FINAL TECHNICAL REPORT FOR GRANT NUMBER: 04-HQGR0090

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 significant progress beyond last year's results to better understand the gel weakening phenomenon we discovered, to characterize the gel on the sliding surface, and to better understand and characterize the rock types for which gel weakening can occur.

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 04-HQGR0090. The grant covers a one-year period, from March 1, 2004 to February 28, 2005. 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.

PUBLICATIONS RESULTING FROM THIS GRANT

Roig Silva, C., D.L. Goldsby, G. Di Toro, and T.E. Tullis, The role of silica content in dynamic fault weakening due to gel lubrication, in *2004 SCEC Annual Meeting Proceedings and Abstracts*, pp. 150, Southern California Earthquake Center, Palm Springs, California, 2004a.

Roig Silva, C., D.L. Goldsby, G.D. Toro, and T.E. Tullis, The role of silica content in dynamic fault weakening due to gel lubrication, *Eos. Trans. Am. Geophys. Union, Fall Meeting Suppl.*, *85* (47), T21D-07, 2004b.

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. During the past year we have shown how the amount of gel weakening depends on the SiO_2 content of the rock, independent of the presence of quartz. We have also shown some interesting interplay between water, temperature, and the degree of weakening. 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 also extended our experiments on flash heating/melting. Our results on flash melting and their agreement with theory suggest that *all silicate rocks slide with low friction 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.

Recent results and insights from high-speed friction experiments

Introduction. Our research efforts of the past year have focused on further understanding the frictional behavior of crustal rocks at near-seismic slip rates. A major thrust of that effort has been to further understand the silica gel weakening mechanism we discovered in experiments on quartz rocks, which we now believe may be important for other rocks of sufficiently high silica content. In last year's report, we presented the results of a series of high-speed friction experiments on (in order of increasing silica content) calcite, Tanco feldspar, granite, aplite and novaculite. In those tests, we observed a dramatic decrease in friction with increasing velocity at lower slip rates, and an increasing trend of friction with velocity at higher slip rates. The degree of weakening at a given velocity appeared to be a function of the silica content of the samples. We postulated that 1) the increase in friction with velocity may have been caused by frictional heating, which effectively drove off the water from the sliding surface, and 2) silica content may be fundamental to gel formation and frictional weakening. To test these ideas, we have conducted new high-speed friction tests on gabbro, Tanco feldspar, and granite. These experiments complement, and the results contrast with those from, the tests described above and in last year's proposal. The new results further underscore the important role played by water in gel weakening, and also strongly suggest the critical role of silica content. Our results suggest that dynamic weakening due to gel formation may be an important process for not only quartz rocks, but for a variety of important crustal rocks. In addition to these silica gel experiments, we have also continued to investigate flash heating/melting as a dynamic fault weakening mechanism.

High-speed friction experiments on crustal rocks of varying silica content. Last year we reported the results of a suite of experiments on several crustal rocks of varying quartz and silica contents. These previous tests were conducted in a manner similar to that described in [*Di Toro et al.*, 2004]. The Instron torsion apparatus used for these experiments can only rotate the sample through an angle of ~90^{o}, or a sliding displacement of ~40 mm. Large cumulative displacements are obtained by repeatedly reversing the sliding direction.

The results of these previous experiments are shown in the plot of 'steady state' friction coefficient vs. log velocity in Fig. 1. The plot shows data for novaculite, aplite, granite, Tanco feldspar, and calcite. As shown in Fig. 1, tests on all of the rocks except calcite reveal decreasing trends of friction with increasing slip velocity below ~10 mm/s. The degree of weakening depends not on the amount of quartz present, but rather on silica content (since Tanco feldspar contains no quartz and would not weaken if the weakening mechanism depended on the amount of quartz present). Interestingly, data for aplite, granite and Tanco feldspar reveal *increasing* friction for *V* > ~10 mm/s. A similar increase in friction may occur for novaculite ('quartz' in the figure) at *V* >100 mm/s, in contrast to the extrapolation to essentially zero strength at ~1 m/s as we proposed in [*Di Toro et al.*, 2004].

