Characterization of Microstructures Relevant to Earthquake Mechanics in Natural and Experimental Slip Surfaces

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As part of our prior SCEC-funded research, we have documented the detailed microstructure and mineralogy of a natural slip surface within the ultracataclasite of the Punchbowl fault zone, southern California, to understand the processes of weakening and strength of earthquake faults (Chester et al., 2003). In addition, we have used particle size distributions and thicknesses of the structural domains comprising the Punchbowl fault zone, and previous mesoscopic and microscopic fracture density data across the fault zone, to calculate the total fracture surface energy recorded in the fault zone and have compared this calculation with the fracture energy of earthquake rupture (Chester et al., 2004, 2005a). This latter SCEC-funded research formed the basis of a NSF proposal to investigate pulverization and fracture surface energy along the San Andreas fault (awarded July, 2005).

For our FY2005 SCEC project we initiated a new collaboration with Toshihiko Shimamoto, of Kyoto University, to conduct high-speed friction experiments on natural Punchbowl fault ultracataclasite. This new work was motivated by microstructural observations of recent high-speed friction experiments on the Nojima fault gouge (Mizoguchi & Shimamoto, 2004; Shimamoto, 2004; Mizoguchi et al., 2004) that revealed remarkable similarities to the optical-scale microstructures documented along the natural slip surface of the Punchbowl fault ultracataclasite (Fig. 1).

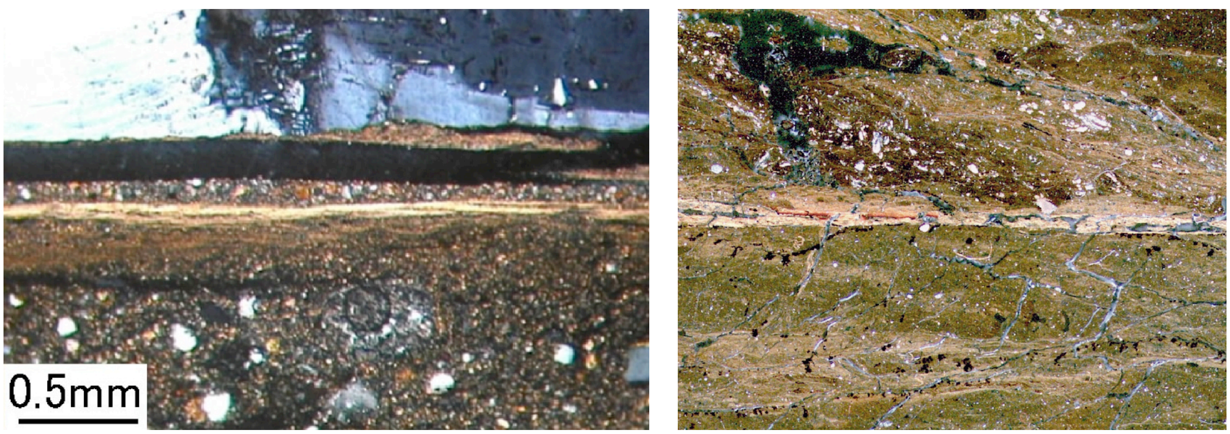

Figure 1. Photomicrographs of experimental and natural principal slip surfaces under crossed polarized light in optical microscope. Left) Phyllosilicate rich Nojima fault gouge after shear in Shimamoto's high-speed friction apparatus at Kyoto University (fig. 3d, Mizoguchi et al., 2004). Slip surface is evident by localized zone of comminution and high birefringence, presumably from the preferred alignment of phyllosilicates. Right) Ultracataclasite from the Punchbowl fault containing a segment of the principal slip surface mapped by Chester & Chester (1998). Similar to the experimental lip surface, the natural surface is characterized by a thin layer of cataclastically reworked material with high, uniform birefringence.

The purpose of FY2005 SCEC research is 1) to study the high-speed frictional behavior of ultracataclasite from the Punchbowl fault, 2) to characterize the microstructures of the products of the friction experiments with the goal of identifying dynamic weakening mechanisms, if activated, and 3) to compare the resultant microstructures to those documented for the natural slip-surface of the Punchbowl fault.

