Geochemical Investigation of Fluid Involvement in Exhumed Faults of the San Andreas System: Collaborative Research with Texas A&M University and Saint Louis University

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Annual Project Summary

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Investigations Undertaken

Many models have been proposed to account for the weak-fault behavior of large strike-slip faults in the San Andreas system. Fundamental to many of these models are the physical and/or chemical role(s) of fluids. In addition, several models have been proposed that invoke chemical and mechanical effects of fluids in the nucleation, propagation, and arrest of seismic ruptures. These models envision significantly different sources, quantities, compartmentalization, and residence times for fluids in seismogenic fault zones. On the basis of existing data, it is difficult to discern which model(s) most accurately describes the fluid-rock interaction in faults and the role fluids play in the seismogenic cycle. This difficulty is due, in part, to the very limited amount of geochemical data that is presently available for faults of the San Andreas system. Study of the mineral phases, the major and trace element chemistry, and in particular, the stable isotope geochemistry of rocks in fault zones is one of the most effective tools to document fluid-rock interaction. At this time, however, only a few geochemical studies have been conducted on fault rocks in the San Andreas system.

It is the goal of this study to determine the extent of fluid involvement in the seismogenic cycle and to discern which model(s) most accurately describes fluid-rock interaction in large strike-slip faults of the San Andreas system. This will be accomplished through an integrated structural-geochemical study of fault rocks exposed in the two most deeply exhumed, large-displacement faults in the San Andreas system. The structural analysis will provide the requisite control that is so vital for collecting samples for geochemical analyses and interpreting the geochemical data in relation to the seismogenic cycle. The geochemical portion of the study will characterize the mineral phases, the major and trace element chemistry, and the stable isotope geochemistry of the fault rocks and adjacent host rocks. The results from the geochemical analyses, especially the stable isotope analyses, will better constrain the fluid-rock interaction in fault zones than is possible with the current data.

Results

Geology of Punchbowl Fault

The Punchbowl and San Andreas faults have approximately parallel trends through the San Gabriel Mountains and join to the northwest and southeast (Figure 1). The Punchbowl fault was a main component of the San Andreas transform system in the central Transverse Ranges of southern California during the Miocene and Pliocene. The fault cuts post-Paleocene sedimentary rocks and Proterozoic, Jurassic and Cretaceous crystalline rocks of the San Gabriel basement complex. Uplift and erosion has exhumed the Punchbowl fault to provide excellent exposures of the products of faulting at 2 to 4 km depth. Microstructures and mineral assemblages of the fault rocks from the Punchbowl fault are consistent with faulting at several kilometers depth (Chester & Logan, Pure Applied Geophysics, v. 124, 1986). By analogy with nearby active faults, we assume that the Punchbowl fault was seismogenic and that the structure of the fault records the passage of numerous earthquake ruptures. Total right-lateral separation on the Punchbowl fault is approximately 44 km.

The Punchbowl fault zone commonly consists of two sub-parallel principal faults spaced several hundred meters apart. At the Devil's Punchbowl Los Angeles County Park, the principal faults bound a block of cataclastically deformed basement up to ~0.5 km thick (Figure 1). The southernmost principal fault, referred to informally as the Cocktail fault, is segmented and probably accounts for only a few kilometers of right-lateral separation. The northernmost principal fault, referred to as the Punchbowl fault, places the cataclastically deformed basement rock against arkosic sedimentary rocks of the Punchbowl Formation along a single, continuous ultracataclasite layer approximately 0.5 m thick. Previous structural studies indicate that nearly all of the displacement on the Punchbowl Fault zone was localized to the ultracataclasite layer of the northernmost trace (Chester and Chester, Tectonophysics, in press, 1998). Mineralogical alteration associated with cataclastic deformation is common in the Punchbowl fault zone. Alteration products include chlorite, illite, smectites, and several zeolites. Generally, the higher-grade alteration products (e.g., chlorite) are found in the faulted basement rocks and the very low-grade alteration products (e.g., smectite) occur in the Punchbowl fault ultracataclasite. We interpret the petrologic and structural relationships as indicating the deformation and alteration in the Punchbowl ultracataclasite records the shallowest conditions and the last stages of fault movement. The Cocktail fault appears to record early deformation at greater depth with some later deformation at shallower conditions.