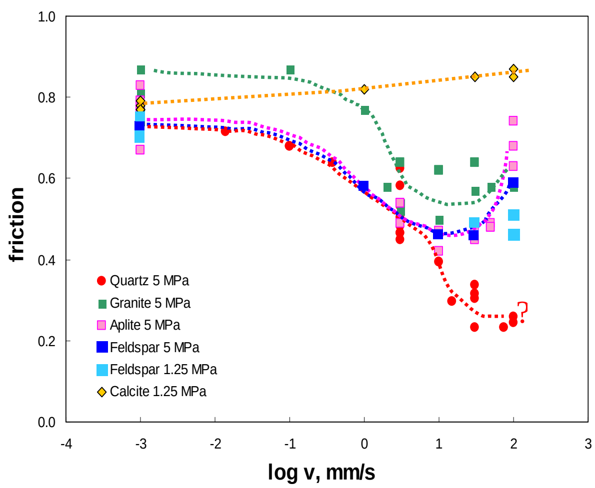

Fig. 1- Plot of 'steady state' friction coefficient vs. log velocity for tests on the rocks listed in Table 1. Note the increase in friction at the highest velocities for Tanco feldspar and aplite. Lines are not curve fits, but are provided merely to show the general trends.

An intriguing explanation for the transition from decreasing to increasing friction with increasing velocity is that friction increases when the temperature of the sliding surface is high enough (>100 ^{o}C?) to drive off water. Previous temperature measurements and finite element modeling calculations indicate ~100 ^{o}C or higher at *V* > 10 mm/s for comparable values of friction coefficient and displacement [*Di Toro et al.*, 2004; *Goldsby and Tullis*, 2002]. This hypothesis is also supported by the shift of this transition (minima in the curves in Fig. 1) toward higher sliding velocities with decreasing values of the friction coefficient, since heat input on the sliding surface is proportional to the friction coefficient.

If true, this hypothesis would have important implications for dynamic fault weakening in the Earth. Since faults at depth are typically saturated with pressurized water, elevated temperature from frictional heating will not be able to dry out the rocks, in contrast to our experimental configuration. Thus, the trend of decreasing friction with velocity observed at velocities less than the transition velocity in our experiments might continue to seismic slip rates in the Earth [*Di Toro et al.*, 2004]. This hypothesis is supported by new data (see below) from tests at humid conditions, which show a continuously decreasing trend of friction with velocity.

To test these hypotheses, we have conducted new experiments on a variety of important crustal rocks, as previously, but under more humid conditions. The experiments were conducted at Brown with Carla Roig Silva, an undergraduate from the University of Puerto Rico, who interned in the Leadership Alliance Program for minority students. The results of these experiments were reported at the 2004 SCEC Annual Meeting and at 2004 Fall AGU [*Roig Silva et al.*, 2004a; *Roig Silva et al.*, 2004b]. Tests were conducted in the same Instron compression/torsion apparatus described above, on all of the rocks shown in Fig. 1 except calcite and aplite. To further test our hypothesis concerning the importance of silica content in gel weakening, we also conducted experiments on a fine-grained gabbro, procured from Toshi Shimamoto of Kyoto University in Japan (the same rock used in high-speed friction experiments in Shimamoto's laboratory, e.g., [*Tsutsumi and Shimamoto*, 1997]. This gabbro contains ~50 wt.% silica.

The results of these new experiments are shown in Fig. 2. The friction coefficient is observed to decrease systematically with increasing velocity over the entire velocity range for the quartz and Tanco feldspar samples. Friction for the granite samples decreases with velocity above ~1 mm/s. This is in stark contrast to the data in Fig. 1, which show an *increase* in friction with velocity for V >10 mm/s for granite, Tanco feldspar and aplite. One difference between the experiments which yielded the data in Fig. 1 and those yielding the data in Fig. 2 is the ambient humidity, a factor that we had not intentionally varied. Tests for Fig. 1 were conducted in relatively dry, wintertime Providence air, whereas tests for Fig. 2 were conducted in very humid, summertime Providence air. Thus, the difference in the dependence of the 'steady state' friction coefficient on velocity in the two data sets at V >10 mm/s may reflect differences in humidity.

