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Contribution of Gouge Surface-Area to the Energy Balance of Earthquakes Along the San Andreas Fault

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SUMMARY

Our efforts were directed into two main directions.

The first direction was to further study the exhumed part of the San Andreas Fault (SAF) in the Tejon Pass area, California. In this area, where the SAF has undergone a right-lateral displacement of approximately 160 km, Wilson (2004) and Ramirez (1984) found that the fault zone include 3-4 main, subparallel segments trending N60°W, including the active segment of the SAF that slipped during the 1857 earthquake. The fault segments bound distinct zones of three types of fault rocks: pulverized granite, cataclasite, and organic shales.

The new main finding of the extension study indicate that (1) The fault rocks in Tejon Pass underwent multiple stages of fracturing, vein filling, healing and shear; (2) The dominant mechanisms of deformation in the fault-zone are pulverization, cataclasis, fluid-assisted processes, and local shear along planar micro-zones; (3) The micrstructure analysis supports the field observation of lack of slip parallel to the San Andreas fault; and (4). Based on the present results (exhumation depth of 3-5 km and slip history), we think that the Tejon Pass ares is the exposed equivalent of the San Andreas Fault drilled in SAFOD, close to Parkfield, California.

The second direction was devoted to analyze the properties of siliceous gouge samples from the San Andreas Fault as well as rupture-zones of recent earthquakes and fresh gouge that formed in rock mechanics experiments. The samples were analyzed in a few techniques: laser particle size analyzer, Zeta particle analyzer, TEM (dark-field and bright-field), and BET. We also explored various dispersion methods to disintegrate fine-grain gouge powder.

The TEM analysis (five samples: two from South African earthquakes, two from the San Andreas fault, and one from rock mechanics experiment) revealed that most grains have similar aspect ratios (up to 1:3), and that grains are angular to very angular. The samples display wide ranges of grain sizes (5 nm to 5 microns), and we used the dark-field and FFT-filter methods to map the internal structure of tens of aggregated grains ranging from a few nanometers to about 2 microns. With the exception of one grain, all examined grains are composites of 3 to more than 15 secondary grains that are as small as a few nanometers in size. These direct observations of the grain structure indicate that the true grain size of gouge powder is in the sub-micron range, probably within the 0.1 micron and below. The apparent abundance of particles in the 10-100 nanometer range in gouge powder has significant implications to earthquake energy balance and to slip weakening mechanisms as presented in the original proposal.

PUBLICATION LIST

Borges G., 2004, Characterization of the San Andreas Fault at Tejon Pass performed with Seismic Reflection. Thesis Project, 24 pp, University of Oklahoma, Norman, OK.

Reches Z, Tetsuya M, Strout G, Lockner D, Hamilton M, Heesakkers V, 2007. Gouge powder from earthquakes rupture zones and laboratory rupture experiments: Sub-microscopic observations and particle size distribution. AGU, 88(52), Fall Meet. Suppl., Abstract T11A-0338.

Reches Z, Tetsuya MD, Strout G, Lockner D, and Heesakkers V, 2007. New observations of gouge powder from rupture-zones of recent earthquakes, laboratory rupture experiments, and an active fault-zone. 2007 SCEC Annual Meeting, Sept. 8-12, Abs. & Proc., p. 164.

Reches, Z. Verrett, JD, Borjes, G., Dewers T., Witten, A, Brune, JN, 2006. Structure, Composition and Strain of the San Andreas Fault-Zone at Tejon Pass, California. Seismological Research Letters, 77 (2) 257.

Verrett JD, 2006, Structural and Compositional Analysis of Fault Rocks of the San Andreas Fault at Tejon Pass, California. MSc thesis, 114 pp, University of Oklahoma, Norman, OK.

Verrett, JD, Heesakkers, V, and Reches, Z, 2006. Structure and composition of the fault-zone of the San Andreas Fault in Tejon Pass, California. GSA, South-Central Section, Annual Meeting, March 2006, Abstract 11-3.

