FINAL TECHNICAL REPORT

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EARTHQUAKE PROCESSES AND INTERNAL FAULT STRUCTURE

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TECHNICAL ABSTRACT

Structural studies of the exhumed Punchbowl fault zone, San Andreas system, California, and mechanical modeling of fault related deformation were conducted to determine the relationship of the internal structures of fault zones to processes of fault growth, wear, and the earthquake cycle. The Punchbowl fault was a main trace of the San Andreas System during the Mio-Pliocene and accommodated > 40 km of right-lateral displacement. Subsequent uplift and erosion exposed fault rocks that were formed at depths of 2-4 km. The fault juxtaposes pebbly arkosic sandstone and siltstone of the Punchbowl Formation against a heterogeneous assemblage of crystalline rocks of the San Gabriel basement complex along much of the fault trace. The fault consists of a meters-thick core of cataclasite and ultracataclasite bordered by damage zones of fractured and brecciated rock. Detailed mapping (1:10 and 1:1) of the fault core has documented several important features: 1) most displacement on the fault occurred within a < 1 m wide zone of ultracataclasite; 2) the boundaries between the ultracataclasite and surrounding (proto)cataclasite are extremely sharp, but not parallel or planar on the meter-scale; 3) there are two distinct ultracataclasite units that are juxtaposed along a very planar, principal slip surface that was active during the last stages of fault movement.

Study of microfractures along traverses across the Punchbowl fault zone have revealed systematic preferred orientations of fractures relative to position in the fault zone. The microfracture fabric within the damage zone is relatively homogeneous, whereas outside the damage zone the preferred orientations are more variable (Figure 3). In the damage zone and within 2.5 m of the fault surface (inner damage zone), microfractures display preferred orientations that are parallel and perpendicular to the fault surface. Between 2.5 and approximately 100 m from the fault surface, microfractures display a single preferred orientation that is perpendicular to the fault surface and to the slip direction of the fault. The microfracture fabrics are inconsistent with models of fracture formation during the initial stages of fault growth and localization. Fabrics are, however, consistent with prolonged fracturing and wear during accumulation of large displacement.

We use an analytical model of elastic deformation along a wavy frictional fault to evaluate the variation in local stress states as a function of surface roughness, elastic modulus, slip, coefficient of friction, and far-field stress. Assuming roughness and modulus appropriate to crustal faults, models indicate that a large variation in principal stress orientations and magnitudes along a fault should exist, and that the variation increases with a decrease in the coefficient of friction of the fault. The location and size of regions with high likelihood for brittle failure depend on the orientation of the far-field principal stress and fault friction. The average orientation of the principal stresses in the region of likely failure is not the same as the far field principal stress orientation. Application of the model to the Punchbowl fault, for which independent information suggests that the far-field maximum principal compressive stress was at a high angle to the fault, indicates that the maximum principal compressive stress in actively deforming regions near the fault should be nearly fault-normal as observed in the microfracture fabric.

NON-TECHNICAL ABSTRACT

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 geologic study of ancient faults that have been exhumed to expose structures produced at seismogenic depths. We have used a variety of analytic techniques to study the earthquake process, and during this phase of our study we have focused on the distribution of slip and the friction processes operative during seismogenic faulting. The structure of the core of a fault is consistent with the hypothesis that an earthquake rupture at depth is an extremely localized and can occur repeatedly on a long-lived slip surface. Deformation structures in the rock surrounding a slip surface is consistent with predictions of mechanical models for of the accumulation of damage associated with slip on an irregular, frictional surface. 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 which will help us understand how and why earthquakes occur.

Investigations Undertaken

Geologic studies of exhumed fault zones provide information on the structure and composition of fault zones, and when combined with laboratory investigations allow us to infer environmental conditions, faulting mechanisms, and mechanical properties of fault zones at hypocentral depths. Study of exhumed fault zones complements study of the surface expression of active faults and geophysical investigations of fault zones at depth. Definition of fault zone structure is important for the development and testing of physical models of earthquake genesis. Based on our previous studies we have developed a fairly robust generic model of the internal structure of San Andreas type faults that applies to the shallower portions of the seismogenic zone within the crust (Chester et al., 1993, JGR , 98: 771-786). One of the most significant findings is that large-displacement fault zones are characterized by an internally zoned structure with distinct rock fabrics. Unfortunately, we do not completely understand the origin or significance of the internal fault structure. The goal of this project is to relate the internal structures of fault zones to processes of fault growth, wear, and the earthquake cycle. We are following two related avenues of research: 1) continued geologic studies of exhumed active and ancient fault zones, and 2) mechanical modeling of fault related deformation. By combining structural observations with mechanical models we hope to develop a basis to infer fault zone mechanical properties and earthquake rupture parameters from fault structure.

