Investigation of Weakening Mechanisms in High-speed Experimental and Natural Slip-surfaces

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Frictional behavior of SAFOD fault-rocks sheared at seismic slip rates

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Abstract

Fault-rocks collected from the scientific borehole at the San Andreas Fault Observatory at Depth (SAFOD) were sheared at 1.3 m/s sliding velocity and normal stresses of 0.3, 0.6, and 1.3 MPa in order to determine the magnitude of dynamic weakening and the influence of fault-rock type on frictional behavior. The samples investigated were taken from a prominent shear zone at 3067 m measured depth (MD) in the lower spot core recovered during Phase 1 drilling. The samples show a progressive and dramatic reduction in the coefficient of sliding friction when subjected to a few meters of shear displacement, dropping from a coefficient of friction of 0.5 to 0.6 at the initiation of slip to a coefficient of friction of 0.1 to 0.05. The transient weakening behavior varies with fault-rock lithology, and the slip necessary for weakening decreases systematically with an increase in normal stress. These observations are consistent with thermally activated weakening induced by frictional heating in the shearing layers. Permanent weakening also is demonstrated and is likely a result of microstructural changes including the evolution to extremely localized slip and progressive alignment of phyllosilicates. The observed dynamic weakening could explain the apparent low strength and normal heat flow along the seismic slipping sections of the San Andreas fault; however, additional work is needed to identify the exact microscopic mechanisms of weakening and whether these same mechanisms induce dynamic weakening during earthquakes in natural fault systems.

Introduction

Documenting the quasi-static and dynamic friction behavior of faults is crucial to understanding the apparent low-strength of plate-boundary faults (e.g., Zoback et al., 1987) as well as understanding the characteristics of earthquake rupture nucleation, propagation and arrest (e.g., Kanamori & Heaton, 2000; Rice and Cocco, 2007). Samples collected from Phase 1 and 2 drilling of the scientific borehole at the San Andreas Fault Observatory at Depth (SAFOD) provide a unique opportunity to study the frictional behavior of fault rocks from an active, major plate bounding fault zone at a seismogenic depth of approximately 3 km. To date, quasi-static laboratory friction experiments have been conducted on cleaned cuttings collected during drilling, and on samples taken from the spot cores located adjacent to the fault zone (Tembe et al., 2006). These experiments provide evidence that the quasi-static coefficients of friction for rock materials from the San Andreas fault at SAFOD are somewhat lower than average friction values for rock, but are not low enough to explain the stress-heat flow paradox (Lachenbruch and Sass, 1980; Zoback et al., 1987; Hickman and Zoback, 2004; Tembe et al., 2007). Some of the lowest coefficients of friction (e.g., 0.4) documented by Tembe et al. (2007) were obtained for fault rocks, one collected in cuttings in the depth range of 2560 m MD, and the other collected from a prominent shear zone cutting the spot core at 3067 m MD.

The purpose of this paper is to document the coseismic frictional behavior of a full suite of fault-rocks collected from within and on the border of the 3067 m MD shear zone, report the conditions over which dynamic weakening occurs, and compare these results to the frictional behavior at the intermediate slip rates, typical of standard biaxial and triaxial laboratory friction investigations, and documented for SAFOD materials by Tembe (et al. (2007).