ABSTRACTS OF PUBLICATIONS APPEARS IN THE FOLLOWING PAGES

UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

STRUCTURAL AND COMPOSITIONAL ANALYSIS OF FAULT ROCKS OF THE SAN ANDREAS FAULT AT TEJON PASS, CALIFORNIA

A THESIS
SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

MASTER OF SCIENCE

By
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Norman, Oklahoma
2006

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ABSTRACT

We present here a study of the exhumed part of the San Andreas Fault (SAF) in the Tejon Pass area, about 80 km north of Los Angeles, California. At this site, the SAF juxtaposed two terrains, and has undergone a right-lateral displacement of approximately 160 km. The deep exhumation of 3-5 km of this region, as determined in this study, provides access to the deep part of the fault-zone.

The present work is based, in part, on the previous analyses by Ramirez (1984) and Wilson (2004). They found the SAF separates two juxtaposed terrains and has undergone a right-lateral displacement of approximately 160 km. They also found that the fault zone includes 3-4 main, subparallel segments trending N60°W that bound distinct zones of three types of fault rocks: pulverized granite, cataclasite, and organic shales, and faulted blocks of young clastic sediments and Neenach volcanics.

The present study includes field mapping of a 152 m long profile across the fault-zone in Tejon Pass, microstructural and compositional analysis on the fault rocks in thin-sections and electron microprobe, estimation of the exhumation depth, and discussion of mechanisms of formation of fault-rocks. The main findings are as follows. The pulverized granite, which appears as a solid rock, disintegrates into a white powder, and it contains multiple, small localized shear surfaces. The cataclasite is composed of the following four members: a white powdery member, a red member, a banded granite member, and a dark green-black member. The young sediments that probably originated in a lake environment are Quaternary and contain organic material, different colored zones, caliche, and many continuous faults. The many small faults and shear surfaces

throughout the outcrop display transport direction, which is normal to trend of the San Andreas fault.

The microstructural analysis reveals several generations of microfaults and veins filled with alteration minerals and microshear zones. The results indicate that fluid was restricted to the fault-zone causing significant mineral alteration. Vein mineralization, mostly laumontite, is an important implication to the depth of exhumation of the fault zone. Based upon laumontite-calcite-chlorite mineral assemblages in both the pulverized granite and cataclasite, we estimate the depth of exhumation for Tejon Pass to be 3-5 km.

The main findings of the study indicate that (1) The fault rocks in Tejon Pass underwent multiple stages of fracturing, vein filling, healing, and shear; (2) The dominant mechanisms of deformation in the fault-zone are pulverization, cataclasis, fluid-assisted processes, and local shear along planar micro-zones; (3) The microstructural analysis supports the field observation of lack of slip parallel to the San Andreas fault; and (4) Based on the present results (exhumation depth of 3-5 km and slip history), we think that the Tejon Pass area is the exposed equivalent of the San Andreas fault drilled in SAFOD, close to Parkfield, California.

THE UNIVERSITY OF OKLAHOMA
SCHOOL OF GEOLOGY AND GEOPHYSICS
ADVISOR: ALAN J. WITTEN

CHARACTERIZATION OF THE SAN ANDREAS FAULT AT TEJON PASS PERFORMED WITH SEISMIC REFLECTION

Gabriel Borges (December 2004)
Thesis project

ABSTRACT

I have characterized the San Andreas fault in Southern California, at Tejon Pass, achieving a seismic interpretation along an almost 600 m path where was expected to localize three sub-parallel segments separated by three faults. These segments stepped one another, were found at the transect, beginning by the southernmost that I interpreted as the Hungry Valley Formation, where the first fault appeared separating this formation from the Tejon Lookout Granite which is followed the casaclasite zone. This contact is visible at the seismic profile as an abrupt change in the frequencies that got higher at the casaclasite. Then, the transect shows another fault which I have interpreted as the fault that separates the Quaternary sediments from the former block. A third fault was identified and I set this fault as the one that depict the separation of the Quaternary deposits and the Neenach Volcanic Formation, which is interrupted by another block with similar elastic properties to those of the Quaternary deposits, as I have interpreted in a sudden change in the frequencies and a non expected fault that follows the trend of a fault recognized by the geologic reconnaissance but though to end farther southeast from the area of our study.

