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OBSERVATIONS, INFERENCES AND CONSTRAINTS FROM OPTICAL, SEM AND TEM ANALYSES OF GOUGE AND CATACLASITE FROM THE SAN ANDREAS AND SAN GABRIEL FAULT ZONES

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Abstract

Two recent studies of the size distribution of fragments in cataclasite and gouge from exhumed fault zones suggest new ways that fault zone structure might be used to constrain the temperature, stress, and strain-rate during an earthquake. Chester et al. (2005) found that the particle distribution in cataclasite from the core of the Punchbowl fault is fractal (with dimension D=2.0 in 2-D section) down to a fragment size of 40 nanometers, and that smaller particles can be seen down to 4 nanometers. Wilson et al. (2005) also observed 40 nanometer size particles in gouge adjacent to the core of the San Andreas Fault in the Tejon Pass in southern California.

The observation by Chester et al. (2005) that the fractal dimension of strained ultracataclasites is D=2 in 2-D section is consistent with other studies that have found that the fractal dimension in highly strained fault zone rock is larger than the D=1.6 commonly observed in low-strain gouge and fault breccia. Sammis and King (2007) extended their model for "constrained comminution" at low-strain fragmentation, which predicts D=1.6 (Sammis et al., 1987) to high-strain fragmentation which predicts D=2.0, and a systematic reduction of the upper fractal limit with strain.

Wilson et al. (2005) also observed nanometer-sized fragments in fault gouge from the San Andreas fault in the Tejon Pass north of Los Angeles, which raises the same questions about their formation and survivability discussed above – although temperatures are not expected to rise as high in the fault gouge during an earthquake as in the ultracataclasites. However, they also challenged prior observations that fault gouge has a fractal size distribution, suggesting that previously observed fractal distributions were artifacts of partial disaggregation.

We began our research by examining gouge samples from the Tejon Pass to better understand the hypothesis of Wilson et al. (2005) that extreme disaggregation destroys the fractal distribution of fault gouge. It is important that their result be checked, first because they cast doubt on all prior fractal observations, and second since it implies a very large contribution from fragmentation to the energy budget of an earthquake.

A key objective of the research program funded last year was to characterize gouge from the Tejon Pass using optical microscopy to see if it could be described by a fractal distribution of particles formed from cemented gouge grains, or, if it is a more uniform distribution of very smalll particles that require long periods of disaggregation to get the true distribution formed in the last earthquake. Our preliminary results have found broad particle size distributions more consistent with a fractal particle size distribution. Also, most of the larger grains were single crystals and not healed composites of smaller grains.

This work has resulted in one publication:

Sammis, C. G., and G. C. P. King, Mechanical origin of power law scaling in fault zone rock, *Geophys. Res. Lett,* ***34***, L04312, doi:10.1029/2006GL028548, 2007.

Summary of Results During This Award Period

Detailed studies of fault zone structure are motivated by two fundamental and related questions: 1) how does the structure form, and, more significantly, does it contain information about prior earthquakes on the fault, and 2) how does the existing fault structure affect the propagation of a subsequent earthquake rupture.

During this award period we chose to focus on the first question, and specifically ask what can be learned from the texture and particle distributions in the cataclasite, gouge and breccia? Our short answer is that the fractal dimension may give a measure of the accommodated strain and the minimum grain-size should place constraints on the mode of fragmentation, the strain rate and the maximum temperature-time pulse during faulting. A primary objective of our research program is to experimentally and theoretically explore these constraints to see if they are consistent with recent poroelastic models of earthquake slip in a granular fault zone.

A key objective of this research program is to characterize gouge from the Tejon Pass using optical, SEM and TEM microscopy. We decided to continue our analysis of these samples from the San Andreas Fault to see if we can develop the following five constraints on the mechanics of recent earthquakes:

1) Use the fracture surface area to estimate the contribution of off-fault damage to the fracture energy of an event.
2) Use the fractal dimension and the upper fractal limit to estimate the local strain as a function of position in the fault zone.
3) Use the minimum fragment size to constrain the loading mode, the stress, and the strain-rate, under which it could be formed during an earthquake.
4) Also use the minimum fragment size, in combination with grain growth kinetics to constrain the temperature-time pulse during faulting.
5) Use the morphology of "exploded grains" to search for evidence of macroscopic tension.

Thus far we have made significant progress toward Constraint 2 by developing a model that can explain the fractal dimension of D=2.0 reported by Chester et al. (2005). This work resulted in the publication of an article by Sammis and King (2007).