Description of Samples

The second spot core taken during Phase 1 drilling at SAFOD penetrated a sedimentary rock sequence composed of pebble conglomerates and coarse to very fine-grained, well-cemented arkosic sandstones in the upper portion of the core. The pebble conglomerate contains lithic fragments of granite, sandstone, siltstone, and volcanic clasts. The beds are massive, well-cemented, and contain rare cobble-sized clasts. The lower portion of this spot core consists of a fine-grained, well-cemented arkosic sandstone that grades down-hole into a fine- to very fine-grained siltstone. The core is cut by numerous small fractures and cataclastic zones, and also by two larger faults that juxtapose different lithologies. The first fault is located at 3062 m MD, and juxtaposes coarse-gained and very-fine-grained sandstones. The second fault, that was brought up in the core catcher at the base of the spot core, juxtaposes a very fine-grained cataclastic siltstone (above) and another section of coarse-grained cataclastic sandstone (below). The rock near this lower fault is heavily fractured and displays two distinct, parallel gouge layers separated by a 4-cm-thick slice of fractured siltstone. The upper gouge layer within the fractured siltstone is an irregular, cm-thick, red-brown gouge layer, and the lower gouge layer at the contact between the cataclastic siltstone and sandstone is a several-mm thick, approximately planar layer of dark-brown gouge. Four distinct fault-rocks from the 3067 m MD fault were sheared at 1.3 m/s in this study: samples of the dark-brown gouge, the red-brown gouge, the cataclastic sandstone, and the cataclastic siltstone.

Method

For the high-speed friction experiments all samples were disaggregated to less than 106 μm grain size with a mortar and pestle. Each experiment used 1 g of disaggregated sample wetted with 0.3g of distilled water to form a 1.3 mm thick layer between the faces of two, 24.5-mm diameter cylinders of gabbro or granite. The rock faces bounding the sample layer were ground with #80 SiC abrasive grit to produce uniformly rough surfaces in an attempt to promote slip inside the disaggregated sample rather than along the boundaries. A Teflon sleeve, pressed around the cylindrical specimen and that spanned the sample layer, was used to confine the layer and prevent the loss of the disaggregated material during the experiment.

Experiments were conducted in a high-speed rotary-shear testing apparatus at Kyoto University using procedures similar to those described by Mizoguchi et al. (2006). In this apparatus, one cylinder is fixed in a rotary holder and the other is held in a stationary holder. Layers were subjected to normal stresses of 0.2, 0.65, or 1.3 MPa, and sheared by driving the rotary holder at 1500 rotations per minute, which corresponds to an equivalent velocity of 1.3 m/s. The equivalent velocity is derived from the observed rate of work done assuming that the shear stress is constant at every point on the surface (see Shimamoto and Tsutsumi, 1994; Hirose and Shimamoto, 2005). All experiments were conducted at room temperature and humidity. Sample layers were conditioned just prior to the experiments by turning the rotary holder by hand under very light normal loads to ensure that the disaggregated material was uniformly distributed over the cylindrical faces and that the assembly was aligned.

During the experiments, normal force, torque, axial shortening, and rotation speed were recorded at 200 Hz. For preliminary analysis, we assume that stress on the layer is homogeneous for calculations of normal and shear stress on the sheared layer. Normal stress is calculated directly from the normal force and area of the layer. Shear stress is determined from the torque measurements and area of the layer, taking into account that the total torque must be decreased by the amount of torque supported by the Teflon sleeve. Estimates of the strength of the Teflon sleeve were based on experiments designed to directly measure the strength of the Teflon during high-speed shear, as well as from torque measurements made during experiments on SAFOD samples sheared at different normal loads. For the latter experiments, we assume that the torque increases with normal load due to the frictional strength of the sheared layer, and that the torque at zero normal load results entirely from the Teflon sleeve. Experiment data are consistent with the assumption that the total torque carried by a sample increases linearly with normal load. We find that the extrapolation of best-fit lines to the total torque versus normal load data predicts a torque at zero normal load that is consistent with the direct measure of the strength of the Teflon sleeve and with the Teflon friction. We use this torque, which is equivalent to a 0.1 MPa shear stress on the sheared layer, to correct for sleeve strength in all data shown in this paper.

Results

The general response of all SAFOD fault-rocks sheared at coseismic slip-rates is similar (Figures 1 and 2). The coefficient of friction at initiation of slip is fairly typical of rock friction, on the order of 0.5 to 0.6. Whereas the coefficient of friction at large displacement, at the end of the experiments, is significantly lower, about 0.1 to 0.05 (Figures 2 and 3). Therefore, unlike the typical friction behavior recorded in experiments run at intermediate sliding rates (Tembe et al., 2006), at the high (coseismic) slip rate of 1.3 m/s, samples show a progressive and dramatic reduction in the coefficient of sliding friction over a shear displacement of the order of meters. Although some samples show a couple of large magnitude fluctuations in frictional strength superposed on the progressive weakening, particularly at displacements less than a few meters, the overall response is an approximate exponential decay in the friction coefficient with slip.