INTRODUCCTION

The structure of a fault system is featured by its seismic activity and slipped displacements. Tejon Pass represents a critical witness of the San Andreas fault history harboring vestiges of very intense seismic activity in the past. Suitable area for its good outcrops, Tejon Pass is also a great location for the study of the San Andreas fault, because it depicts a high uplift rate area that has risen 2-5 millimeters by year (Smith and Sandwell, 2003) disclosing exhumed features of San Andreas fault zone, that could reach more that 4 Kilometers of depth if we assume that this rate has been the seem since the Pliocene and we take into account the effect of recurrent erosion to this uplift trend.

Tejon Pass is embedded in what is called by geologist the Big Bend (Hill and Dibblee, 1953) at the San Andreas fault zone. It has been divided into three 100 meters wide zone main segments, with quasi-linear and discontinuous traces, stepped one another and featuring a few small pull apart linear valleys, and sag ponds (Ramirez, 1984). The southernmost segment divides The Hungry Valley Formation and the Tejon Lookout granite, this last rock body extends for almost 1 Kilometer along the San Andreas fault and has been pulverized acquiring a powder

consistency. The second and central segment is the only currently active. This segment divides the Tejon Lookout granite and a 50-60 m wide block of Quaternary sediments that lay filling a small pull apart. A cataclasite zone is observed at the zone separating these two main rock bodies. The third segment separates the Quaternary deposits from the Naneech Volcanics and marble (Reches and Dewers, 2004)

One of the most used geophysical methods for featuring the upper crust is the seismic reflection. This technique was performed across the Tejon Pass area in order to visualize interesting geological structures such as these three faults that separate the segments described former. The acquisition consisted in three 48 geophones continuous lines and one 24 geophones line along a steeped terrain. The space between the geophones was 4 meters and the array depicted was conformed by five sources off each extreme of the lines and all along the geophones in the half of the distance between them.

The source was a sledge hammer beating a flat aluminum plate, releasing a source that created a response from the subsurface recorded as individual files of data, acquired as 1024 temporal samples taken at 1 millisecond sampling. Electromagnetic induction was either performed in the area. The processing of the data contemplated a simple computational processing method introduced by A.Witten, B. Witten and R. Slatt. This computational processing attempts to synthesize the response to a plane wave that penetrates straight downward on a variable terrain, with a time-shifted sum over any data set displayed from an array or sources and geophones

LOCALIZATION OF THE AREA OF STUDY

The area where the study has been done is at Tejon Pass localized on the northern part of the Tranverse Ranges of Southern California, along the Interstate 5, at almost two miles northwest of Gorman, California.

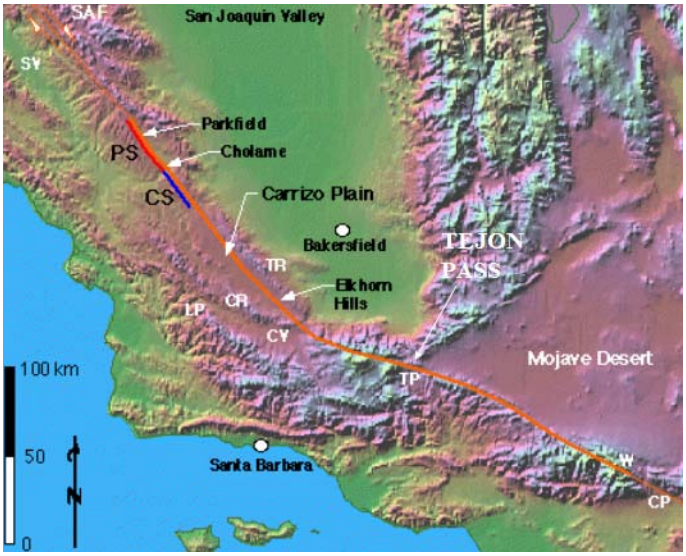


Fig 1. Tejon Pass and the San Andreas fault

CONCLUSIONS

Seismic reflection is a valuable tool in the characterization of the shallow geological features. We achieved to identify fairly three fault expected and another one non expected following reflectors along a seismic profile regarding of abrupt discontinuities that cause the contact of two different layers with clear differences in their elastic properties.

