Using TDR, Helium density, digital grain size analysis, and chemical data to characterize the physical properties of near surface fault zones: a proof-of-concept approach.

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Abstract

We have mapped a conjugate set of strike-slip faults consisting of over 35 individual faults that are probably younger than ~0.5 – 0.6 million years in the San Felipe Hills, SE, California. The faults have been exhumed from a minimum of 300 meters depth. Hinge lines of early formed folds serve as piercing points for determining amounts of offset for many of the faults, and indicate that displacements mostly vary from 1-3 meters to as great as 250+ meters. The faults cut poorly consolidated mudstones and sandstones of the Pliocene-Pleistocene Borrego Formation and sandstones and minor gravels of the overlying Pleistocene Ocotillo Conglomerate (~1.1 to ~0.5 Ma).

Fault zones in the San Felipe Hills vary from ~10 to 615 cm in thickness, and fault zone thickness (fzt) correlates with fault displacement (fd) (fzt = 0.003*fd + 0.222; R2 = 0.67). From the initial set of 35 faults, we selected two faults for detailed study, one recording dextral, and the other sinistral slip. Eleven samples were collected beginning ~9 m outside the dextral fault zone, the last 2 samples being within the fault core. Samples were spaced ~1.5 m apart in sandy siltstone just below and above the contact separating the Ocotillo Conglomerate and Borrego Formation. For the sinistral fault beginning ~9 m outside the fault zone 5 samples were collected at a spacing of ~ 2 m within laminated siltstones of the lower Ocotillo Conglomerate. At each sample site dry bulk density was measured using time domain reflectometry (TDR), while collected samples yielded helium density (grain density), digital grain size distributions, and chemical data. From these data porosity and volume strains are calculated. Preliminary data from one traverse show that porosity systematically decreases from ~42% outside the fault zone to ~14% within the fault zone. This change in porosity translates into an ~47% decrease in volume. Thin sections of the damaged zone show that granulation and fragmentation did not accommodate observed volume strains or porosity reduction. Though we are currently completing our analyses of data collected from other traverses, we suggest based on the above observations, that when faults transect sandy to silty intervals, the majority of slip occurs along a single slip surface (the principal slip surface), while packing and reduction of pore space is a major process operating within a narrow ~1 m zone adjacent to the fault zone.

Purpose

In the San Felipe Hills, south of the Clark strand of the San Jacinto fault (Fig. 1), over 35 different faults have been mapped by Dr. Gary H. Girty and graduate students at San Diego State University (Fig. 2). Our preliminary excavations of two of these faults reveal a well defined fault core composed of foliated to non-foliated white gouge, surrounded by damaged zones consisting of brecciated red mudstone and shear banded sandstone (Fig. 2). We have been able to trench the faults to about 1 – 1.5 m depths. The fault zones appear to be tabular to these depths.

The purpose of this study is to understand how fault cores and damage zones develop and how they scale over various displacement histories and lengths ranging from ~2 to ~250 meters (this study) to ~21 kilometers (Clark segment San Jacinto) to ~41+ kilometers (Punchbowl) or more. In answering this, the development of numerical solutions focused on the dynamics of fault rupture, and the extension of the general model of Chester et al. (2004) to near surface faults with a simple history and displacements varying from 2-3 m to ~1 km will be aided. Data obtained during this study may provide information as to when in the displacement history of a fault damage zone asymmetry and principal slip surfaces develop.

Key questions that will be addressed during this study include the following.

(1) What chemical, textural, and grain size changes occur during the development of damage zones and fault cores from host mudstones and sandstones?

(2) What changes in bulk density, average grain density, and porosity accompany the development of damage zones and fault cores from host mudstones and sandstones?

(3) Are quantifiable volume strains involved in damage zones and fault core development?

(4) Do any of the attributes determined in (1) through (3) above vary in a way that would suggest a spatially asymmetric development of the damage zones (e.g., Dor et al., 2006)?

(5) Do any of the attributes determined in (1) through (3) above vary spatially along the trace of individual faults or correlate with amount of displacement or fault length (e.g., Shipton et al., in press) or proximity to fault discontinuities and irregularities?

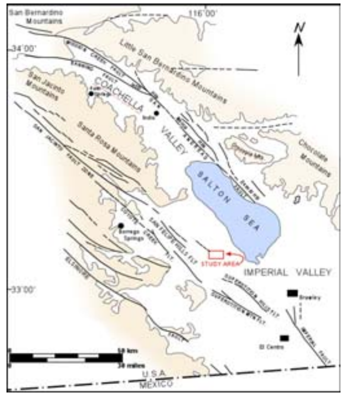


Figure 1. Generalized map of southern California showing the Salton Trough region and the proximity of the San Felipe Hills to the San Andreas, San Jacinto, Coyote Creek, and Elsinore Fault zones.

