Mesoscale fracture fabric, paleostress state, and dynamic weakening of the San Andreas Fault at SAFOD

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Understanding the physics of earthquake faulting and dynamic rupture demands study over a wide range of spatial and temporal scales. Macroscopic behavior during rupture nucleation, propagation and arrest depends, in part, on processes operating at the mesoscopic and microscopic scales. For example, local-scale processes contribute to energy dissipation in the tip region of propagating ruptures, dynamic weakening during coseismic slip, and recovery of strength during interseismic periods. Similarly, local weakening processes may be responsible for the apparent low strength of plate-boundary faults. Here we present observations of spot core taken at the San Andreas Fault Observatory at Depth (SAFOD), and high-speed friction experiments on samples from the core, to address the characteristics of damage, local stress state in the fault zone and the potential for dynamic weakening in localized zones of slip.

Determining paleostress states from fracture fabrics and other indicators is complementary to measurements of in situ stress in boreholes. Rock adjacent to faults accumulates damage during fault displacement, so for large faults the resultant fracture fabric at any one location represents a spatial and temporal average. In contrast, in situ measurements represent a point measure in space and time. Analyses of borehole-breakouts and shear-velocity-anisotropy along the SAFOD pilot hole and main hole across the SAFZ (Figure 1) indicate that there is a progressive increase in the angle between the maximum horizontal stress and the SAFZ with increasing depth and decreasing distance from the fault (Boness & Zoback, 2006). At the boundary of the SAFZ, in the vicinity of the lower Phase 1 spot core, the maximum horizontal in situ stress is oriented approximately 80^{o} to the fault plane.

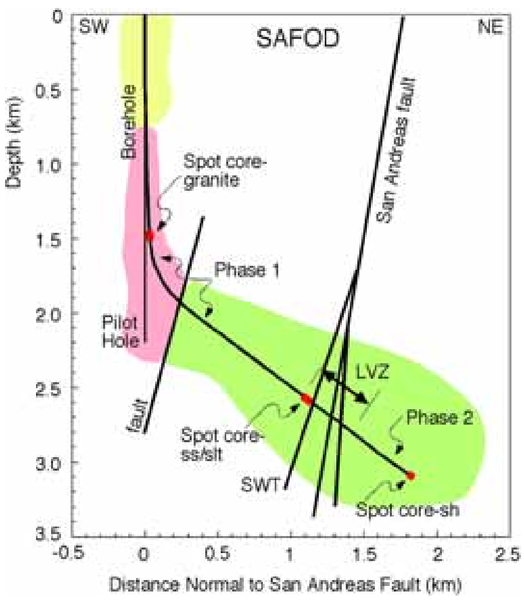

Figure 1. Cross-section of SAFOD borehole geometry after phase 1 and 2 drilling showing major lithologic boundaries, location of spot cores, and the low-velocity zone corresponding to the San Andreas fault zone.

The lower Phase 1 spot core, taken at a measured depth of 3055.6-3067.2 m (Figure 1), is cut by a dense array of fractures, subsidiary shears and cataclastic zones that cut and juxtapose units of pebbly sandstone, fine-grained sandstone, and siltstone. The subsidiary shears display strong preferred orientations. Using bedding and image logs to orient the core, we find that the fracture fabric is characterized by a conjugate pattern consistent with strike-slip faulting, and indicates that the maximum principal compressive paleostress also was oriented at high angles to the fault (Figure 2). The density and fabric of subsidiary shears at SAFOD are similar to that documented along inactive, exhumed faults of the San Andreas system (e.g., Punchbowl and San Gabriel faults). The similarity between the current- and paleo- stress states supports the general applicability of the "weak fault in strong crust" model and the conclusion that the San Andreas fault zone has been, on average, weak over geologic time.