The processing performed depicts an easy way of synthesize the response of a plane wave penetrating straight down. The events that were recorded as elliptical features, passed to be horizontals with this processing, summing all the contribution of all the sources on every channel. By the other hand, we saw the effect of the irregular terrain in a seismic profile, and programming to solve this out was accomplished with visible results. The delays caused for the time spent on traveling across this sloped surface was removed with the direct wave speed and the source and receiver locations.

The seismic profile obtained was adjusted to that expected for the geological reconnaissance. Further it is relevant to regard the fact that using more than one geophysical method, we can guarantee that what a seismic profile is depicting is reliable. In this sense, the Electromagnetic induction method is another important tool that geophysics have for matching the information provided by a seismic survey. The match obtained in this study fairly demonstrated the reliability of the results.

Tejon Pass, California: A view into the deeply exhumed, yet active fault-zone of the San Andreas

Ze'ev Reches (reches@ou.edu), Joni Verrett, Gabriel Borges, Alan Witten, Tom Dewers (all in U of Oklahoma), and James Brune (U of Nevada)

In memory of Alan Witten, a colleague, a friend and a teacher.
Alan Passed away on February 13, 2005, two months after our fieldwork at Tejon Pass.

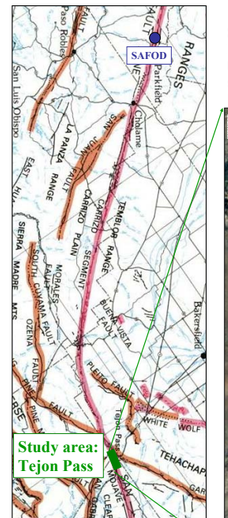
The San Andreas Fault in Tejon Pass area, Southern California, was exhumed to an estimated depth a few kilometers. We study the structure and composition of the San Andreas fault-zone in this area by field mapping of a region of ~1.5 km by 100-200 m along the San Andreas, grain-size analysis of the fault rocks, seismic profile across the fault-zone, as well as meso-structural and micro-structural analyses.

The local fault-zone (based on mapping and seismic profiling) includes 3-4 major fault segments of the San Andreas (at least one is currently inactive) trending N60°W direction. These segments bound four zones:
(1)A gouge zone, 50-100 m wide, composed of **pulverized granite** with extremely fine-grain (Wilson et al., 2005).
(2)A 0-15 m wide zone of **cataclasite**/ultracataclasite with 5-6 colored, subparallel banded zones that dip steeply toward N30°E;
(3)An elongated pull-apart basin (~ 50 m wide) filled with **young sediments**; and
(4)A ~1 m wide zone of dark, **organic shale** that marked the segment which slipped during the 1857 earthquake.

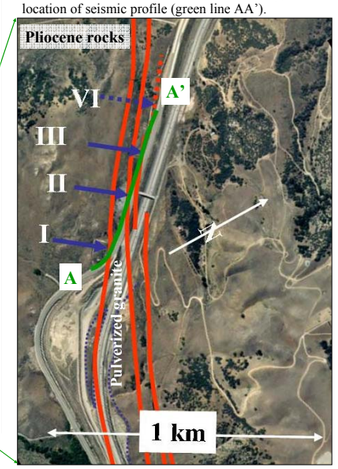
The dominant meso-structures in the first three zones are slickensided small faults that indicate transport direction normal to the trend of the San Andreas Fault. We noted a lack of meso-structures with slip indicators parallel to the San Andreas Fault. This pattern is observed also in the micro-structural analysis

We used XRD, electron-microprobe and microstructural techniques to analyze the alteration minerals within veins and fracture zones in the rocks units (1) and 2) above. The alteration minerals assemblages suggest that the pulverized granite and banded cataclasite were deformed and damaged at depth of 3-5 km.

