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Using drill cutting separates to estimate the strength of narrow shear zones at SAFOD

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[1] A technique is presented for estimating frictional strength of narrow shear zones based on hand selection of drillhole cuttings separates. Tests were conducted on cuttings from the SAFOD scientific drillhole near Parkfield, California. Since cuttings are mixed with adjacent material as they travel up the drillhole, these fault-derived separates give a better representation of the frictional properties of narrow features than measurements from the bulk material alone. Cuttings from two shear zones (one an active trace of the San Andreas fault) contain a significant weight percent of clay-rich grains that exhibit deformation-induced slickensides. In addition, cuttings from the active SAF trace contain around 1% serpentine. Coefficients of friction for clay-rich and serpentine grains were 0.3–0.5 and 0.4–0.45, respectively. These values are around 0.12 lower than the friction coefficient of the corresponding bulk cuttings, providing an improved estimate of the frictional strength of the San Andreas fault. **Citation:** Morrow, C., J. Solum, S. Tembe, D. Lockner, and T.-F. Wong (2007), Using drill cutting separates to estimate the strength of narrow shear zones at SAFOD, *Geophys. Res. Lett.*, *34*, L11301, doi:10.1029/2007GL029665.

1. Introduction

[2] The San Andreas Fault Observatory at Depth (SAFOD) drillhole passes through numerous shear zones, including at least one actively deforming trace of the San Andreas fault [*Hickman et al.*, 2005]. However, only cuttings and limited spot cores are available from Phases 1 and 2 of drilling for determining the mechanical properties of the shear zones and rock formations encountered. Since cuttings at SAFOD are collected over a depth range of 3 m, and may be further contaminated by material from shallower formations as they travel up the borehole to the surface, important features such as faults and shear zones that may be less than a meter thick can be masked in the bulk samples.

[3] *Tembe et al.* [2006] reported on the frictional properties of washed cuttings from 1890 m measured depth (MD) to 3991 m MD, corresponding to the interval between the granite-sedimentary boundary and the bottom of the hole at the end of Phase 2 (1.85 to 3.1 km true vertical depth). They found a range of values depending on lithology, with friction, μ (=shear stress/effective normal stress), ranging from 0.4–0.55 in the shale, claystone and siltstone units, and $\mu \geq 0.6$ in the quartzo-feldspathic rocks (Figure 1, dark shaded area). Spot cores provide a more precise look at specific depths. For instance, at 3067 m MD, the borehole encountered a narrow shear zone approximately 0.3 m thick and composed of 62–69% illite and illite-smectite phases. The coefficient of friction of this core material was 0.40–0.45 (Figure 1), 33% weaker than for cuttings from the same depth. This narrow shear zone was situated adjacent to several meters of a granite-derived arkose, and it is not surprising that the higher friction of the arkosic material dominated the strength of the cuttings from the shear zone interval. *Tembe et al.* and others have estimated that the shear zone would have to be at least 2 to 3 meters thick in order to be detected unambiguously in the cuttings.

[4] In this paper, we explore a technique for estimating the frictional strength of such narrow structures based on the extraction of selected cuttings from regions identified as potential shear zones based on borehole geophysical logging data. Our procedure is to use velocity, breakout, resistivity, caliper and televiewer data to identify possible shear features in the borehole. Next we analyze the cuttings from the corresponding depths to identify material likely to be associated with faulting. We also look at zones above this level to check for differences in composition that might help to uniquely identify the area of interest. Shearing-related grains are plucked from the bulk material, and finally, both the bulk and plucked materials are characterized by XRD and mechanical tests.

[5] As a test of this technique, two shear zones were identified using this method from a depth of 2551 m MD (part of an interval containing multiple shears) and 3322 m MD (an active trace of the San Andreas fault). In both cases the bulk cuttings contain a significant weight percent of clay-rich grains that exhibit slickensides, indicating in-situ fault deformation. *Schleicher et al.* [2006] describe this material in more detail. In addition to the slickensides, cuttings from 3322 m contain around 1% serpentine, a mineral often associated with faulting in the SAF system. Clay-rich and serpentine grains were plucked from the bulk samples, then crushed and sieved. Frictional sliding tests were conducted on sawcut samples containing either a thin layer of the reconstructed gouge or a layer of the crushed bulk material, at 10 and 40 MPa effective normal stress. These tests showed that the friction of the clay-rich and serpentine gouges were around 0.12 lower than the corresponding parent bulk samples.