Mechanical Origin of Power Law Scaling in Fault Zone Rock

Motivated by Chester et al.(2005), Sammis and King (2007) extended the constrained comminution model of Sammis et al. (1987) to the case of large strains. At low strains the elimination of same-sized nearest neighbors was shown to produce a power law distribution characterized by a fractal dimension $D_3 = 2.6$ (Fig. 1). With increasing shear strain these isolated same-size neighbors can now collide causing one of them to fracture (Fig. 2). The probability of two same size neighbors colliding and fragmenting in a simple shear flow is a simple function of the size and density of the two particles. By assuming that a particle fractures only when it collides with a same-sized particle during shear flow, they found that any starting distribution will evolve to a fractal distribution with $D_2 = 2$ (in 2D section). They also demonstrated that this is a stable value; if $D_2 < 2$, larger particles will be preferentially fractured and the slope will increase toward the stable value $D_2 = 2$. If $D_2 > 2$, then the smaller particles will be preferentially removed and the slope will decrease toward $D_2 = 2$. Their model also works in 3-D where an arbitrary distribution of particles was shown to evolve to a stable fractal distribution with dimension $D_3 = 3$.

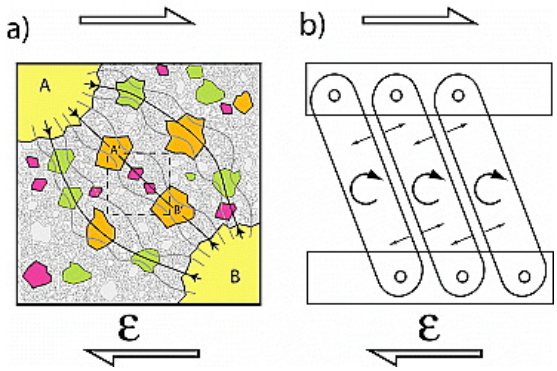

Figure 1. Low-strain fault gouge. (a) Stress paths. The stress between the largest particles shown (A and B in yellow) is transferred by a number of paths. Within the dashed square inset, the same geometry occurs at a smaller scale where the largest particles are now A′ and B′ in orange. This self-similarity can occur at successively smaller scales. (b) Grain bridges form when the material is strained. The increase in stress along the bridge causes particles to fracture in tension. The reduction in normal stress perpendicular to the bridges (associated with the rotation) further enables this tensile splitting. At any scale the tensile stress within a particle is greatest when in contact with a particle of similar size. Thus one of two adjacent particles of the same size is preferentially broken.

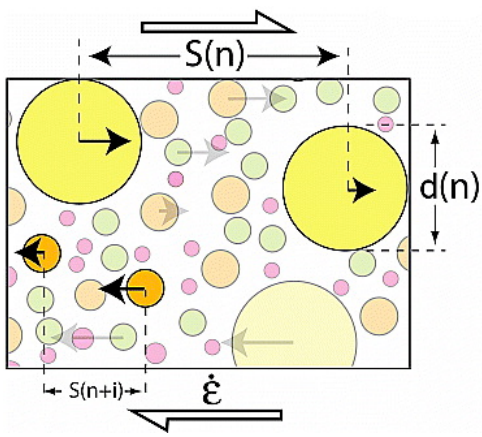

Figure 2. High strain fault gouge. For large strains, particles of the same dimensions that are isolated in the low-strain comminution can, as a result of flow, come into contact and cause one to fracture.

Sammis and King (2007) illustrated the stability of $D_f = 2$ with a simple automaton that uses a random number generator to choose the particle size to be fractured at each time step using the relative fracture probabilities predicted by their model.

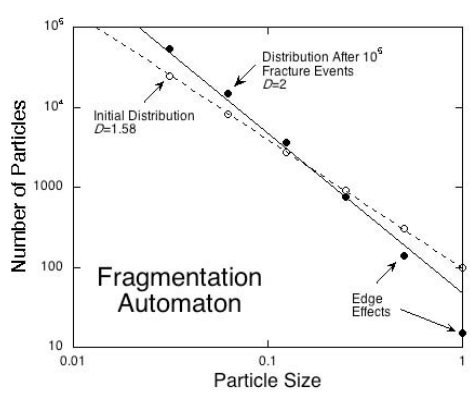

Figure 3. Evolution of an initial particle distribution having D=1.58 into one having D=2.0 using the fragmentation automaton described in the text. The deviation of large particles from the D=2.0 line is an edge effect, since there are no particles being supplied at this end of the distribution from the fragmentation of still larger particles. (From Sammis and King, 2007)

The number of particles in the chosen class is decreased by one, while the number in the next smaller class is increased by four. The relative probabilities are then recalculated using the new values for the particle distribution, the selection process is repeated, and so on. Figure 3 shows the evolution from an initial Sierpinski distribution $D_f = 1.58$ toward the stable value of $D_f = 2$. Note that the lack of larger particles

produces an edge effect that can look like a fractal dimension greater than $D_f = 2$ over a limited range of grain sizes at the upper limit of the distribution. Our hypothesis is that this "upper fractal limit" may give a quantitative estimate of the total strain.