Results

Studies of the exhumed Punchbowl fault zone, San Andreas system, California, has focused on 1) additional detailed mapping of the ultracataclasite core of the fault, 2) characterization of the microfracture fabric of the fault and surrounding host rock, and 3) modeling stress and deformation associated with slip on a rough fault surface.

Mesoscopic Structure of the Punchbowl Fault Core

The results of the detailed mapping are reported in the paper Chester and Chester [1998] appended to this report. This work served as the basis for a FY 1998 USGS contract to study the structure and geochemistry of the Punchbowl and San Gabriel fault cores to identify the chemical-mechanical role of fluids and the source of fluids during faulting.

For this part of the project we conducted additional mapping of the ultracataclasite layer at 1:1 and 1:10 to determine the mode of failure and to constrain the processes of seismic slip. 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 continuous contact that is often coincident with a single, continuous, nearly planar, prominent fracture surface (pfs) that extends the length of the ultracataclasite layer in all exposures. 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 suggest that 1) the black and brown ultracataclasite were derived from the basement and sandstone, respectively, 2) the black and brown ultracataclasites were juxtaposed along the pfs, 3) the subsequent, final several kilometers of slip on the

Punchbowl fault occurred along the pfs, and 4) earthquake ruptures followed the pfs without significant branching or jumping to other locations in the ultracataclasite. By comparison with rock friction experiments, the slip localization along the pfs in the ultracataclasite implies rate weakening behavior with a critical slip distance similar to laboratory values, and thus relatively small nucleation and breakdown dimensions for earthquake ruptures. Of the various mechanisms proposed to explain the low strength of the San Andreas and to produce dynamic weakening of faults, those that require or assume extreme localization of slip are most compatible with our observations.

Study of the Microfracture Fabric of the Punchbowl Fault

The study of the microfracture fabric of the Punchbowl fault was carried out by Jennifer E. Wilson, Texas A&M University, and will be reported in her M.S. Thesis to be completed December, 1998. The results of the microfracture study are summarized in the following.

Samples of Punchbowl Formation sandstone have been collected from less than a meter to greater than 1 km from the fault surface along transects across the Punchbowl fault in the Devil's Punchbowl basin (Figure 1). We have characterized the types of microfractures, types of fracture filling and pore cements, and the relative timing relationships of the fracture and cementation events. In general, healed fractures are the oldest, and open fractures are the youngest. Sealing of fractures and pore cementation appear to have occurred after the healed fractures and before the open fractures were formed. Laumontite appears to be the oldest cement, and at least two calcite cementation events followed. Fracture density measurements show a pronounced increase in density with proximity to the fault, and define a microfracture damage zone on the order of 100 m in thickness (Figure 2).

Microfractures show preferred orientations, particularly within the damage zone of the Punchbowl fault. Generally, healed and open microfractures have similar preferred orientations within each sample. We have carried out fold tests to see how microfracture orientations relate to bedding orientations and to check the relative timing of folding and microfracturing. Results suggest that microfracture orientations do not relate to the orientation of bedding, and that the majority of the folding occurred prior to establishing the preferred orientations of microfractures.

Microfracture fabric within the damage zone are relatively homogeneous, whereas outside the damage zone the preferred orientations are more variable (Figure 3). In the damage zone and within 2.5 m of the fault surface (inner damage zone), microfractures display preferred orientations that are parallel and perpendicular to the fault surface. Between 2.5 and approximately 100 m from the fault surface, microfractures display a single preferred orientation that is perpendicular to the fault surface and to the slip direction of the fault.