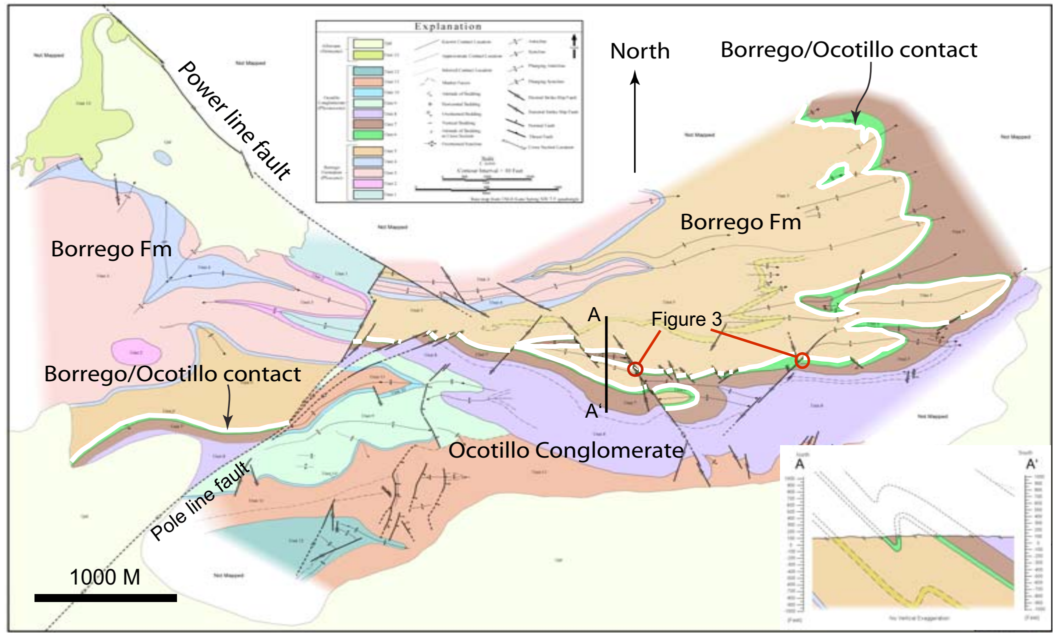


Figure 2. Simplified structural map of a portion of the San Felipe Hills. The NW trending dextral strike slip fault studied is shown in Figure 3a. Shown in Figure 3b is the NE trending sinistral strike slip fault. Cross section A-A' shows that although shallow, the faults within the San Felipe Hills have been exhumed from minimum of 300 m in depth.

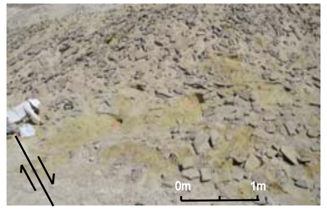


Figure 3a. View looking north at NW trending dextral fault which shows11m of displacement within the sandstone/mudstone member of the Borrego Fm. Close up of the core is shown in Figure 4.

Figure 3b. View looking south at the NE trending sinistral fault showing the sandstone/mudstone members of the Borrego Fm.

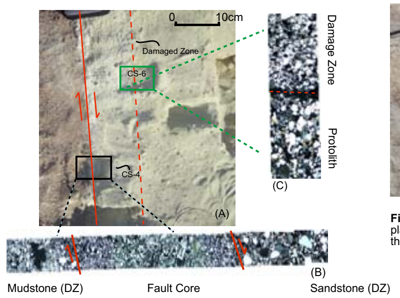


Figure 4. (A) Close up of the NW trending dextral strike-slip fault showing the relation between the fault core/damage zone and protolith in outcrop. (B) Photomicrograph mosaic of CS-4 taken in XPL viewed at 40X shows the fault core displace the mudstone and sandstone of the Borrego Fm. (C) Photomicrograph of CS-6 in XPL viewed at 40x showing the DZ/protolith boundary of the Borrego Fm.

Figure 5. Shown here is the TDR unit being used along the NW striking dextral fault, measuring the bulk density in situ.

Figure 6. Close up of Figure 5 showing the placement of the TDR ground probe adjaent to the NW striking dextral fault.

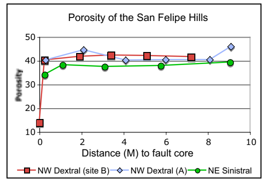


Figure 7. Porosity trends associated with the NW trending dextral and NE trending sinistral faults.