2. Description of the Cuttings

[6] Cuttings from 2551 m were found to contain about 53% by weight of dark reddish-brown grains, many of

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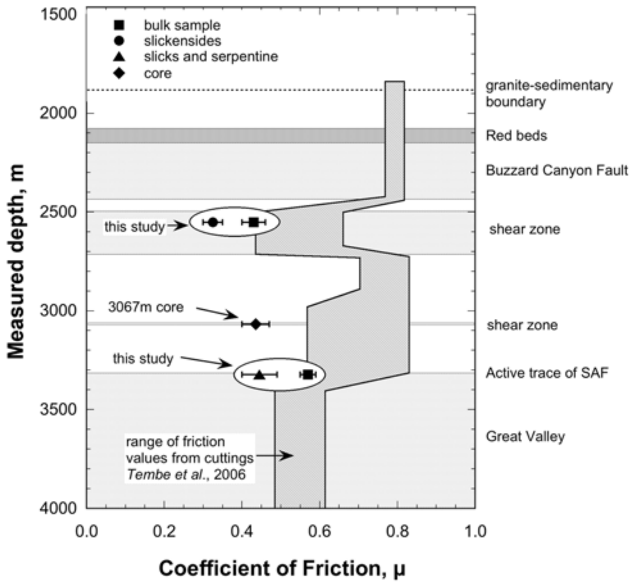

Figure 1. Data points show the coefficient of friction of cuttings from this study and the 3067 m core from *Tembe et al.* [2006], with error bars indicating the range of the values measured at normal stresses of 10 and 40 MPa. At 3322 m, the slickenside and serpentine separates have similar friction values and are grouped together. The dark shaded area shows the extent of friction values of bulk cuttings from *Tembe et al.* [2006].

which contained striations that were interpreted as slickensides caused by shearing on slip surfaces. These markings were different in character than the obvious damage from drilling (conchoidal fracturing, etc.). These grains were clay-rich (Table 1) compared to the more quartzo-feldspathic composition of the rest of the bulk material. (Throughout this paper we refer to "clay-rich" as meaning "clay-mineral rich" rather than a description of particle size). To determine the extent of mixing along the length of the drillhole during extraction, cuttings from 174 m higher in the drillhole (2377 m MD) were also examined. These cuttings contained none of the dark clay-rich grains that distinguish the 2551 m shear zone. Cuttings from 3322 m were similar in appearance to the cuttings from 2551 m, and contained about 43% of the clay-rich slickenside-bearing grains (note the slightly different mineral composition, Table 1). In addition, this deeper sample, located where the drillhole intersected an active trace of the San Andreas fault, contained <1 weight% serpentine, and was the only depth in the drillhole where serpentine was observed. Many serpentine grains were composed of pure lizardite (or occasionally pure chrysotile), although the majority were a microcrystalline mixture of lizardite and other minerals (Table 1). *Solum et al.* [2006] gives a detailed x-ray analysis of all cuttings from Phase 1 and 2.

[7] The clay-rich grains were hand plucked from the bulk material at the two test depths to create "slickenside gouge", representing the reconstruction of narrow shear zones of the two clay-rich gouge materials. In addition, pure serpentine and serpentine-rich grains were plucked from the 3322 m sample to obtain a serpentine gouge representing a narrow serpentine shear zone.

[8] The technique employed in this study depends on selective extraction of grains. For the technique to be useful, this selection process should result in a sample that is as close as possible to the mineralogy of the target shear zone. Problems can arise if, for example, an important clay or weak mineral fraction is lost in the drilling mud and is not preserved as intact grains. The importance of this lost material can, in principle, be estimated by analysis of the drilling mud itself. It should be possible to determine the relative amounts of formation clays and drilling mud. This procedure will be explored at a future time. Also, there may be cases where large quartz, feldspar or carbonate grains are present in the natural shear zone. It is likely that such grains would be under-sampled by the procedure described here. However, "typical" shear zones that have undergone significant deformation tend to reduce the gouge grain size, especially on the shear surface. For example, the core of the Punchbowl fault (part of the San Andreas fault system) is composed of an ultracataclasite composed primarily of grains less than 10 μm [*Chester et al.*, 2005]. Because our

Table 1. Composition and Mechanical Properties of Cuttings and Core

	2551 m bulk wt%	2551 m slicks wt%	3322 m bulk wt%	3322 m slicks wt%	3322 m serpentine wt%	3067 m core wt%
Composition[a]						
albite	26	17	24	20	10	21
quartz	40	26	42	41	14	13
chlorite	13	27	13	21	23	1
illite	12	20	15	18	9	49
mixed mont/ill	6	10				16
calcite	3	0	4	0	9	tr
lizardite and chrysotile			2	0	36	
Strength[b]						
μ, 10 MPa	0.40	0.30	0.56	0.40	0.44	0.45
μ, 40 MPa	0.46	0.35	0.59	0.49	0.47	0.40
average a-b[c]	0.0029	0.0025	0.0019	0.0020	−0.0029	0.0056

[a]Composition determined by XRD analysis and accurate to ∼5%.
[b]Typical uncertainty in μ is ±0.03 (see text).
[c]One standard deviation for uncertainty of a-b is typically 0.0004, uncertainty for serpentine is 0.0026 (see text).