The high-speed friction experiments were done in Toshihiko Shimamoto's deformation laboratory at Kyoto University, and the detailed microstructural analyses on the products of the experiments are underway at Texas A&M University. For our original proposal, we intended to run a limited suite of experiments (less than 10) to identify whether a weakening response could be demonstrated at high slip-rates. In response to the preliminary results, Ms. Hiroko Kitajima, a Ph.D. student at Texas A&M University, conducted 50 high-speed friction experiments with a nearly 50% success rate (Table 1).

Table 1. Experiments Available for Microstructure Study

Experiment #	Ultracataclasite Type	Slip Rate (m/s)	Normal Stress (MPa)	Total Displacment (m)
515	DP4F	0.1	0.6	1.3
530	DP4F	0.7	0.6	29
519	DP4F	1.3	0.2	37
509	DP4F	1.3	0.6	2.5
494	DP4F	1.3	0.6	3.16
504	DP4F	1.3	0.6	6.5
486	DP4F	1.3	0.6	14.6
482	DP4F	1.3	0.6	83.4
475	DP4F	1.3	0.6	84.2
514	DP4F	1.3	1.2	36.4
500	DP189A	0.1	0.6	1.5
506	DP189A	0.1	0.6	3.3
497	DP189A	0.1	0.6	5.3
496	DP189A	0.1	0.6	7.7
507	DP189A	0.1	0.6	8.9
529	DP189A	0.7	0.6	25.6
526	DP189A	1.3	0.2	28.3
508	DP189A	1.3	0.6	2.6
505	DP189A	1.3	0.6	3.5
499	DP189A	1.3	0.6	3.8
498	DP189A	1.3	0.6	8.5
502	DP189A	1.3	0.6	25.7
495	DP189A	1.3	0.6	43
528	DP189A	1.3	1.2	28.3

The two main types of ultracataclasite from the Punchbowl fault were used for our experiments. One type is the olive-black ultracataclasite (DP189A) that is in contact with the basement, and the other is of the less-cohesive dark yellow-brown ultracataclasite (DP4F) that is adjacent to the sandstone (Chester & Chester, 1998). Both types were collected along the principal slip surface of the fault. The ultracataclasites were distinguished on the basis of color, cohesion, fracture and vein fabric, and porphyroclast lithology. In all exposures the two ultracataclasites are juxtaposed along a continuous contact that is often coincident with a single, continuous, nearly planar, principal slip surface that extends the length of the ultracataclasite layer. Samples of the ultracataclasite were disaggregated to a particle size less than 100 μm, which is much larger than the natural particle size of the ultracataclaite (Chester et al. 2005b). Approximately 1 mm thick layers of the dissagregated ultracataclasite was sheared in a high-velocity rotary apparatus at slip speeds of 0.1, 0.7 and 1.3 m/s, normal stress of 0.2, 0.6, and 1.3 MPa, to displacements from 1.5 m to 80 m.

24 out of 50 experiments were successful (Table 1). All experiments show normal quasi-static frictional strength at the beginning of slip, followed by gradual weakening of varying magnitude depending on the slip-velocity and normal stress. Overall, the two types of ultracataclasite show

similar behavior. An example of the mechanical data is provided by an experiment run at 1.3 m/s (Figure 1). At this high slip-rate, the friction coefficient rapidly increases to a peak of about 0.8 to 1.0 followed by gradual decrease to 0.05 over a slip-weakening distance (Dc) of about 15 m.

