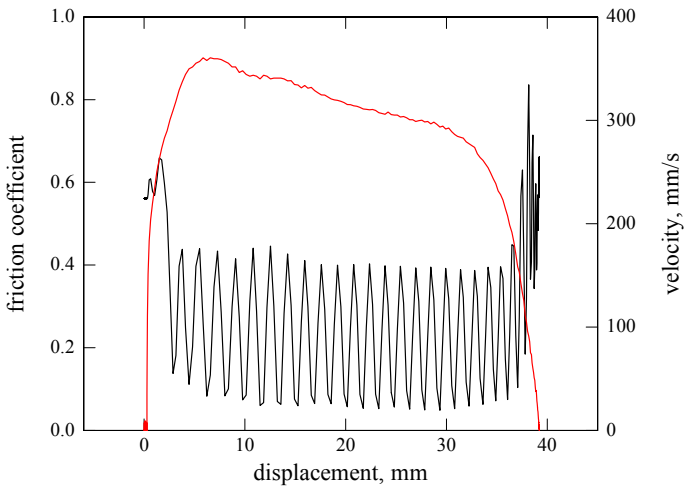

Figure 2- Plot of friction coefficient (in black) and sliding velocity (in red) vs. displacement in mm. Sliding at slow speeds (10 μm/s) yields a value of the friction coefficient of ~0.6; at higher speeds up to ~360 mm/s, the value of the friction coefficient decreases to an average value of ~0.2. As the sliding velocity decreases toward the end of the test, friction increases back to a value of ~0.6.

Results from an experiment at a lower velocity of ~100 mm/s are shown in Figure 3. Again, the sample was slid at a low velocity of 10 μm/s for 1.2 mm of displacement, then at a higher velocity of ~100 mm/s for the duration of each test. In contrast to the data in Figure 2, the data in Figure 3 show only moderate to no weakening.

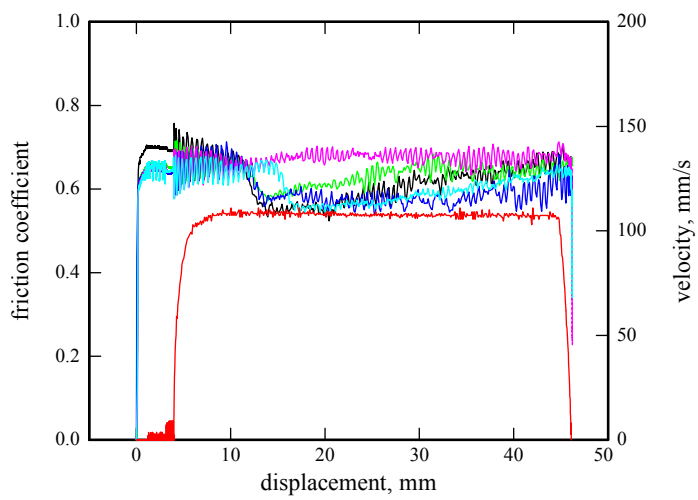

Figure 3- Plot of friction coefficient and velocity (for a representative experiment, in red) vs. sliding displacement for a novaculite sample. All of the experiments were conducted on one sample with a starting roughness (for the first test) derived from grinding the surface with loose #60 grit on a glass plate. The experiments were done in the order indicated by the following succession of colors: black, green, dark blue, magenta, and light blue. All of the data except those shown in magenta indicate a slight decrease in friction at a displacement of 12 to 14 mm, in contrast to the dramatic behavior observed at 360 mm/s in Figure 2.

The sliding displacements in all of these tests are too small for the extreme comminution of material required for the gel weakening mechanism which we have proposed for rapid sliding of quartz rocks to large displacement to be operative [*Di Toro et al.*, 2003]. An intriguing explanation for the dramatic weakening observed in Figure 2 is that it results from melting of asperities on the sliding surface due to flash heating, whereas at lower velocities flash

temperatures are insufficient to cause melting. Flash melting should exhibit almost no slip dependence, since the asperities reach their maximum temperature over displacements on the order of the contact size [*Jaegar*, 1942]. Examination of the flash temperature predictions of Figure 1 suggest a flash temperature of ~3400 ^{o}C at a sliding speed of 360 mm/s, well in excess of the quartz melting temperature, whereas a flash temperature of only ~1000 ^{o}C is predicted for a sliding speed of 100 mm/s. The flash temperature estimates are strongly dependent on the size of the contacting asperities on the sliding surface. The estimates in Figure 1 are based on an assumed contact diameter of 10 μm, consistent with those inferred from low speed friction experiments at similar sliding displacements as in the flash heating experiments.