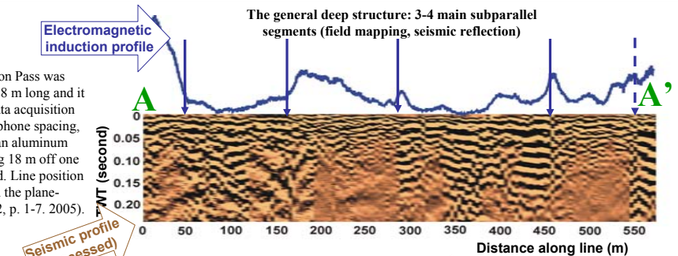
Macrostructure

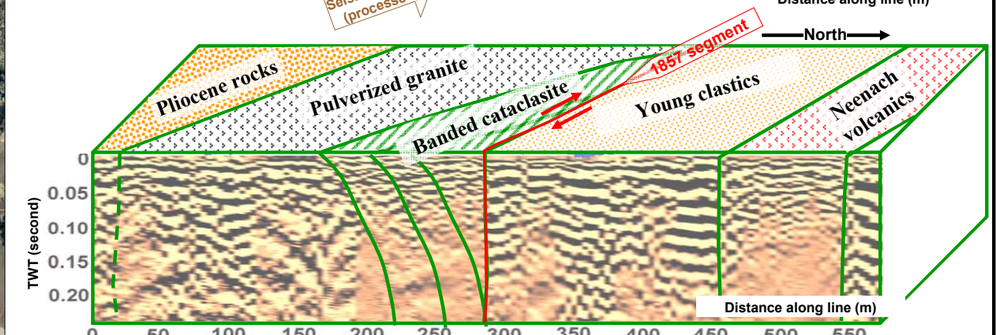


Simplified map of the San Andreas fault in Tejon Pass. Highway 5 is the grey curve from top to bottom and the with bridge at the center. The map shows the main fault segments I-IV (red lines), and location of seismic profile (green line AA').



The subsurface structure of the San Andreas at Tejon Pass was analyzed with our seismic profile. The profile is 588 m long and it crossed the fault-zone at an angle of about 20°. Data acquisition system included a 48 geophones line with 4 m geophone spacing, and the energy source was a sling hammer hitting an aluminum plate. Hitting was conducted at 4 m spacing starting 18 m off one end of the line, and finishing 18 m off the other end. Line position was measured with GPS. Data processing followed the plane-wave procedure of Witten et al., (J. Geophy. Eng. 2, p. 1-7. 2005).



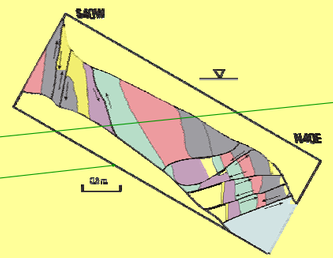


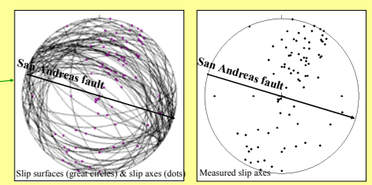
A 120 m long view of the exposure of the SAN Andreas fault along Highway 5. The 1857 slip occurred along segment.