Ananlysis of gouge and cataclasite from the San Andreas Fault Zone

In parallel with developing a mechanical model for gouge evolution, we are attempting to tie our model to field observations of fault gouge from the San Andreas Fault. Toward that goal, we sampled a profile across the San Andreas Fault zone at Tejon Pass (Fig. 4) and prepared thin sections at each site (Table 1). Representative photomicrographs are shown below. Our hope is that in some future funding period we can use optical microscopy and SEM to *measure* the particle size distributions, and use TEM to search for the *minimum* particle size. We also have samples of cataclasite from the San Gabriel Fault (Anderson et al., 1983) for which we also plan to measure the particle size distribution to as small a scale as possible.

1) Site Location

We sampled the fault gouge exposure of the San Andreas fault in Tejon Pass at the site used by Wilson et al. (2004). Five samples were collected at the sites in Fig. 4 as detailed in Table 1.

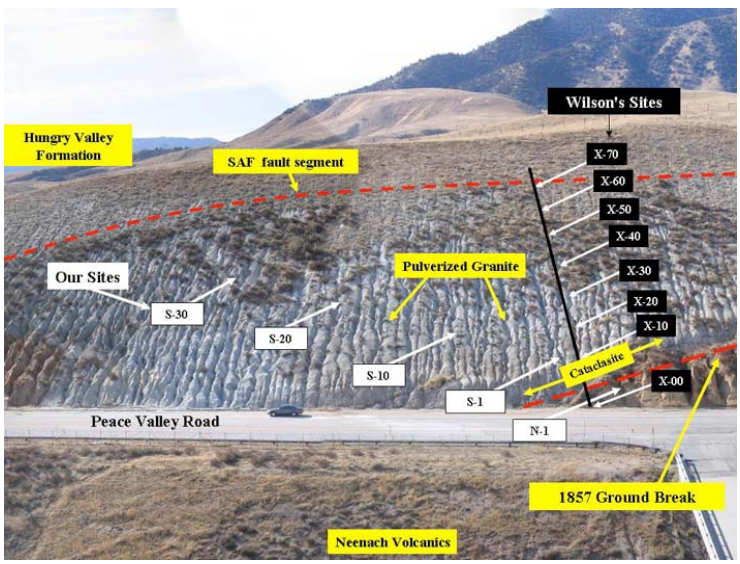

Figure 4. Gouge exposure on the south side of I-5 at the Tejon Pass. The red line in the lower right corner is the 1857 ground rupture. The red line in the upper left corner is an older trace of the fault. The picture faces southwest. Sample sites currently under investigation have white labels. Sample sites used by Wilson et al. (2004) are indicated by black labels.

Table 1. Description of samples from Tejon Pass

Sample Name	Distance from1857 Fault Trace	Comments
S-1	~1 m SW	Cataclasite (3 orthogonal sections)
S-10	~10 m SW	Gouge
S-20	~20 m SW	Gouge (3 orthogonal sections)
S-30	~30 m SW	Gouge
N-1	~1 m N	Cataclasite

2) Preliminary Observations

At the macroscopic scale, all of the sites had dark colored, nearly vertical layers of fine-grained fault gouge trending subparallel to the 1857 fault rupture. Samples from the five sites were epoxy impregnated, cut into thin sections and polished. Three orthogonal thin sections were made from samples at two sites, S-1 and S-10. Figure 5 is a typical digital micro-photo taken in reflected light.