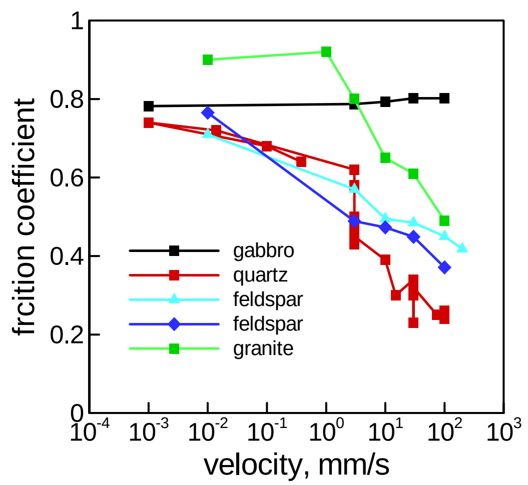

Fig. 2 - Plot of 'steady state' friction coefficient vs. velocity on a log scale for high-speed friction tests on rocks of varying silica content, conducted in humid summer air. Data in red for novaculite are from [*Di Toro et al.*, 2004]. Note that the friction coefficient decreases with increasing velocity over the entire velocity range (except for gabbro and granite in the range 10^{-2} to 1 mm/s). Normal stress 5 MPa.

Role of silica content. As for the data in Fig. 1, the friction coefficient at a given velocity increases with decreasing silica content above ~50 wt.%. This trend is illustrated in Fig. 3, a plot of 'steady state' friction coefficient at 100 mm/s (all data are taken from Fig. 2 except the calcite data which is taken from Fig. 1) plotted against silica content in wt.%. As shown in Fig. 3, above ~50 wt.% silica, a strong dependence of friction coefficient on velocity is observed. These data demonstrate the fundamental role of silica content in gel formation.

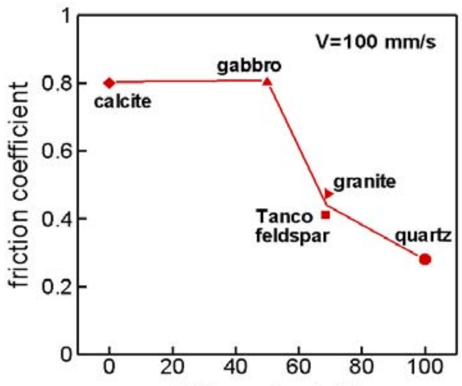

Fig. 3- Dependence of 'steady state' friction coefficient at *V*=100 mm/s on the silica content of the rocks, in wt.%. No weakening is observed for gabbro and calcite rocks, as shown above in Figs. 1 and 2.

Tests on granite under dry conditions. We have performed a series of high-speed, long displacement sliding experiments on Westerly granite under 'dry' conditions to explore further the role played by water in gel formation. The experiment was conducted on an undried, 'as-is' sample encased in a dry nitrogen chamber. The experiment was conducted by first sliding at a low velocity of 10 µm/s for several millimeters of slip, followed by slip at a higher, constant velocity in the range 1 to 100 mm/s, over an additional 4 m of slip.

The results are shown in Fig. 4. The experiments were done in sequence from lowest to highest velocity in the order given in the legend. As shown in Fig. 4, the initial tests at 1 and 3 mm/s yield the lowest friction, 0.2 to 0.3. For the series of velocities 10-30-30-100 mm/s, a progressive increase in steady state friction was observed. At the highest slip rate, friction is ~0.7. The strong trend of *increasing* friction with increasing velocity is in stark contrast to the behavior described above (see Fig. 2) for rocks slid in humid environments. We believe these results on granite reflect the profound effect of water on the gel weakening mechanism. The behavior seen in Fig. 4 suggests that the sample is effectively 'drying out' over the course of the experiments, due to the high temperatures (>100 ^{o}C) generated by high-speed sliding and the dry nitrogen environment, which effectively whisks away water driven off the sample by heating and prevents rewetting of the sample.