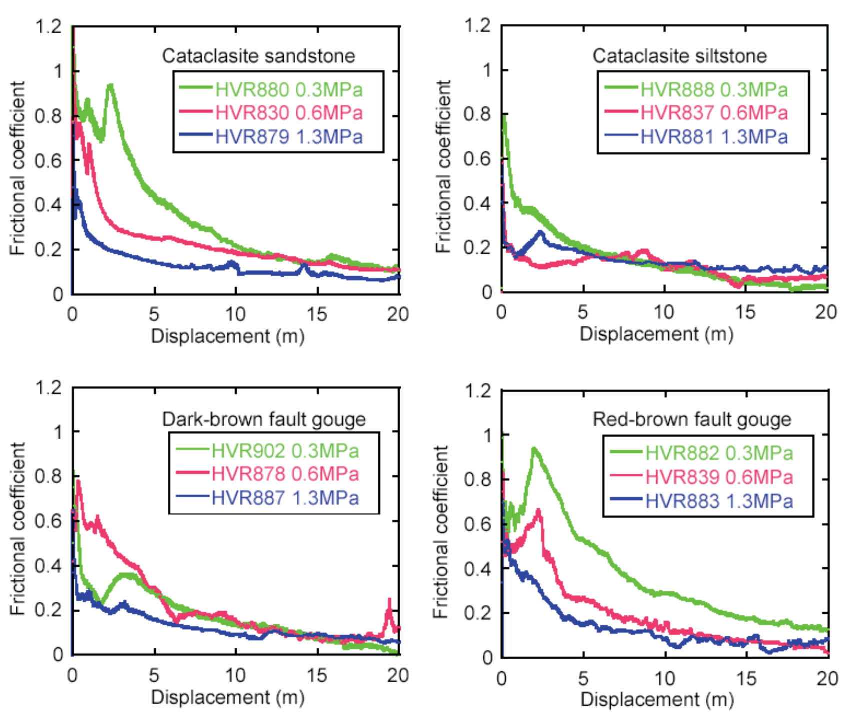

Figure 1. Frictional coefficient of the four SAFOD fault-rock samples as a function of displacement at a slip rate of 1.3 m/s. Samples from the 3067 m MD fault consist of (a) cataclastic sandstone, (b) cataclastic siltstone, (c) dark-brown fault gouge, (d) red-brown fault gouge. Each color line shows data at the different normal stress. Frictional coefficient and the magnitude of slip for weakening decrease with increase in normal stress.

The greatest variability in behavior between samples is seen in the transient weakening response, particularly in the amount of slip necessary for weakening to occur. Of the four different fault-rocks tested, the cataclastic siltstone and dark-brown gouge weaken most rapidly (Figures 1 and 2). The transient behavior changes with normal stress for all fault-rock types. In addition, the slip necessary for weakening decreases systematically with an increase in normal stress (Figure 1).

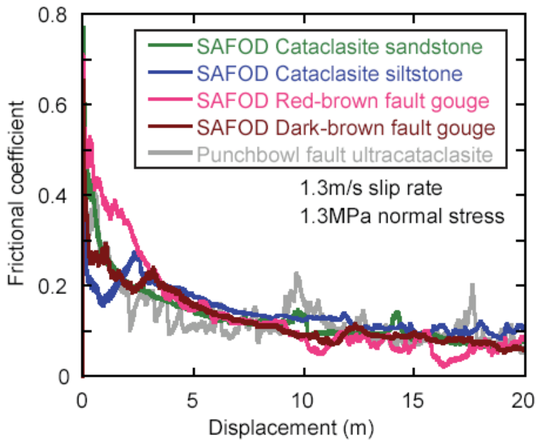

Figure 2. Summary of friction strength at slip rate of 1.3m/s and normal stress of 1.3 MPa. All SAFOD samples and Punchbowl fault ultracataclasite show large weakening after the initial peak strength, although the transient weakening behavior up to a few meters displacement depends on sample type.