Equations

In order to assess the dependence of volumetric strains, changes in bulk mass, and changes in the mass of individual elements as a function of fault zone architecture, the mass balance arguments developed by Brimhall and Dietrich (1987) were used.

Bulk Mass, T

$$\mathrm{T} = \frac{c_i^o}{c_i'} - 1 \quad (1)$$

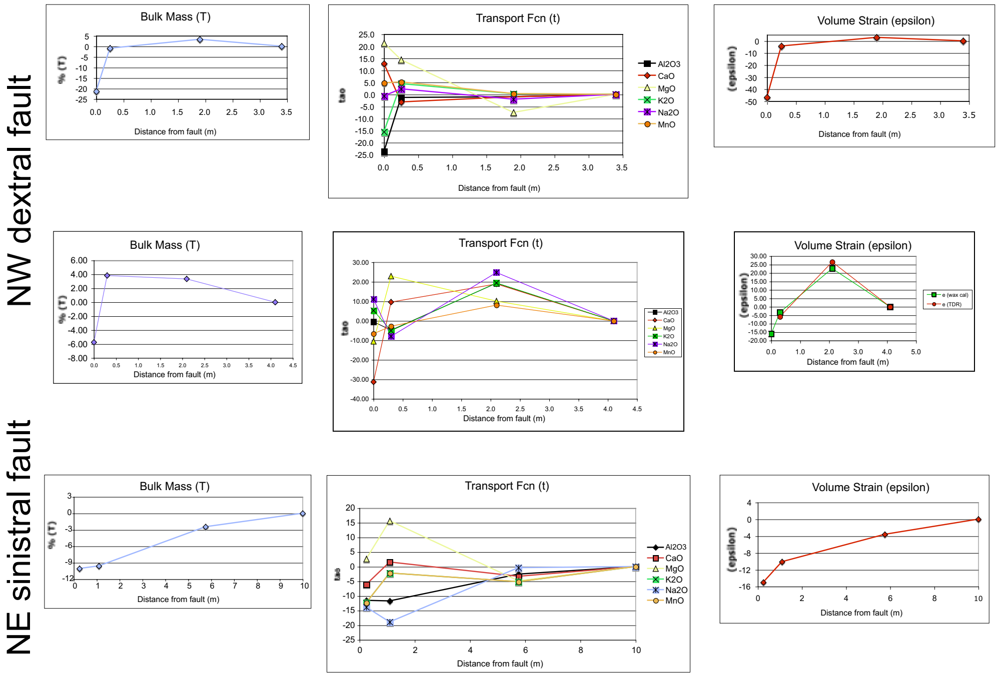
Transport Function, τ

$$\tau_i^j = \frac{c_i^o}{c_i'}\frac{c_j'}{c_j^o} - 1 \quad (2)$$

Vo lume Strain, ε

$$\varepsilon = \frac{\rho^o c_i^o}{\rho' c_i'} - 1 \quad (3)$$

Summary



The above plots illustrate the following.

(1) The function T decreases to negative values within a narrow 20-40 cm thick interval adjacent to the primary slip surface. This result suggests that there is a loss of bulk mass in this region.

(2) Volumetric strain values (ε) also decrease within the 20-40 cm interval adjacent to the primary slip surface.

(3) Changes in elemental mass indicated by τ values are variable from fault to fault.

References

Brimhall, G.H., and Deitrich, W.E., 1987, Constitutive mass balance relations between chemical composition, volume, density, porosity, and strain in metasomatic hydrochemical systems: Results on weathering and pedogenesis: Geochemica et Cosmochimica Acta, vol. 51, p. 567-587.

Chester, F. M., and Chester, J. S., 1998, Ultracataclasite structure and friction processes of the Punchbowl fault, San Andreas system, California, in Techtonophysics vol. 295, p199-221.

Dor, O., Rockwell, T.K., and Ben-Zion, Y., 2006; Geological observations of damage zone asymmetry in the structure of the San Jacinto, San Andreas, and Punchbowl faults in southern California: A possible indicator for preferred rupture propagation,Pure and Applied Geophysics, v. 163, p. 301-349.

Shipton, Z.K., Soden A.M., Kirkpatrick J.D., Bright A.M. and Lunn, R.J. 2006, How thick is a fault? Fault displacement-thickness scaling revisited. In: Geophysical Monograph Series, Volume 170, Earthquakes: Radiated Energy and the Physics of Faulting. Editors: Rachel Abercrombie, Art McGarr, Hiroo Kanamori and Giulio Di Toro