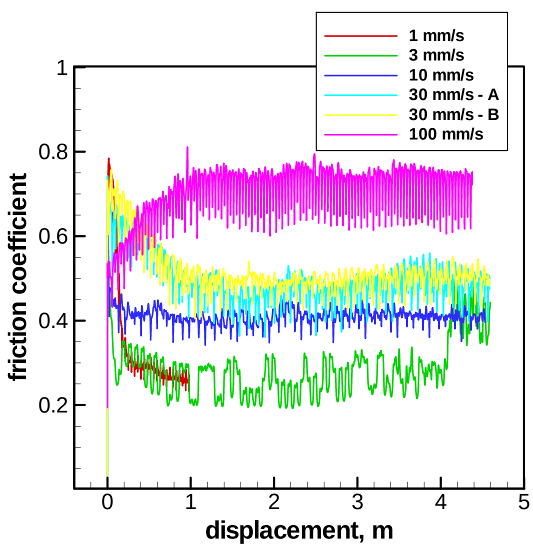

Fig. 4 – Plot of 'steady state' friction coefficient vs. sliding displacement in meters for an undried granite sample slid in a dry nitrogen environment. Experiments were conducted in the sequence of velocities shown in the legend. The jagged character of the curves results from the reversals in sliding direction [*Di Toro et al.*, 2004]

Characterization of the water content of the silica gel layer. We previously attempted to use three materials characterization techniques to determine the hydrogen or water content of the gel layer on the sliding surfaces of our samples: FTIR spectroscopy, X-Ray Photoelectron Spectroscopy, and electron microprobe microscopy. None of these attempts were successful at determining water content, as we detailed in last year's report.

However, within the past year, we have been very successful in measuring the hydrogen content of the gel layer from our friction experiments using Forward Recoil Spectroscopy

(FRES) at the Rutherford Backscatter Spectroscopy (RBS) facility at the University of Minnesota in Minneapolis. During an RBS analysis, a sample is bombarded with helium ions, which collide with atoms on or near the surface of the sample. Elements heavier than helium cause the incoming helium ions to be backscattered; their detection forms the basis for RBS. Being lighter than helium, hydrogen ions are instead scattered in the forward direction. These forward scattered hydrogen ions can be counted with a detector (screened to block out forward scattered He ions) placed in the forward direction from the ion beam. This latter technique is termed FRES, and is a commonly used method for hydrogen detection in thin films. The gel layer in our novaculite samples is essentially a thin film (3 - 5 μm thick) on a novaculite substrate.

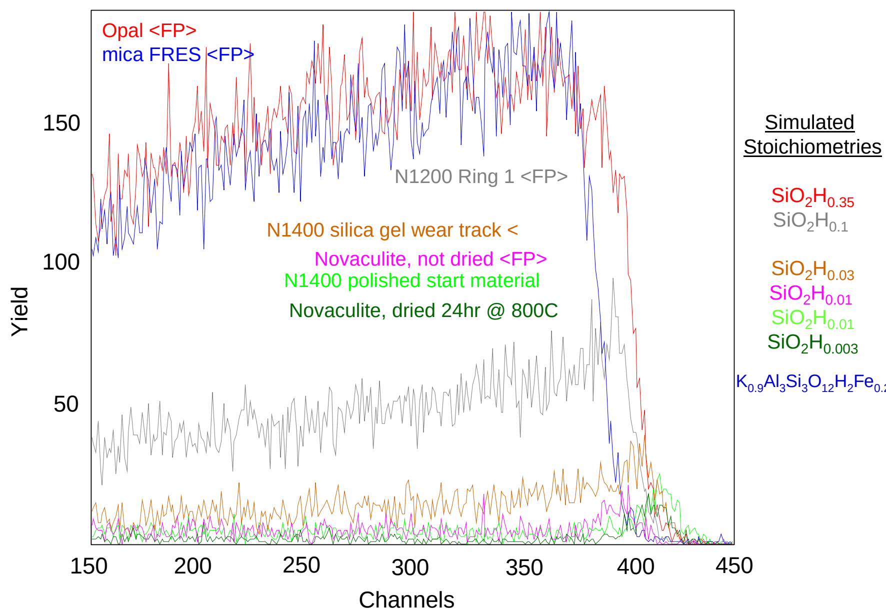

Fig. 5 – H yield vs. channel from FRES analyses. Mica (data in blue) and opal (data in red) are reference samples. Data for 'N1200 Ring 1' (in gray) are from sliding surface of a sample dried at 800 °C for 24 h, then exposed to room humidity during sliding. Data for 'N1400 silica gel wear track' (brown) are from sliding surface of an undried novaculite sample slid at room humidity. Data for 'Novaculite, not dried' (violet) and 'N1400 start material' (light green) are for polished samples of undried novaculite with no sliding. Data for 'Novaculite, dried 24 hr@800C' (dark green) are for a sample polished, then dried overnight in an oven at 800 °C .