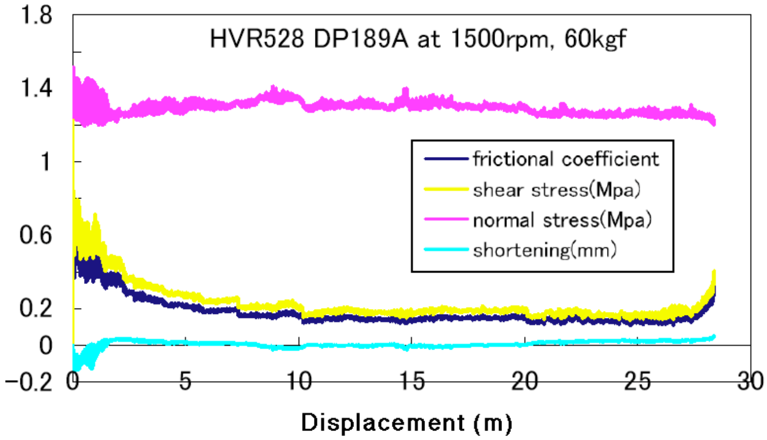

Figure 1. Raw data from a high velocity friction experiment. The disaggregated layer of ultracataclasite displays some shortening at small displacements due to consolidation and loss of material at edges of the sample. The normal stress is held constant, whereas shear strength decreases with slip to a nearly steady value at large displacements. The disaggregated material is contained during the high velocity shearing by a ring of Teflon. The Teflon adds some shear strength to the assembly, which must be removed during data reduction to determine true coefficient of friction. The Teflon strength correction is not shown in this raw data.

At the lower speed of 0.1m/s, the coefficient friction is about 0.8 and there is little change in strength with slip. At the higher slip-rates, Dc decreases with an increase in normal stress and an increase in slip-rate. That significant weakening is only observed at higher slip-rates, and that the critical slip distance for weakening decreases with an increase in normal stress and slip-rate, implies that weakening results from an increase in temperature of the slipping surface. Moreover, slide-hold-slide tests show rapid strength recovery consistent with transient thermal effects.

a. b.

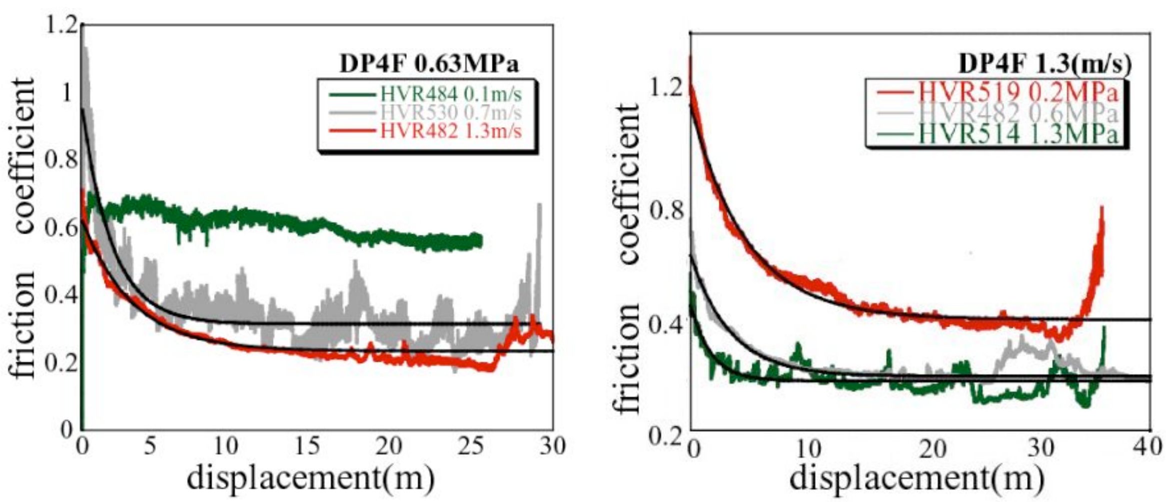

Figure 2. Example of mechanical data from friction experiments on Punchbowl ultracataclasite using the high-velocity rotary apparatus at Kyoto University. a) Dependence of friction and weakening distance on slip velocity. b) Dependence of friction and weakening distance on normal stress. In these figures the data are uncorrected for jacket strength; the steady-state friction coefficient at high velocity and large displacements is less than 0.1 with jacket strength corrections.

The high-speed friction experiments demonstrate significant weakening at high speeds and large displacements; a weakening that does not appear to be caused by thermal pressurization of pore fluids or melting, but rather some other weakening process that occurs during extremely localized shear in the ultracataclasite layer (Chester et al, 2005b; Kitajima et al., 2005). The response is similar to that found by Mizoguchi & Shimamoto (2004a, b) for the Nojima fault gouge. Current work is directed at correlating the microstructure with frictional behavior, identification of the weakening mechanisms, and comparing the microstructures of the experiments to the natural Punchbowl ultracataclasite microstructures.

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