Progress report for 2009 SCEC Proposal

Title of Project:
Characterization of Pulverized Granitoids in the Little Rock Core Along the San Andreas Fault

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Data Gathering and Products
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Introduction

Pulverized fault zone rocks have become a recent focus of attention, having been recognized as a fundamental characteristic of the damage zone along large active faults, such as the San Andreas Fault (Dor et al. 2006, Rockwell et al. 2009), the Garlock Fault (Rockwell et al., 2009), the San Jacinto Fault (Stillings, 2007), and the Arima-Takatsuki Fault zone in Japan (Mitchell et al. 2009). All of the mentioned studies examined pulverized rocks from surface outcrops, where surface related processes can affect some of the fundamental properties of the rock. The generation of this particular damage type is not yet well understood, although efforts have been made to recreate similar pulverization damage in lab experiments (Doan and Gary, 2009).

In order to study pulverized rocks in detail and to understand their genesis, we obtained a nearly continuous (~95% recovery), 42 meter-deep, 6.35 cm diameter, oriented core of pulverized fault zone rock from a location adjacent to the San Andreas Fault near Little Rock, southeast of Palmdale (Fig. 1). Funds for drilling and coring, as well as core analysis were provided by previous SCEC grants. The core is composed mainly of granitic and granodioritic rocks, and crosses several secondary fault zones that contain gouge that is up to several cm thick. Our primary goal was to characterize the host rock and secondary fault zones mineralogy and the damage structure as a function of depth through the cored interval at the Little Rock site. We have examined the composition of the core and particle size distribution (PSD) as a function of rock type and depth. We also used SEM and probe technologies to investigate the different damage textures and chemical alterations seen in the rocks, and to try and determine relative timing of the various observed damage textures.

Area characterization

In order to put the core in context, we mapped the extent of the pulverized rocks outcrops in the Little Rock creek area, and collected and analyzed samples from various outcrops within the study area. We excavated and logged a shallow 20m long trench across the SAF for mapping and sampling purposes. The outcrop and trench samples were analyzed for PSD, major and minor element chemistry, and porosity. The PSD of the pulverized rocks changes as a function of distance from the fault, where the mean particle size increases further from the fault (Fig. 2). This demonstrates that pulverization is indeed fault related and that it is spatially correlated to the current active strand of the SAF and
is therefore a relatively shallow/young damage zone. Rocks up to ~300m away from the fault were still highly damaged – enough damage to enable us to measure their mechanical PSD. The samples that were taken from furthest away were quite intact and it was not possible to measure their PSD by mechanical methods. We used those samples as our benchmark for the original rocks composition, and compared them to our core samples (see below).

**Core characterization**

Point counts were performed on eight representative thin sections from various depths to determine the composition of the different rock types. The rocks are mostly granitic and granodioritic in composition. At the bottom of the core there is a dioritic rock body which appears darker in hand samples. The granitic samples appear pink in hand samples, are rich in quartz, and contain Ca bearing-plag, orthoclase, and minor amounts of white mica (muscovite?) and epidote. The granodioritic samples are less quartz rich, and contain Ca bearing-plag, albite, orthoclase, biotite that is partially replaced by chlorite (Fig. 3a), calcite, and titanite. The diorite has the least amount of quartz, and contains Ca bearing-plag, albite, orthoclase, biotite that is partially replaced by Chlorite and significant amounts of amphibole. The plagioclase in most samples is sericitized to various degrees (Fig. 3b). Two thin sections were taken from secondary fault zones; these contained ~40% clay-size minerals.

Elemental maps of distinct fault rock types were obtained in order to characterize the mineralogy and alteration reactions, and their relation to brittle fracturing. The elemental map images were produced in the Microprobe facility in TAMU by progressively rastering the electron beam point by point over an area of interest, to obtain the spatial distribution of 8 major elements - Si, Al, Na, Ca, K, Fe, Mg, and Ti. The element maps would then be combined to an index-color image, where every number represents a distinct elemental composition (Fig. 4).

**Porosity.** The porosity of the pulverized rocks, both in the core and in the surface samples was quite high, in some samples over 20%, while in the gouge zones the porosity was as low as 1%.

**Chemistry and PSD**

We have characterized the core composition by collecting and analyzing 85 samples from the cored interval at about ~50 cm spacing and from the secondary fault zones, as well as from comparable surface outcrops. For each sample we performed a full chemical analysis by XRF to determine the chemical composition using the Phillips MajiX Pro spectrometer in SDSU, and XRD of the fine (>2 microns) fraction to study clay mineralogy using the Phillips XRD machine in SDSU.
The XRF analysis results show that the three different rock types are indeed distinct in their composition. There appears to be depth variation in composition which occurs at certain depths for several elements (Fig. 5). In order to determine if the vicinity to a major fault zone had affected our samples chemistry, several samples from the furthest comparable rock exposure (about 500m away from the fault zone) were obtained and analyzed. The changes in bulk rock composition between the assumed protolith and the fault zone samples are minor. For granodiorites, the rocks are essentially the same. For granites, there is a slight increase in Fe, K, Ti, Ba, Y and Nb, and a strong depletion of Ca. We also compare the gouge samples to the host rock around them, and find that their composition falls between that of the granodiorite and the diorite in the core.