Structure of the Fault Core

We have mapped four localities along the Punchbowl fault in detail (at scales of 1:10 and 1:1) and have collected approximately one hundred samples within and adjacent to the fault core (Figure 2). Several important features of the fault core are common to all of the mapped segments even though the map locations are spaced up to two kilometers apart. Most displacement on the fault occurred within a < 1-m wide zone of ultracataclasite. The boundaries between the ultracataclasite and surrounding (proto)cataclasite are extremely sharp, but not parallel nor planar on the meter-scale. On the basis of color, cohesion, fracture and vein fabric, and porphyroclast lithology, two main types of ultracataclasite are distinguished in the layer: an olive-black ultracataclasite in contact with the basement, and a dark yellowish brown ultracataclasite in contact with the sandstone. The two are juxtaposed along a contact that is often coincident with a single, continuous, nearly planar, prominent fracture surface (pfs) that extends the length of the

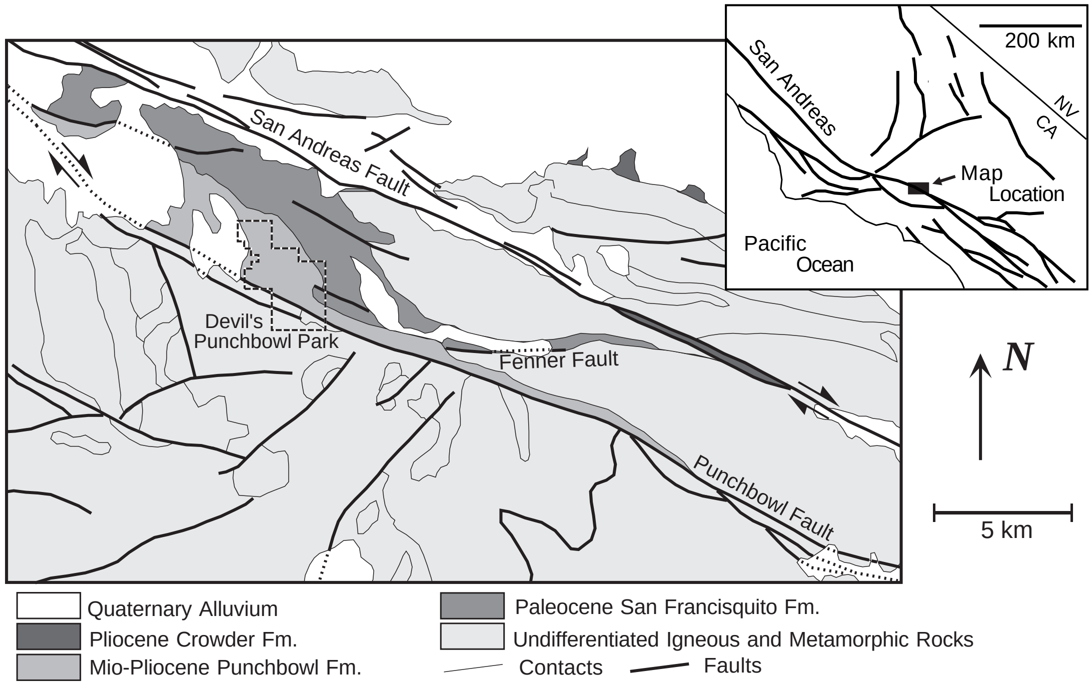

Figure 1. Geologic map of the Punchbowl fault on the northeast side of the San Gabriel Mountains, southern California. The study area is in the Devil's Punchbowl Los Angeles County Park.

ultracataclasite layer in all exposures (Figure 2). No significant mixing of the brown and black ultracataclasites occurred by offset on anastamosing shear surfaces that cut the contact or by mobilization and injection of one ultracataclasite into the other. The ultracataclasites are cohesive throughout except for thin accumulations of less cohesive, reworked ultracataclasite along the pfs. Structural relations are consistent with 1) the black and brown ultracataclasite having been derived from the basement and sandstone, respectively, 2) the final several kilometers of slip having occurred along the pfs, and 3) earthquake ruptures having followed the pfs without significant branching or jumping to other locations in the ultracataclasite.

Geochemistry of the Fault Rocks

Seventy samples of fault rocks and host rocks have been analyzed by XRD and XRF methods. Quartz, potasium feldspar, plagioclase, micas, amphiboles, laumontite, and calcite are the dominant minerals in the host rock. The largest variations in mineralogy and element concentrations occur in the (proto)cataclasite and surrounding damaged zone rocks. Quartz, intermediate plagioclase, and clays (smectite) are the dominant mineral components in the ultracataclasite. The mineralogy and major and trace element concentrations are similar along and across the ultracataclasite layer; however, there are small systematic variations in the relative abundance of the minerals and some elements across the ultracataclasite layer and between the ultracataclasite and surrounding rocks. Comparison of host rock and fault rock geochemistry are consistent with the ultracataclasite being the product of mechanical mixing of the host lithologies, mass transfer and minor volume loss, chemical exchange with pore fluids, and hydration reactions. Oxygen isotope data from along two traverses across the fault core indicate that the system was not fluid-starved and that some isotopic exchange with the fluid occurred during (de)formation of the ultracataclasite (Figure 3). The stable isotope data will be used to help delimit the origin of the fluids in the ultracataclasite and distinguish between open and semi-open system behavior.