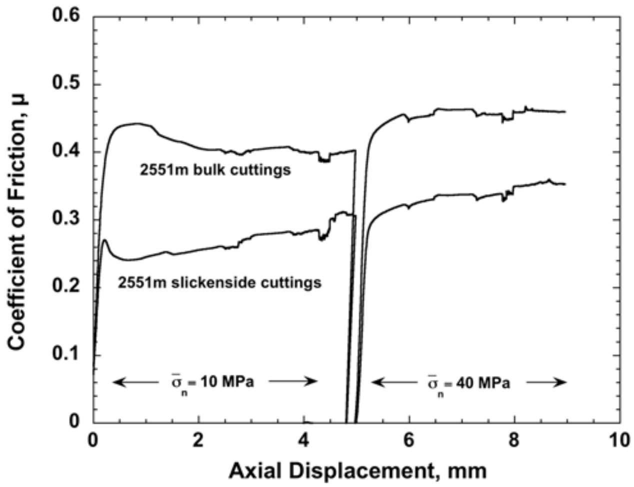

Figure 2. Coefficient of friction of bulk and plucked cuttings from 2551 m as a function of axial displacement. Sliding on the inclined fault surface is 1.15 times axial displacement. The effective normal stress was increased from 10 to 40 MPa after 5 mm of displacement. Decade changes in displacement rate during sliding show velocity-strengthening behavior in both cuttings samples.

plucked grains (0.5–1.0 mm in diameter) typically contain a microcrystalline mix and are large compared to the ultracataclasite grain size, they would preserve the mineral ratios present in the natural shear zone. This is why, as shown in Table 1, the plucked grains contain a significant fraction of quartz, feldspar and calcite. For this reason, we believe that the grain separates that we have tested provide a good approximation to the shear zone material.

3. Experimental Method

[9] Room temperature triaxial sliding experiments were performed in the laboratory on both the plucked and bulk material from 2551 and 3322 m. The gouge was washed at the drill site and again prior to testing to remove milling debris. The material was then crushed and sieved through a 100 μm mesh screen. The resulting fine powder was mixed with distilled water to form a paste, and then applied as a 1 mm layer between 30° sawcut sliding blocks. The top block was composed of sandstone in order to allow for free flow of water into the gouge layer from the pore pressure system, while a less porous granite block was used on the bottom to prevent fluids from becoming trapped and pressurized below the gouge layer. The samples were then jacketed in polyurethane tubes and secured between steel endplugs with hose clamps. Normal stress and pore pressures of 11 and 1 MPa, respectively, were applied to the sample for a total effective normal stress of 10 MPa during the first 5 mm of axial displacement. The load was then dropped and the normal stress increased to 41 MPa, (effective normal stress = 40 MPa), before continued sliding from 5 to 9 mm displacement. In this way, two friction measurements could be obtained in one run. Sliding began at a rate of 1.0 μm/sec, and then alternated between 1.0, 0.1 and 0.01 μm/sec throughout the experiment to observe the effect of sliding rate on strength.

[10] The coefficient of friction, μ, during the 10 MPa and 40 MPa segments were picked at 5 mm and 9 mm, respectively. The 10 MPa values tend to be lower than at 40 MPa because in many cases the samples showed strain hardening. The uncertainty in pressures and jacket strength give an accuracy of 0.01 for μ, and variability in sample preparation gives a repeatability of about 0.03.

4. Results

[11] The coefficient of friction as a function of axial displacement is shown in Figure 2 for cuttings from 2551 m. The bulk cuttings ($\mu = 0.4 - 0.47$) were consistently stronger than the plucked, clay-rich grains containing slickensides ($\mu = 0.25 - 0.35$). By the end of the experiment, the difference in coefficient of friction between the bulk and plucked cuttings was about 0.12. Coefficients of friction for cuttings at 3322 m (Figure 3) were generally a bit higher than those for the 2551m samples; $\mu = 0.5 - 0.6$ for the bulk cuttings and $\mu = 0.35 - 0.5$ for the slickensides. The serpentine separate ($\mu = 0.34 - 0.48$), was similar in strength to the clay–rich slickenside separate. Average friction values at the two normal stresses are compared with the bulk cuttings results under the same conditions as employed by *Tembe et al.* [2006] in Figure 1.