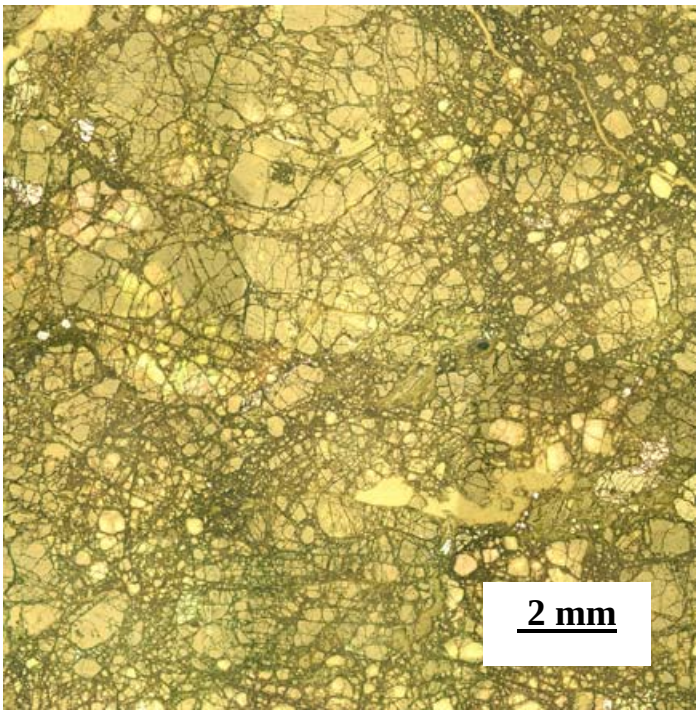

Figure 5. Photo-mosaic in reflected light from site S-1. Note many particles with diameters > 1 mm. Site S-1 is in the cataclastic layer ~1 m south of the 1857 fault trace (Fig. 4).

When we examined our suite of thin sections, we observed a heterogeneous structure at the microscopic scale similar to that often observed at the macroscopic (road-cut) scale. Some regions contained many grains with diameters >1 mm, while other regions contained very few large grains. The fine-grained regions formed contiguous bands surrounding the coarse grained regions suggesting flow.

3) "Exploding grains"with diameters greater than 1 mm.

It is intriguing that many of the larger grains in the sections seem to be "exploding" by breaking apart into angular sub-grains (Fig.6). These "explosions" do not appear to be isotropic as would be expected for hydrostatic unloading. Another interesting finding we made was a fine matrix visible between particles that were probably once intact. One of our future objectives will be to use the orientations and displacements of these fractures that are breaking up the individual grains to determine the dynamic strain field. We want to know if the strain tensor is uniform across the entire thin-section as would be expected in the case of macroscopic unloading? Or is the strain different at each grain or neighborhood of grains as would be expected if the explosions are due to local loading by neighboring grains? Orthogonal sections will allow us to do this analysis in 3D.

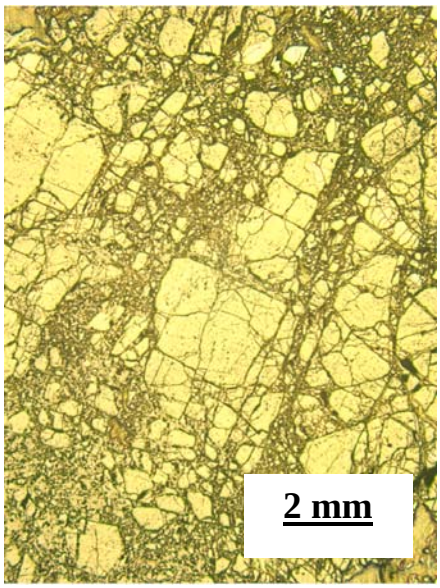

Figure 6. Fault gouge with a large "exploding" grain (identified as quartz in transmitted light). Note that the tensile fracture appear to have preferred orientations. We are not certain if these orientations are controlled by mineral cleavage or the stress field.

4) Localized shear zones with grain diam <1 micron

A second set of interesting structures we identified were localized bands that appeared to contain high concentrations of fine-grained matrix, probably composed of submicron sized particles (Fig. 7). A single localized band of variable width often spanned an entire thin section.

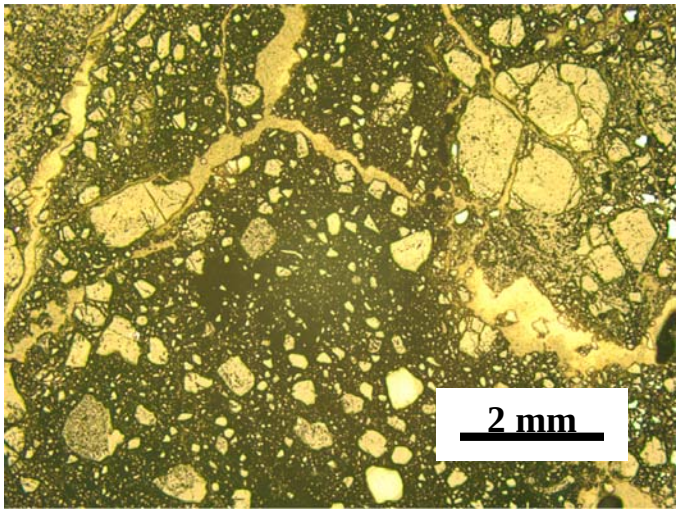

Figure 7. Photograph in reflected light of a localized band. Note the large fraction of unresolved matrix. These areas will require use of SEM and TEM to identify and characterize submicron size grains.

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