Implications for Faulting Mechanisms

Structural and geochemical relations indicate that slip was extremely localized to the principal fracture surface within the ultracataclasite layer during the final stages of faulting.

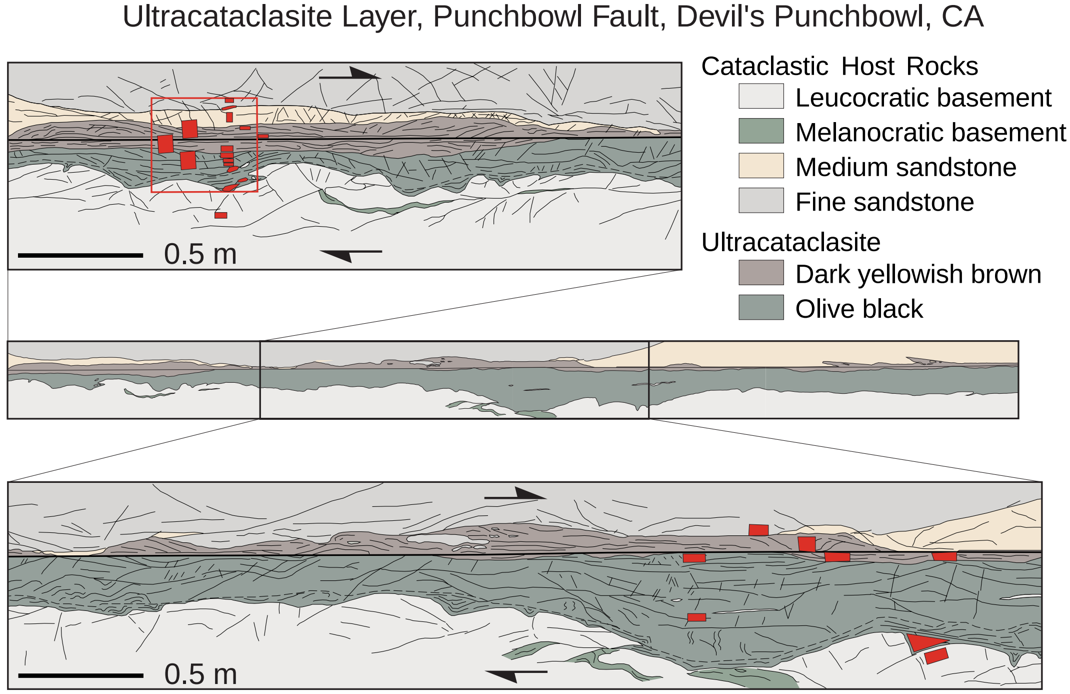

Figure 2. One of four detailed maps made of the core of the Punchbowl fault showing structure of the ultracataclasite layer and locations of samples (depicted as small polygons) collected for geochemical analyses. The thick black line shows the location of the principal fracture surface interpreted as the slip surface that was active during final stages of faulting. Geochemical data shown in Figure 3 are from the samples shown in the left side of the upper map.

Although structural evidence indicates that the ultracataclasite layer must have formed early in the fault history, the timing of formation of the principal fracture surface is uncertain. Two possible models for ultracataclasite evolution are envisioned -- 1) progressive localization of strain develops a single slip surface late in the faulting history, and 2) the slip surface forms early in the faulting history and laterally migrates through the ultracatalaclasite during subsequent deformation. The fact that different types of ultracataclasite occur in the fault and are in sharp contact along the slip surface imply that earthquake ruptures repeatedly followed the surface without significant branching or jumping to other locations in the ultracataclasite. In addition, the structure and geochemistry imply that fluid-assisted chemical exchange and mass transfer were restricted, consistent with fluid compartmentalization and fluid flow at the outcrop scale. The geochemical data are consistent with somewhat accelerated alteration and dissolution of the finely comminuted rocks in the fault core and fluid-assisted transfer of mass from the ultracataclasite to the surrounding fault rocks, resulting in minor volume loss. The stable isotope data are consistent with a semi-open to open fluid system. Of the various mechanisms proposed to explain the low strength of the San Andreas system and to produce dynamic weakening of faults, those that assume extreme localization of slip and moderately restricted fluid flow appear most compatible with our observations and data.