Technical progress toward coseismic slip rates at high pressure.

In the past year we have made important progress in the two technical requirements that presently limit our ability to slide at seismic slip rates at high confining pressure, the need for a drive system with enough horsepower and speed to rotate our samples at ≥1 m/s , and the need to isolate samples from the gas confining medium with a sliding jacket assembly that can withstand the high temperatures generated at high slip speeds.

We have purchased all the required components for the high speed drive system, for which a 100 HP BMW motorcycle engine is the most important component. The other major parts include a right angle gear box, a brake/clutch assembly, a harmonic drive assembly, and four TB Wood's sprockets splined for their toothed "QT Power Chain" belts. We have disassembled the BMW motorcycle we purchased with previous USGS funding – it is shown in Figure 4. The motorcycle has a drive shaft that will be coupled to the right angle gearbox as shown in the CAD drawing of our high speed design assembly (Figure 5). The output of this 1.5:1 right angle gear box is fed into a brake/clutch assembly that is used to select one of two possible speed ranges. This allows either selection of or bypassing of a harmonic drive assembly which provides a 50:1 speed reduction. The output of the harmonic drive is connected to the first of four drive sprockets; the last of these sprockets is mounted in-line with the existing piston and thrust bearing assembly of the pressure vessel. This drive assembly, in conjunction with the gear range available in the BMW transmission and the RPM range of the engine, allows in theory an infinite range of slip speeds in the range 0.5 mm/s to 1.0 m/s. Changing the sizes of one or both of the drive sprocket pairs will allow even higher speeds, but we are building it with the design shown in Figure 5, so that our initial experiments will be restricted to 1m/s.

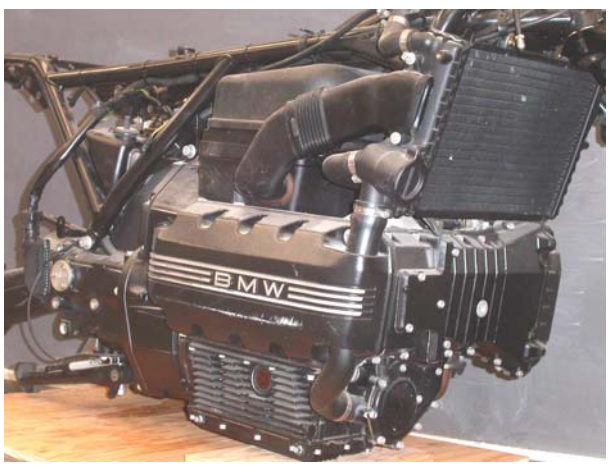

Figure 4. Photograph of 100 HP Engine and subframe removed from BMW K100RS motorcycle. Smooth running 4 cylinder engine is water cooled with drive shaft output. The engine will remain in the original frame, with electrical, fuel and cooling systems intact, and the frame will be adapted to mount on the high pressure rotary shear apparatus.

Another critical technical hurdle is to design and implement a new high-speed sample jacket-assembly that will withstand the high temperatures generated by sliding at high speeds. The sliding jackets must be flexible enough to effectively transmit the gas confining pressure to