Figure 5: A. Depth variation diagrams of Al2O3, CaO, Zr and CIA. Grey zones mark zones with outlier samples. B. Major shears and alteration bands, as well as gouge zones in the core.
We convert our major element data to molecular proportions, and calculate the chemical index of alteration (CIA) following Nesbitt and Young (1982). We calculate:

1. \[ A = \frac{Al_2O_3}{Al_2O_3 + CaO + N_2O + K_2O} \]
2. \[ CN = \frac{CaO + N_2O}{Al_2O_3 + CaO + N_2O + K_2O} \]
3. \[ K = \frac{K_2O}{Al_2O_3 + CaO + N_2O + K_2O} \]

In A-CN-K space the proportion of molecular Al2O3 (A) is also the chemical index of alteration (CIA). An increase in CIA is expected for weathered samples, while for a typical un-weathered granitic rock, CIA should be about 0.5. The majority of the samples have CIA~0.5, which is consistent with little to no alteration of feldspatoids to secondary clay, a characteristic reaction during the weathering process. In other words, the samples do not follow the theoretical compositional changes seen during progressive weathering (Nesbitt et al., 1996) for granites. The only deviations are samples taken in the vicinity of secondary fault zones (Fig. 5), where there is enrichment in Ca.

The diffractograms from all our clay smears (<2 micron fraction) derived from the samples, regardless of depth or type, contain Illite (10.1A and 5A) and chlorite (14.25A and 7A). The typical Illite-Smectite (I-S) mixed layer diffractogram, that can be an indication of clay weathering, is recognized by the collapse of the Smectite peak (15-20A) and its shift into the Illite space after glycolation and heating. The I-S pattern is found in most of the surface samples taken from the adjacent outcrop, are similar to previous analyses of weathering products in surface samples (Stillings 2007, Rockwell et al. 2009). The diffractograms for granitic and dioritic rocks in the core do not have the I-S peaks, while the granodiorites have them only down to ~28m (Fig. 6). The gouge samples contain Illite-smectite and possibly Kaolinite. Kaolinite also appears in some of the Probe elemental maps.

All of the samples also were analyzed for PSD using a method that combines the Horiba laser analyzer and Camsizer in the Quaternary Lab at SDSU. This method was calibrated to the classical pipette-sieve method by measuring sieved fractions in the Horiba analyzer and comparing the results to measurements of grain size done under light microscopy using grain mounts of the same samples. Once calibrated, the Horiba data could be combined with the Camsizer to produce a PSD for each sample. PSD on 18 samples were compared to results obtained from the classical pipette-sieve method. Our calibrated measurements were very similar to the classical method results. The PSD of the core samples plotted vs. depth shows a small decrease of mean particle size with depth, and a significantly finer PSD in secondary faults gouge zones (Fig. 7). The PSD results were converted into D-values by assuming spherical
grains and converting the volumetric PSD to number of grains per diameter range, and calculating the power-law fit on a log-log scale, as done by previous authors. The D-values range is between 3 (for samples taken from secondary fault zones gouge) and 2.5, with a strong correlation between mean particle size and D-value (Fig. 7).

The distribution and characteristics of the pulverized particles and cataclastic zones indicate that multiple fracture-healing cycles occurred to produce an outcrop that reduces to powder when dug with a hammer. Most samples analyzed to date suggest that the cataclastic grain size reduction and shear at the microscale are significant processes in the formation of this pulverized zone. It is important to note that we could not distinguish between pulverized and cataclastic zones in the samples by eye only, due to the crumbly nature of the samples.

**Damage texture characterization**

Mapping using optical and SEM images of core samples at various depths and magnifications defines the distribution of two main fault rock types: pulverized zones displaying primarily opening-mode fractures, and distinct cataclastic fault zones (Fig. 8). The pulverized regions are composed of large host-rock crystals broken into angular grain fragments; the fragments often range from 10-100 microns in diameter. For the most part, the fractured parts maintain optical continuity across the fracture surfaces. These grains also display a high density of fluid inclusion trails suggesting repeated episodes of fracture and healing (Fig. 9). The healed fractures may be a result of pre-SAF deformation, reflecting cooling and exhumation of the igneous body. In contrast, the cataclastic zones are composed of smaller (0.5-10 microns) and more rounded grains, greater clay content,
and sometimes show repeated stages of calcite cementation and shear. Preliminary PSD analysis of the SEM images shows that the D-value of the pulverized regions is close to 2.5, as previously observed in other fault rock studies (Heilbronner et al. 2006, Sammis and Biegel 1989, Chester et al. 2005), while the cataclastic zones have a higher D-value, around 2.9, which is a bit lower than measurements of fault zone gouge (Fig. 10). Comparing those two values to the over-all D-value of an adjacent sample, obtained by the Horiba-Camsizer method, we see that its value is ~2.7, which falls between the pulverized and the cataclastic zones. This value can be explained by a mixture of grain populations, each corresponding to a different damage type. It is not possible to distinguish and separate the two types of deformation in a hand sample that is used for mechanical PSD measurements.

Figure 10: A comparison of D-values derived from mechanical method (left) and two SEM regions (right) for the sample LR023. The mechanical method gives 3-D volumetric distribution, while the SEM method is executed on thin sections and is therefore 2-D, hence the dimension difference in the D-values. The two regions selected for SEM particle size analysis are the same as in figure 8.

**Publications.** The chemical and mechanical PSD core characterization will be published in a soon to be submitted paper (Wechsler et al. in prep.). The surface transect analysis is a part of Katie Anderson’s Master thesis in SDSU. The SEM and probe results are now being analyzed and additional papers will be written about the PSD of various damage textures and about the chemical alterations and their relation to the brittle deformation.
References


Wechsler, N., Allen, E. E., Rockwell, T. K., Girty, G., Chester, J. S. and Ben-Zion, Y., Characterization of Pulverized Granitoids in a Shallow Core along the San Andreas Fault, Little Rock, CA, manuscript in prep.