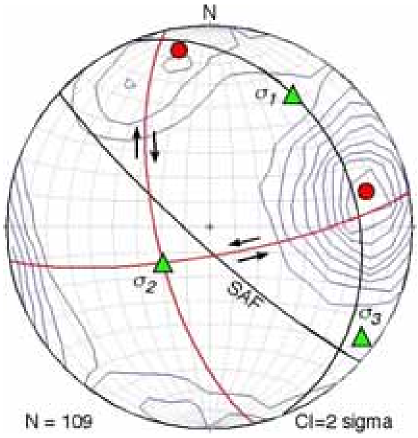

Figure 2. Fabric of subsidiary shears and inferred principal paleostress directions for the lower, Phase 1 SAFOD core sample at 3055.6-3067.2 m MD adjacent to the SAFZ. Lower hemisphere, equal area projection with North at top. Black great circles show bedding and San Andreas fault plane, and poles to shears are contoured using the Kamb technique. The subsidiary shears define a conjugate set, and best fit poles and planes are in red with sense of shear indicated. The right-later and left-lateral shears are mutually cross cutting. The right-lateral set includes the thicker shears and the cataclastic zones up to 1 cm in thickness. The best-fit poles to each set lie in the plane of bedding and the apparent slip direction along the faults showing separation is sub-parallel to bedding. The inferred paleostress directions are indicated by green triangles, and are consistent with strike slip faulting and maximum principal compression axis at 80˚ to the San Andreas fault.

Although samples from SAFOD demonstrate relatively normal friction behavior under quasi-static loading (Tembe et al., 2006), weakening under dynamic loading may provide an explanation for the apparent low strength of the San Andreas fault. Accordingly, four different rock types were taken from the largest fault in the SAFOD spot core (3067 m MD) and sheared between rock cylinders in a high-velocity rotary apparatus. Samples were disaggregated to particles <106 μm diameter, and then sheared at 1.3 m/s sliding velocity and normal stresses of 0.3, 0.6, and 1.3 MPa. The friction coefficient of these samples rapidly increases to a peak-strength of 0.5 to 0.6 initially, and then decreases to 0.05 to 0.1 at tens of meters of displacement. Although there is some variation in initial strength and in slip-weakening distance with rock type, the overall behavior is similar (Figure 3). Unexpectedly, the most rapid weakening (small critical slip distance) is seen for the siltstone host-rock rather than the gouge samples. The processes leading to dynamic weakening are not yet defined. Current microscopy work is directed at testing the hypothesis that the initial friction behavior relates to the initial particle size, and subsequent weakening reflects the effect of fabric development and heat generation rate as a function of localization of slip and displacement.

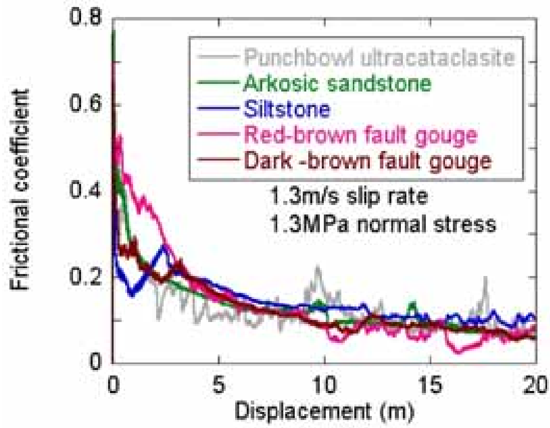

Figure 3. Results of high-speed friction tests on fault-rock samples from a significant fault in the SAFOD spot core. The fault juxtaposes pebbly arkosic sandstone and siltstone along two different gouge layers several mm thick. The fractured wall rock of the fault are represented by the arkosic sandstone and siltstone samples, and the fault-rocks are represented by the two types of gouge.

Boness, N.L. and Zoback, 2006, M.D., A multi-scale study of the mechanisms controlling shear velocity anisotropy in the San Andreas Fault Observatory at Depth, submitted to Geophysics.
Tembe, S., D.A. Lockner, J. Solum, C. Morrow, T-f. Wong, and D.E. Moore, 2006, Implications for strength of the San Andreas Fault Zone from SAFOD cuttings and core, Geophysical Research Abstracts, 8, 05248.