Figure 5 contains results of a series of FRES analyses on a number of our samples. The data are of hydrogen yield plotted against 'channel'; the abscissa is a measure of the kinetic energy of recoiling H, on the order of hundreds of keV. In the raw data, each data acquisition channel is approximately 1 keV in width, and all particles having energy within a given channel window are counted as if at one energy). Each curve can be modeled using the stoichiometry for hydrogen content shown in the corresponding color on the legend to the right of the figure. The results of the FRES analyses indicate that the silica gel layer that forms on the sliding surface in tests conducted in humid air has high water content, 30,000 to 100,000 H per 10^6 Si, significantly higher than both dried and undried novaculite samples with no sliding. This demonstrates that water in the gel layer on the sliding surface is provided primarily by water vapor in the atmosphere, and is not derived from within the specimens.

Flash heating/melting experiments. Within the past year, we have completed 6 new flash heating experiments investigating the phenomenon of flash heating/melting during rapid sliding of a variety of crustal rocks. Flash melting occurs at highly stressed contacting asperities, due to the extremely high but short-lived input of heat into the contact. The experiments are conducted at ambient pressure at high slip speeds (typically up to 0.36 m/s) and small displacements of ~40 mm. The relatively small displacements obtained in these tests insure that insufficient heat is generated to melt the entire or even significant areas of the fault surface, effectively isolating heating/melting phenomena at asperities from bulk melting effects. One of the experiments on gabbro took advantage of improvements we made to the Instron apparatus which increased the maximum rate of rotation of the rotary actuator, increasing the maximum sliding rate by a factor of 2, up to ~0.7 m/s (Fig. 6). At these speeds, theory suggests flash temperatures well in excess of the melting temperature for quartz, feldspar, and pyroxene [*Rice*, 1999]. The new experiments served to replicate earlier flash heating results (with which they are in excellent agreement) and show that gabbro weaken due to flash heating (Fig. 6), even though it does not undergo gel weakening (Figs. 2 and 3).

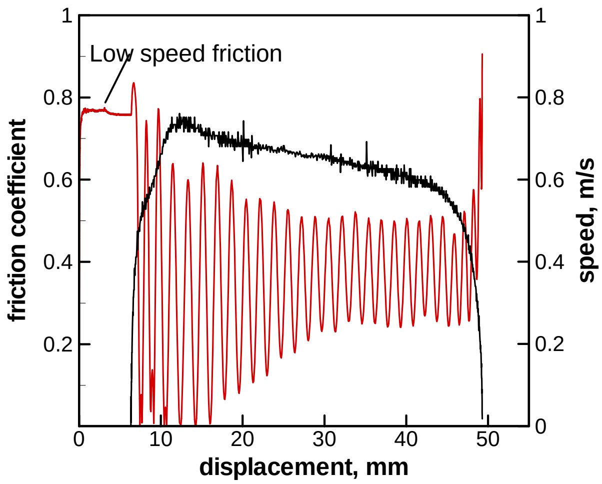

Fig. 6- Plot of friction coefficient (in red) and sliding velocity (in black) vs. displacement from an experiment on gabbro. Sliding at slow speeds (10 μm/s) yields a value of the friction coefficient of ~0.8; at the highest speeds, the value of the friction coefficient decreases to ~0.35. As the sliding velocity decreases toward the end of the test, friction increases back to a value of ~0.8.

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. The water content of this is in the range of 30,000 to 100,000 H per 10^6 Si. The silica gel behaves in a thixotropic manner. The interactions of the roles of sliding velocity, which increases the frictional heating, and of humidity, further demonstrate the important role played by water in the weakening of the gel. Further experiments investigating flash weakening on gabbro are consistent with our earlier results and demonstrate that this is a separate weakening mechanism from gel weakening that is not observed for gabbro. Whether either of these proposed high-speed 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 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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Key Words: Laboratory studies, Source characteristics, Fault dynamics, Strong ground motion

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 continued 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.