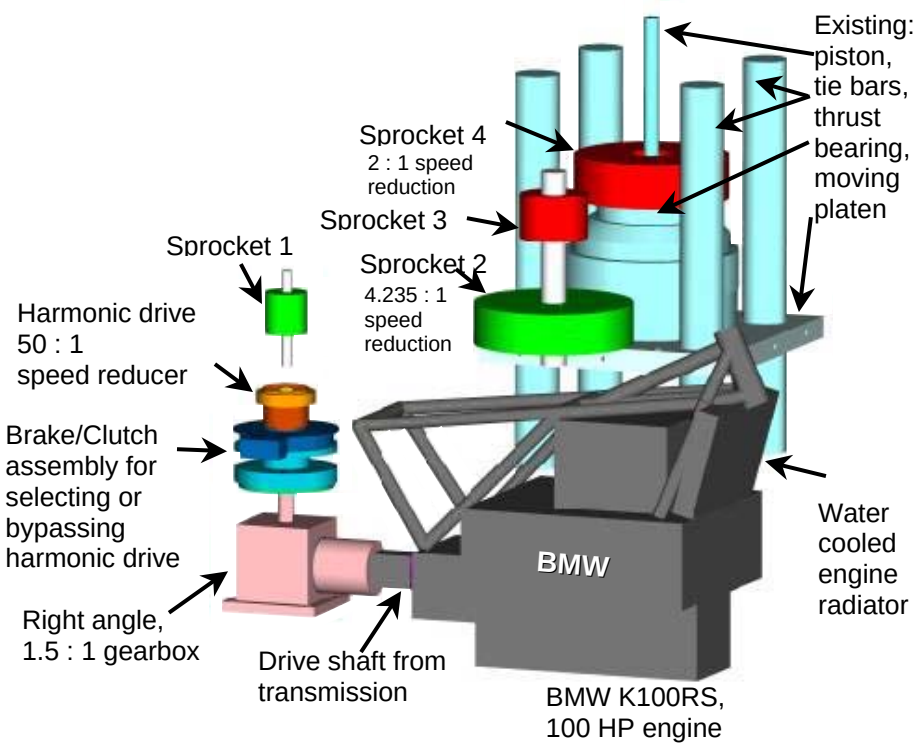

Figure 5. Computer aided design (CAD) image of the high speed drive system Shaft bearings, harmonic drive couplings, and supporting framework are not shown to allow easier viewing of principal elements. Depending on the motorcycle gear selected and the engine RPM, slip speeds at the sample range from 1 to 20 mm/s using the harmonic drive speed reducer and from 50 to 1000 mm/s when the harmonic drive is bypassed. Higher speeds can be achieved by changing sprockets.

the sample, have low enough friction that jacket-on-jacket sliding contributes insignificantly to the measured friction, while being refractory enough to withstand high temperatures. During the past year, we attempted to use a new material, graphite, instead of the usual Teflon, in our sliding jacket assembly. Graphite has the great advantage that it is extremely refractory. We retained our tried and true sliding jacket geometry, but replaced the usual Teflon rings with graphite rings machined from a large block of graphite. The results of preliminary tests using graphite as a sliding jacket material were mixed – the graphite-on-graphite friction coefficient appears to be quite low, but the rings are relatively strong and may not be good transmitters of gas pressure to the rock samples. Furthermore, in our trial tests, the O-rings leaked gas pressure to the samples; this leak was caused by grabbing or tearing of the O-ring where the rubber O-rings contacted the relatively sharp edges of the oppositely rotating sliding graphite jackets. On Mervyn Paterson's recommendation, we are now investigating the possibility that a thermoplastic material may be suitable as a replacement sliding jacket material. One advantage we have in choosing a material is that the jacket only needs to survive for approximately one to a few seconds to be acceptable. In order to prevent destruction of the O-ring component of the sample assembly and of the O-rings that serve as piston seals due to frictional heating, we will use lubricated, temperature resistant Kalrez O-rings. We have already purchased one pair of these very expensive O-rings.

Geophysical implications

The gel-induced weakening we observe in quartz rocks is dramatic and extrapolates to zero strength at just over 1 m/s, as shown in Figure 1. This suggests that coseismic stress drops should be total if this mechanism is operative on a fault in the Earth. 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-like layers during prolonged sliding. We have previously reported similar weakening of a pure feldspar rock and to a lesser extent granite at rapid slip rates. 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 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 [*Killick*, 1994] perhaps because friction on such faults is too low (as a result of the silica gel weakening mechanism) to cause melting.

Many rocks will likely not weaken via this gel mechanism, but may weaken at high slip velocities due to shear melting. Melting can occur at either the asperity scale, i.e., flash melting, or over the entire fault surface. In contrast to the gel mechanism, which may only occur in certain rock types, or along fault zones mineralized with quartz, flash melting is expected to occur for rocks of varying mineralogies. Both flash and bulk melting may result in dramatic decreases in the friction coefficient. 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 continuing to investigate the mechanical behavior of rocks at high slip velocities over a range of 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 wholesale frictional melting. Two weakening mechanisms have been investigated, one involving the production of a weak layer of silica gel on the sliding surface, and another involving local melting at asperity contacts. Whether these weakening mechanisms are 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 close to complete. 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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LABORATORY EXPERIMENTS ON ROCK FRICTION FOCUSED ON UNDERSTANDING EARTHQUAKE MECHANICS

Terry E. Tullis and David L. Goldsby

Brown University, Department of Geological Sciences, Providence RI 02912-1846

Tele: (401) 863-3829, FAX: (401) 863-2058, Email: Terry_Tullis@brown.edu
Web Site. http://www.geo.brown.edu/faculty/ttullis/index.html

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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. We have discovered that two mechanisms can be responsible for this weakening:1) production of a weak layer of silica gel, a mixture of silica and water, and 2) melting at small contacts on the sliding surface. If weakening also occurs by these processes during earthquakes, faults could be so weak that the size of damaging ground motions might be larger than usually expected.