The microfracture fabrics are inconsistent with models of fracture formation during the initial stages of fault growth and localization. Fabrics are, however, consistent with prolonged fracturing and wear during accumulation of large displacement. In fact, the orientations of fractures within the outer damage zone normal to the fault surface and within the inner damage zone parallel and perpendicular to the fault surface are consistent with the predictions of the mechanical model for stress and deformation along wavy frictional faults described below.

Our favored interpretation of the deformation near the Punchbowl fault is that the folding of the Punchbowl Formation occurred relatively early. Microfracturing occurred throughout the faulting phase in orientations consistent with wear along the fault. The episodes of cementation and fracture sealing occurred during the faulting phase.

Stress and Deformation along Wavy Frictional Faults

The results of the modeling study are reported in a manuscript to be submitted to the Journal of Geophysical Research and appended to this report.

We use an analytical model of elastic deformation along a wavy frictional fault to evaluate the variation in local stress states as a function of surface roughness, elastic modulus, slip, coefficient of friction, and far-field stress. The total stress state along the fault may be described by the sum of a basic stress component resulting from frictional slip on a planar fault surface and a perturbed stress component resulting from the presence of roughness elements. Introduction of roughness produces a variation in normal stress across the fault surface due to the perturbed stresses. Assuming roughness and modulus appropriate to crustal faults, normal stress should be reduced to near zero magnitudes locally such that separation of fault walls is likely. The large variation in normal stress along the fault surface resulting from fault roughness may be responsible, in part, for complexity in moment release during large earthquakes and for lateral variation in seismic coupling along faults. The variation in principal stress orientations and magnitudes along a fault increase with a decrease in the coefficient of friction of the fault. The location and size of the regions with high likelihood of brittle failure depend on the orientation of the far-field principal stress and fault friction. The average orientation of the principal stresses in the region of likely failure generally does not reflect the far field principal stress orientation. Although inversion of earthquake and fabric data and for stress orientation along faults may be possible, the model results indicate the inversion result is insufficient to determine far-field stress states and fault friction without additional independent data.

Reports Published

Chester, F. M., and J. S. Chester, Ultracataclasite structure and friction processes of the San Andreas fault, Supplement to Eos Trans. Am. Geophy. Union, 78, F475, 1997.

Chester, F. M., and Chester, J. S., Ultracataclasite structure and friction processes of the Punchbowl fault, San Andreas system, California, Tectonophysics, in press, 1998.

Chester, F. M., and J. S. Chester, Stress and deformation along wavy frictional faults, to be submitted to J. Geophys. Res., 1998.

Wilson, Jennifer E., Microfracture fabric of the Punchbowl fault zone, San Andreas system, California, M.S. Thesis, Texas A&M University, in prep., 1998.

Figure Captions

Fig. 1. Geologic map of the Devil's Punchbowl area showing sample traverses and sample locations. The main trace of the Punchbowl fault places Punchbowl Formation against crystalline basement. Sample traverses terminate at the ultracataclasite layer of the fault.

Fig. 2. Density of microfractures in the Punchbowl Formation sandstone as a function of distance from the Punchbowl fault. Density determined from the total number of fracture intercepts along ninety (90) randomly oriented line segments from 3 mutually perpendicular petrographic sections for each sample.

Fig. 3. Microfracture fabric of the Punchbowl Formation sandstone along the Punchbowl fault, Devil's Punchbowl Los Angeles County Park. Plots are lower hemisphere equal area projections onto the horizontal plane with north at the top. Kamb contour intervals at 3, 4, 5, and 6 σ. (a) Microfracture fabric outside the damage zone of the fault. Grouped data of four samples from greater than 100 m from the fault surface. Fabric is essentially random. (b) Microfracture fabric of the outer damage zone of the fault. Grouped data of eight samples from between 2m and 100m from the fault surface. Microfractures display a preferred orientation approximately perpendicular to the fault surface. (c) Microfracture fabric of the inner damage zone of the fault. Grouped data of four samples from less than 2m from the fault surface. Microfractures display a preferred orientation approximately parallel and perpendicular to the fault surface.