Non-Technical Summary

Knowledge of how and why earthquakes occur is critical in our effort to reduce the loss of life and property as a result of natural hazards. The physical processes operating in fault zones leading to earthquake slip nucleation, propagation and arrest occur deep within the earth's crust and can not be studied directly. One of the primary means of investigating earthquake faulting processes is through careful study of ancient faults that are presently exposed on the earth's surface

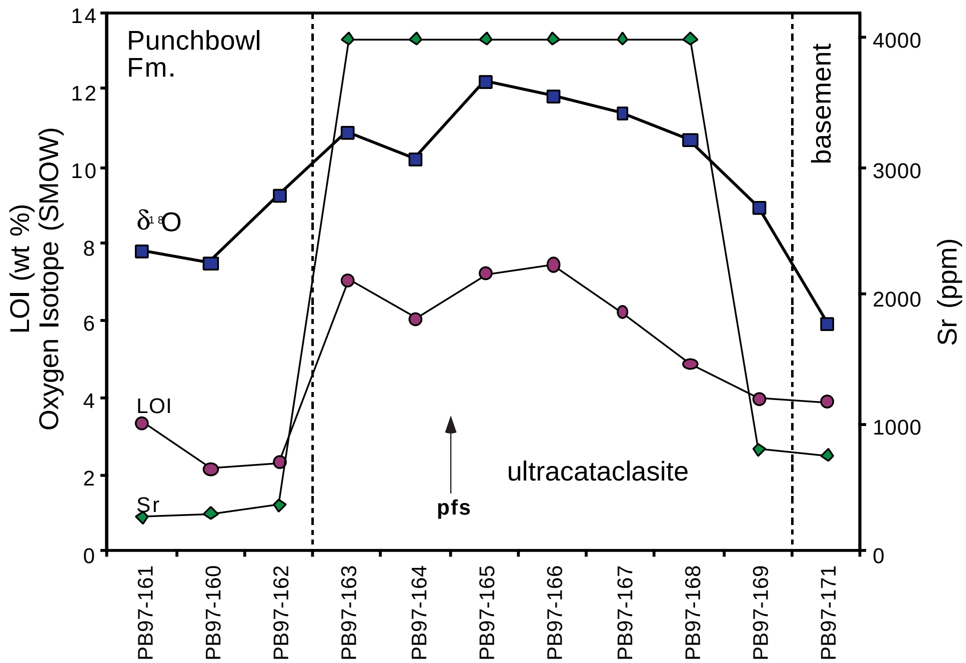

Figure 3. Example of variation in geochemistry across the Punchbowl fault core. Amount of volatiles shown by loss on ignition (LOI) is higher in the ultracataclasite relative to surrounding fault rocks and host rocks. $\delta^{18}O$ correlates with LOI in the ultracataclasites consistent with exchange and fractionation having occurred during the hydration reactions. Concentrations of several minor and trace elements, such as strontium (Sr) in the ultracataclasite differ significantly from those of the surrounding cataclastic and host rock. (Note: The XRF method used for these analyses could not qunatify Sr levels >4000 ppm).

due to erosion of overlying material. We are using a variety of analytic techniques to study the earthquake process, with special attention being given to the mechanical and chemical interaction of pore fluid and rock during faulting. This field study provides information to guide future experimental and theoretical modeling efforts and to test current hypotheses of the faulting process. This and related work will ultimately provide a sound mechanistic understanding of the earthquake faulting process that will help us understand how and why earthquakes occur.

Reports Published

Chester, F. M., Characterization of the Internal Structure of the San Andreas Fault at Depth Based on Study of Surface Exposures of Exhumed Faults, *Eos Trans. AGU*, *79*, F576, 1998.

Chester, F. M., D. L. Kirschner, and J. S. Chester, Structural and geochemical investigations of the Punchbowl fault, San Andreas system, California, in *Program & Abstracts of the International Workshop on Frontiers in Monitoring Science and Technology for Earthquake Environments*, Japan Nuclear Cycle Development Institute Publication, TW7400 98-001, 4 pp., Toki, Japan, 1998

Kirschner, D. L., and F. M. Chester, Structural and geochemical investigation of fault rocks in the core of the Punchbowl Fault, San Andreas system, California. GSA Abstracts w/ Program 30:A324, 1998.