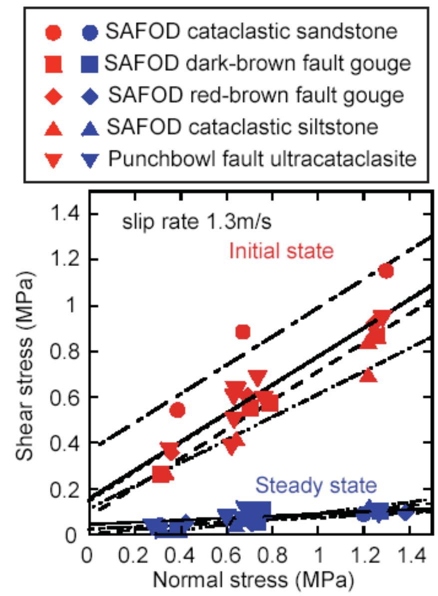

Figure 3. Normal stress vs shear stress both at initial state and steady state. The slopes of the best fit lines are 0.5-0.6 at initial state and 0.05-0.1 at steady state.

Discussion

The frictional behavior of the SAFOD samples sheared at the high slip rates of 1.3 m/s, particularly the observation of dramatic weakening after meters of slip, is consistent with the behavior previously documented for the Punchbowl fault ultracataclasite (Chester et al., 2005, 2006; Kitajima et al., 2005, 2006) and of other polymineralic granular materials (e.g., Mizoguchi et al., 2006). The observations that 1) all polymineralic granular materials appear to show similar weakening behavior, 2) the slip necessary for weakening decreases with normal stress, 3) dramatic weakening is observed only for sliding at very high slip-rates, and 4) the slip magnitude necessary for weakening decreases with an increase in slip-rate (Chester et al., 2005, 2006; Kitajima et al., 2005, 2006), suggest that the weakening is thermally activated, likely resulting from a temperature increase induced by frictional heating in the shearing layers. Additional observations of rapid strength recovery after cessation of slip and a dependence of strength recovery on availability of water has lead Mizoguchi et al. (2006) to conclude that the dramatic weakening reflects the removal of water caused by frictional heating. Our observations that some permanent weakening is observed in high speed slide-hold-slide tests (Chester et al., 2005; Kitajima et al., 2006), and that different fault-rock lithologies show different degrees of weakening and distinct transient behaviors suggest that the dynamic weakening also depends on the microstructural evolution and composition of the shearing layers. Our preliminary microstructural study of the Punchbowl ultracataclasite sheared at high slip-rates suggests that the extreme localization of slip that occurs within the shearing layers and the development of preferred phyllosilicate fabrics along slip surfaces correlate with the occurrence of dramatic slip-weakening. Ongoing microstructure characterizations and modeling efforts are aimed at resolving the relative role of microstructural and thermal changes on the dynamic weakening observed at high slip rates.

The coefficient of friction measured at the initiation of high-speed slip in the SAFOD samples compares well with the quasi-static friction coefficients determined by Tembe et al. (2007) for similar SAFOD samples. Nevertheless, the initial and quasi-static coefficients of friction of 0.4-0.55, that were measured for the siltstones and shear zone materials, are not low enough to explain observations that suggest that the San Andreas fault is weak in an absolute sense. Although we do not as yet understand the physics of the high-speed frictional weakening that we observe for SAFOD fault-rocks during shear at coseismic slip rates in the laboratory, the dramatic weakening could explain the low strength and normal heat flow along segments of the San Andreas that rupture in large magnitude earthquakes. If the dynamic weakening observed in the experiments is related to frictional heating, and similar microscopic processes operate during earthquakes, these data suggest that dynamic weakening could occur at much smaller slip magnitudes under higher normal stresses, and qualitatively would be similar to the critical slip distances for weakening inferred from seismic data.

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