Mesostructure

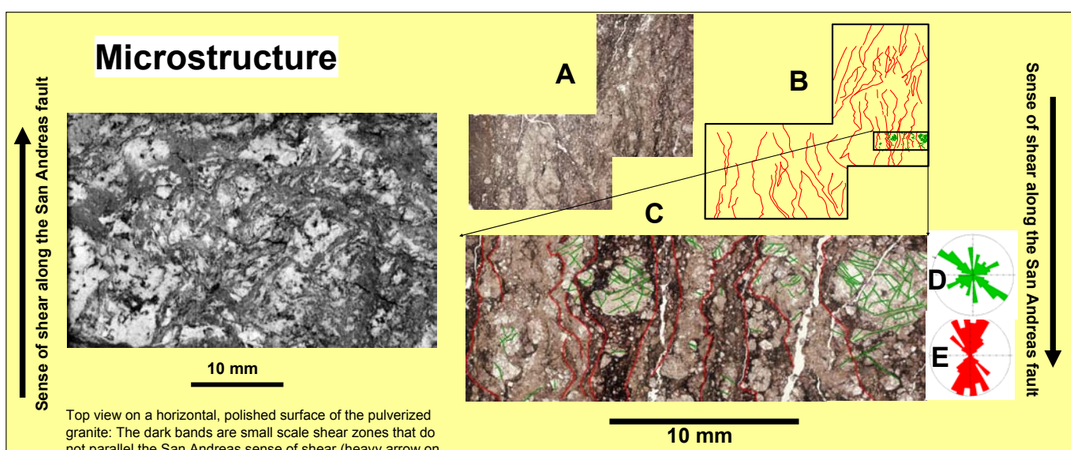
Sense of transport
The dominant transport direction along the many slip surfaces within the **pulverized granite** (streonet projection of small faults with slickensides), and the **banded cataclasite** (cross-section normal to the SAF) is normal to the San Andreas, displaying either normal or reverse dip-slip motion.

There is a striking lack of slip surfaces and slip striations that parallel to the San Andreas fault.





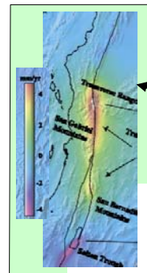
Microstructure



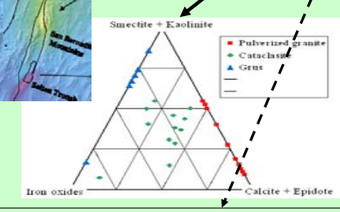
Top view on a horizontal, polished surface of the pulverized granite: The dark bands are small scale shear zones that do not parallel the San Andreas sense of shear (heavy arrow on left).

Top view on horizontal, thin-sections of the banded cataclasites (A); microstructural map of the bands (red lines in B); detailed map of bands (red lines) and microfractures (green lines(in C).
NOTE: The general trend of the bands (rose diagram in E) is subparallel to the San Andreas sense of shear (heavy arrow on right), but most of the microfractures are 30° -40° from the SAF (rose diagram in D).

Depth of exhumation: evidence from mineral alteration

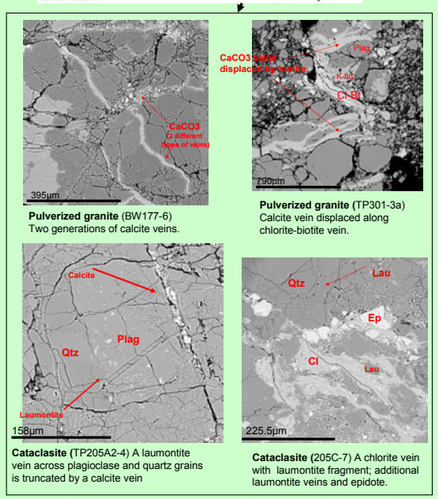


Models of slip along the SAF indicate uplift rates of 3-5 mm/yr at Tejon Pass area (Smith & Sandwell, 2002).
We examine the depth of exhumation due to this uplift by analysis of the alteration mineral within veins and fracture zones. We used XRD, electron-microprobe and microstructural techniques.



The main conclusions:
A. The pulverized granite and cataclasite from the fault-zone underwent a few cycles of damage and healing at elevated temperature (> 100°).
B. The alteration minerals (mostly laumontite and calcite, with some epidote, chlorite and quartz) suggest exhumation depth of 3-5 km.