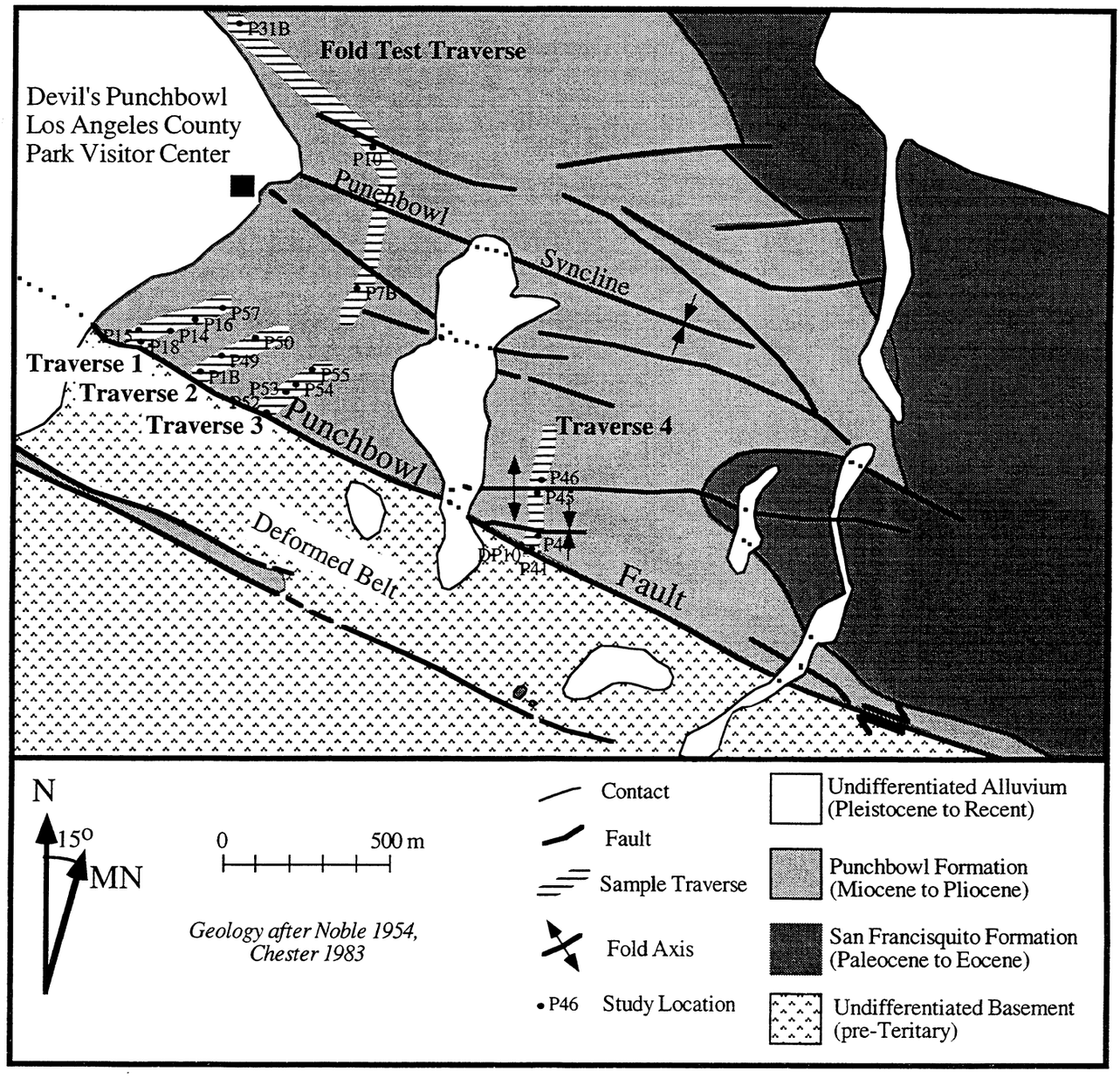
Fold Test Traverse
Devil's Punchbowl
Los Angeles County
Park Visitor Center
P31B
P10
P7B
Punchbowl
Syncline
P57
P16
P15
P14
P18
P50
P49
P1B
P55
P53
P54
P52
Traverse 1
Traverse 2
Traverse 3
Punchbowl
Traverse 4
P46
P45
P44
P10
P41
Deformed Belt
Fault
N
15°
MN
0
500 m
Geology after Noble 1954,
Chester 1983
Contact
Fault
Sample Traverse
Fold Axis
P46 Study Location
Undifferentiated Alluvium
(Pleistocene to Recent)
Punchbowl Formation
(Miocene to Pliocene)
San Francisquito Formation
(Paleocene to Eocene)
Undifferentiated Basement
(pre-Teritary)