[12] Although not the main focus of this paper, velocity steps showed that both the bulk gouge materials and their slickenside separates were velocity strengthening (i.e., the material was slightly stronger at faster sliding rates). Values of a-b (= $d\mu_{ss}$/dlnV), a measure of the change in steady state friction with the change in sliding velocity, varied from around 0.0019 to 0.0029 (±0.0004) for these samples (Table 1). Positive a-b values indicate a tendency for stable sliding (creep). The serpentine gouge, on the other hand, showed both positive and negative a-b, with an average value of −0.0029 and a large uncertainty of ±0.0056. A

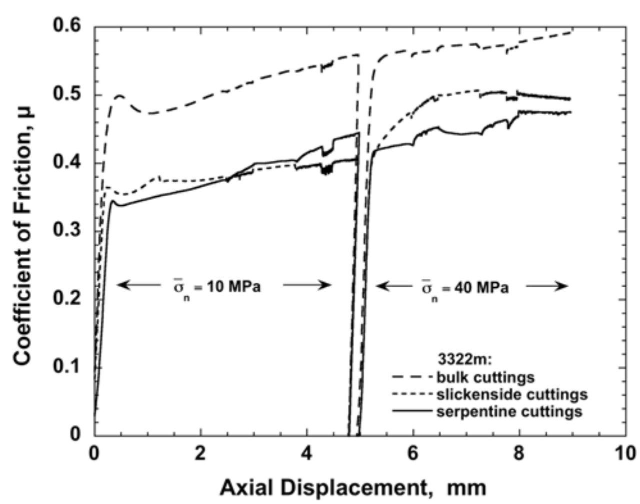

Figure 3. Coefficient of friction of bulk and plucked cuttings from 3322 m as a function of axial displacement. The effective normal stress was increased from 10 to 40 MPa after 5 mm of axial displacement. Clay-rich slickenside cuttings and serpentine separates are weaker than the bulk cuttings.

shift from positive to negative a-b with increasing sliding velocity is a characteristic of serpentine at the temperature, pressure and velocity conditions of our experiments [*Moore et al.*, 1997].

5. Discussion

[13] Although the plucked, clay-rich cuttings at 2551 and 3322 m were visually indistinguishable with a binocular microscope, X-ray analysis showed compositional differences that help explain the higher strength of the deeper clay-rich sample (Table 1). The 3322 m slickenside gouge contained considerably more weight percent of strong minerals such as quartz, albite and calcite, all of which in pure form have a coefficient of friction greater than 0.6 [*Morrow et al.*, 2000]. These minerals contribute to the relatively higher strength of the gouge at 3322 m. However, determining a simple ratio of weak to strong minerals is insufficient to estimate the strength of a multiphase gouge. *Logan and Rauenzahn* [1987] show experimentally that the mixing laws for illite, montmorillonite and quartz are not linear, particularly for clay mineral contents less than 20%. The 3322 m serpentine gouge, containing about a third by weight of the mineral lizardite and small amounts of chrysotile, also had a significant weight percent of strong minerals, comprising about another third of the total weight. Not surprisingly, the coefficient of friction of the serpentine separate was higher after a few mm of shearing than the μ = 0.4 value for pure, water-saturated lizardite [*Morrow et al.*, 2000].

[14] How does the strength of our reconstructed shear zones compare to the strength of real shear zones encountered during drilling? For this we compare the strength of our cuttings samples with that of the illite-rich core material from the southwest shear zone at 3067 m, the only core material retrieved from a known shear zone during drilling Phases 1 and 2. This core sample was crushed, sieved and tested in the same manner as our plucked gouge samples (Table 1). *Tembe et al.* [2006] found that the friction after shearing was 0.4–0.45 (Figure 1), a lower value than most of the other cuttings, but consistent with the lower strength of our plucked, clay-rich gouge samples (μ = 0.35 – 0.50) from shear zones at 2551 and 3322 m. This core measurement provides a good check for the validity of our method.

6. Conclusions

[15] Because the plucked grains containing slickensides from both test depths were more clay–rich than the associated bulk material, our "reconstructed fault zones" exhibited a lower frictional strength typical of a mixed composition gouge containing the weaker sheet-silicate minerals. Likewise, the serpentine gouge was inherently weaker then the more quartzo-feldspathic bulk material. By identifying areas of shearing using borehole logging techniques and then concentrating grains associated with the shearing from the cuttings, we have obtained improved estimates of the strength of narrow shear zones within the SAFOD drillhole. Based on our analysis, fault zone strength is lower than the surrounding material, as expected for active faulting. The determination of frictional properties is most reliable when test samples are taken directly from whole cores. However, in many deep drilling projects this is not practical. In the SAFOD project, for example, considerations of both cost and hole stability meant that the initial drilling phases would provide only limited amounts of core. In this case, cuttings must be used to provide mechanical data. Under these conditions, the technique explored here, based on a combination of borehole logging data and laboratory analysis, can be useful. This is especially true when discrete features such as narrow shear zones control the mechanics of the fault system.

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