Rock Type	Alteration Minerals; shown by relative abundance in XRD analyses (green columns), and electron microprobe analyses (blue columns)					Estimated timing of alteration relatively to fault-zone damage; based on filling vein relations			Depth of Alteration (km) [estimated for 45°/km]
	Laumontite	Calcite	Epidote	Chlorite	Smectite	PRE-damage	SYN-damage	POST-damage	
Pulverized Granite (17 samples)									~3-5
Cataclasite (17 samples)									~3-5
Grus (8 samples)									Shallow
Undeformed granite (1 sample)	No alteration								
Organic clay									Shallow

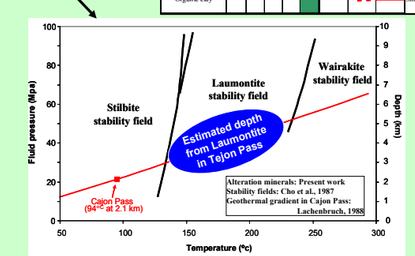


Pulverized granite (BW177-6) Two generations of calcite veins.

Pulverized granite (TP301-3a) Calcite vein displaced along chlorite-biotite vein.

Cataclasite (TP205A2-4) A laumontite vein across plagioclase and quartz grains is truncated by a calcite vein

Cataclasite (205C-7) A chlorite vein with laumontite fragment; additional laumontite veins and epidote.



Discussion:

- Is the observed structure (3-4 main segments that form a 100-200 m wide fault-zone) typical at 3-5 km depth?
- Is the exhumed structure at Tejon Pass similar to the drilled structure in SAFOD?
- Pulverization mechanism: dynamic earthquake propagation?
- What are the implications of lack of evidence for "fault-parallel shear"?

GOUGE POWDER FROM EARTHQUAKES RUPTURE ZONES AND LABORATORY RUPTURE EXPERIMENTS: SUB-MICROSCOPIC OBSERVATIONS AND PARTICLE SIZE DISTRIBUTION

We examine grain features and estimate the particle size distribution (PSD) in gouge collected from three sources: rupture zones of two recent earthquakes in South African mines (m3.7 event in 1997 and m2.2 event in 2004); unstable faulting experiments of quartzite cylinders; and the San Andreas fault-zone at Tejon Pass, California. Studies in nanotechnology indicate that PSD measurements of fine powders are susceptible to major errors due to aggregation and agglomeration of the fine particles that cause a systematic bias toward coarser PSD. Thus, our central analytical objective is to determine the true grain size of the gouge that forms during an earthquake and we have employed several techniques. In the TEM (Jeol-2010F) we use bright-field and dark-field modes for magnifications smaller than 200,000, and FFT-filtering mode for high-resolution (HREM) magnifications of 200,000-500,000. We also test several methods to disperse the agglomerates (with ethanol, silanes and toluene) and measure the PDS in the Dynamic Light Scattering method (using the Zeta particle analyzer ZetaPALS-90Plus of Brookhaven Instruments).

The grains in the TEM analyses of eight gouge samples display similar shapes: aspect ratios range up to 1:3 with small amounts of very elongated grains, and most grains are angular to very angular while grains of the rock mechanics experiment are the most angular. The samples display wide ranges of grain sizes (5 nm to 5 microns). However, quantitative PSD cannot be determined as most (if not all) grains appear in clusters and aggregates that are inseparable in the bright-field mode. We thus use the dark-field and FFT-filter methods to map the internal structure of tens of grains ranging in size from a few nanometers to about 2 microns. With a few exceptions, all examined grains are composites of 3 to 15 (and probably more) secondary grains that are as small as a few nanometers in size. The PSD of these samples is measured with the Zeta analyzer with resolution range of 1 nanometer to 3 micron. For half of the samples we use unsieved gouge powder and for the other half we use the smaller than 63 micron fraction of the gouge. Several dispersion methods are used. The observed PSD is multimodal, and with the exception of one sample, the grain sizes are 0.1-1.0 micron. The TEM direct observations of the agglomerate internal structure indicate that the true grain size of gouge powder is in the sub-micron range as confirmed by the Zeta analyzer. We currently attempt to quantify the abundance of particles in the 10-100 nanometer range in gouge powder by testing nanotechnology dispersion techniques. We discuss the significant implications of such fine grains to earthquake energy balance and to slip weakening mechanisms during earthquakes. This study was supported by a SCEC 2007 grant and by NSF Continental Dynamic grant 0409605.