Figure 1

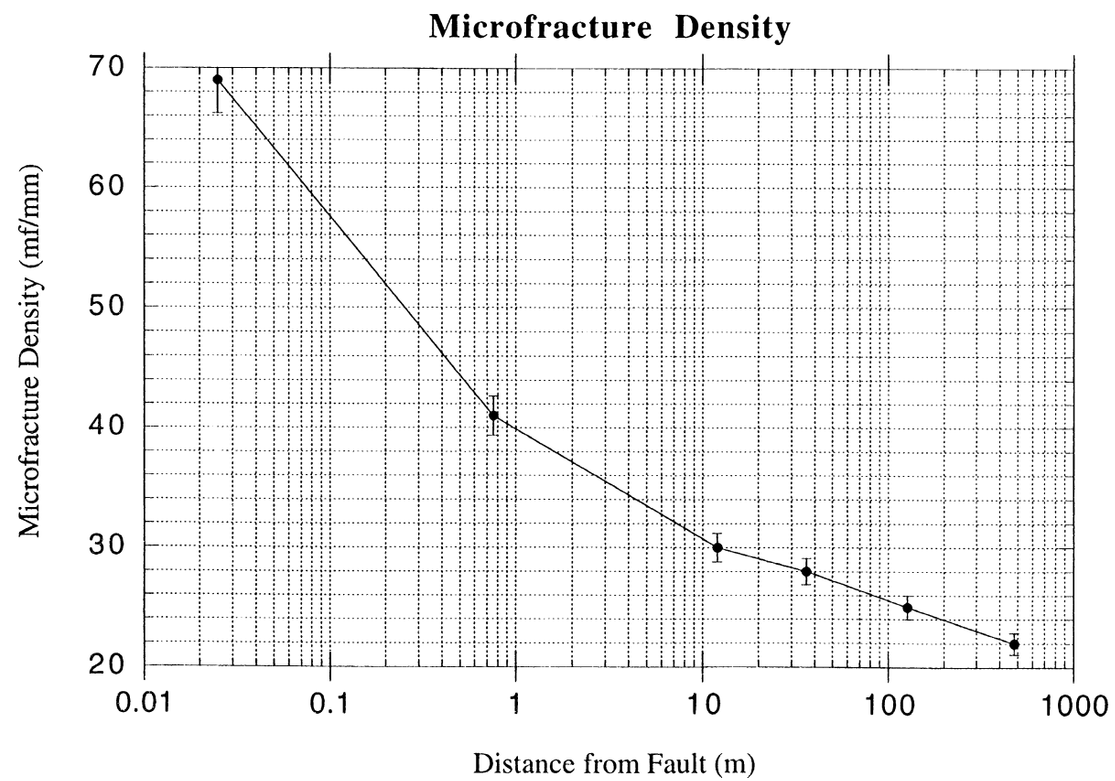
Microfracture Density
Microfracture Density (mf/mm)
70
60
50
40
30
20
0.01
0.1
1
10
100
1000
Distance from Fault (m)

Figure 2

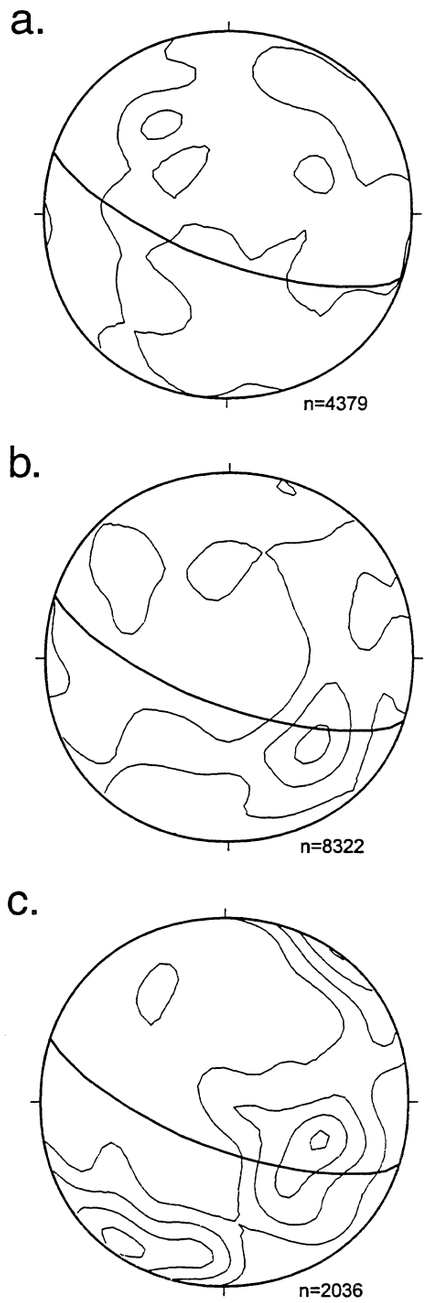

Figure 3

Ultracataclasite structure and friction processes of the Punchbowl fault, San Andreas system, California

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Abstract - The Punchbowl fault is an exhumed, 40+ km displacement fault of the San Andreas system. In the Devil's Punchbowl, the fault contains a continuous ultracataclasite layer along which the Punchbowl Formation sandstone and an igneous and metamorphic basement complex are juxtaposed. The fabric of the ultracataclasite layer and surrounding rock indicate that nearly all of the fault displacement occurred in the layer. By analogy with nearby active faults, we assume that the Punchbowl fault was seismogenic and that the ultracataclasite structure records the passage of numerous earthquake ruptures. We have mapped the ultracataclasite layer at 1:1 and 1:10 to determine the mode of failure and to constrain the processes of seismic slip. 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 continuous contact that is often coincident with a single, continuous, nearly planar, prominent fracture surface (pfs) that extends the length of the ultracataclasite layer in all exposures. 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 suggest that 1) the black and brown ultracataclasite were derived from the basement and sandstone, respectively, 2) the black and brown ultracataclasites were juxtaposed along the pfs, 3) the subsequent, final several kilometers

of slip on the Punchbowl fault occurred along the pfs, and 4) earthquake ruptures followed the pfs without significant branching or jumping to other locations in the ultracataclasite. By comparison with rock friction experiments, the slip localization along the pfs in the ultracataclasite implies rate weakening behavior with a critical slip distance similar to laboratory values, and thus relatively small nucleation and breakdown dimensions for earthquake ruptures. Of the various mechanisms proposed to explain the low strength of the San Andreas and to produce dynamic weakening of faults, those that require or assume extreme localization of slip are most compatible with our observations.

Stress and deformation along wavy frictional faults

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To be submitted to Journal of Geophysical Research

Abstract - Locally inhomogeneous stress states are expected along faults due to slip on geometrically irregular fault surfaces. We use an analytical model of elastic deformation along a wavy frictional fault to evaluate the variation in local stress states as a function of surface roughness, elastic modulus, slip, coefficient of friction, and far-field stress. The total stress state along the fault may be described by the sum of a basic stress component resulting from frictional slip on a planar fault surface and a perturbed stress component resulting from the presence of roughness. Roughness produces a variation in normal stress across the fault surface, and assuming roughness and modulus appropriate to crustal faults, the normal stress should be reduced to a near zero magnitude locally such that separation of fault walls is likely. The large variation in normal stress along the fault surface resulting from fault roughness may be responsible, in part, for complexity in moment release during large earthquakes and for lateral variation in seismic coupling along faults. The variation in principal stress orientations and magnitudes along a fault increase with a decrease in the coefficient of friction of the fault. The location and size of regions with a high likelihood for brittle failure depend on the orientation of the far-field principal stress and fault friction. The average orientation of the principal stresses in the region of likely failure is not the same as the far field principal stress orientation. Although inversion of earthquake and fabric data for stress orientation along a fault may be possible, the model results indicate that the inversion result is insufficient to determine far-field stress states and fault friction without additional independent data.