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Frictional strength of cuttings and core from SAFOD drillhole phases 1 and 2

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[1] We investigated the frictional properties of drill cuttings and core obtained from 1.85–3.1 km true vertical depth in the SAFOD scientific borehole in central California. Triaxial frictional sliding experiments were conducted on samples from primary lithologic units and significant shear zones, including the inferred active trace of the San Andreas fault. The samples were deformed at room temperature under constant effective normal stresses of 10, 40, and 80 MPa with axial shortening rates of 0.01–1.0 μm s^{-1}. The weakest samples were from shale, claystone, and siltstone units with friction coefficient μ = 0.4–0.55. Stronger samples were from quartzo-feldspathic rocks with $\mu \geq 0.6$. Materials tested from two shear zones at 2560 and 3067 m measured depth had μ = 0.4–0.55 and velocity strengthening behavior consistent with fault creep at depths <4 km. The coefficient of friction for bulk samples from the inferred trace of the San Andreas fault was ~0.6.
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1. Introduction

[2] The San Andreas Fault Observatory at Depth (SAFOD) scientific borehole provides a unique opportunity to study samples from seismogenic depths of an active major plate bounding fault. Understanding the state of stress and mechanical behavior of the San Andreas fault (SAF) is critical to resolving the long standing stress-heat flow paradox [*Lachenbruch and Sass*, 1980, 1992; *Zoback et al.*, 1987] and hinges on intrinsic rock properties adjacent to and inside the fault zone. In order to investigate the frictional properties of fault-derived rocks we have conducted laboratory experiments on samples acquired at depth during drilling of phases 1 and 2 of SAFOD.

[3] The SAFOD main hole, located in central California, near the town of Parkfield was drilled vertically into Salinian granitic rocks before being deviated at 1490 m toward the SAF. SAFOD subsequently penetrated over a kilometer of arkosic sandstones and conglomerates, and numerous faults before terminating in sedimentary rocks of the Great Valley sequence (Figure 1a). By the end of phase 2, drilling had yielded 20 m of spot core (from ~1463, 3056, and 3990 m measured depth) and drill cuttings for the entire 4.0 km long borehole (maximum vertical depth of 3.1 km). The SAFOD drilling strategy intentionally limited the amount of core that was retrieved during the initial phases to <1%, with continuous coring planned for phase 3 drilling in 2007. To augment data obtained from the limited core available at this time and to aid in planning the phase 3 drilling strategy, we conducted extensive frictional sliding tests on drill cuttings.

[4] At least three important limitations exist for inferring in situ fault strength from cuttings. (1) The cuttings are mixed as they travel up the borehole so that potentially weak phases contained in narrow shear zones are under-represented or diluted in the samples collected at the surface. (2) Fine particles, including clays and weak minerals, are preferentially lost during drilling as the cuttings pass over the shale shakers and therefore may be under-sampled. (3) Cuttings may be contaminated by drill fluids. We report here our findings and assess the reliability of inferring mechanical properties from cuttings by comparing results to tests on spot cores.

2. Methodology

[5] The SAFOD sampling protocol acquired cuttings at 3 m intervals for drilled sections and at 0.3 m intervals for cored sections of the borehole, and yielded *unwashed* and *washed* cuttings for scientific study. The *unwashed cuttings* (denoted by CUU in Figure 1) were collected from the shale shakers and air dried in their unwashed state. *Washed cuttings* (CU) were gently washed through a 106 μm sieve in tap water on-site to remove the bentonite drilling mud. The material that was left in the sieve was then air dried.

[6] Guided by the local stratigraphy, X-ray diffraction (XRD) clay mineral analyses [*Solum et al.*, 2006] and dipole sonic velocity logs, we selected 36 washed cuttings samples, 4 unwashed cuttings samples, and 6 core samples from depths spanning the length of the deviated main hole from 1890 to 4000 m measured depth (MD) (corresponding to 1.85 to 3.1 km true vertical depth). Cuttings were chosen to represent primary lithologic units as well as significant shear zones, including the inferred active trace of the SAF.

[7] Further preparation of the samples was conducted in the laboratory. Washed cuttings samples were cleaned in an ultrasonic bath in deionized water for 30 minutes to remove any residual drilling fluid. The remaining bathwater was poured off (reserved for later analysis) and the cuttings left to air dry. The majority of our friction tests were carried out on these twice-washed samples which we will denote as CU-W. Subsets of unwashed cuttings were cleaned once

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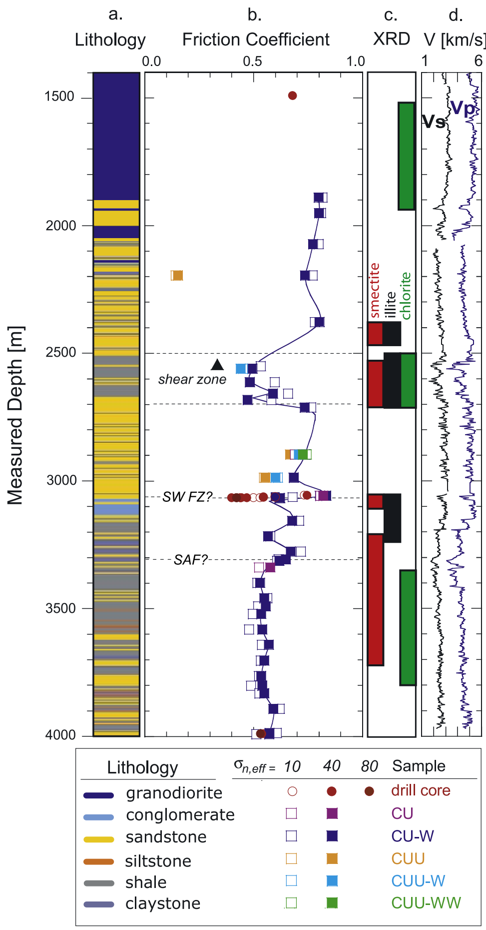

Figure 1. Depth profile of the SAFOD main hole showing (a) simplified lithology (b) friction coefficient of cuttings (indicated by square symbols) and drill core (circles). The points are color coded according to preparation procedure. The black triangle is from a preliminary test on cuttings separates. (c) Sections where typical fault gouge minerals were found in significant abundance are indicated. (d) Seismic velocity log data.

and twice in an ultrasonic bath following the procedure described above in order to evaluate the effect of washing (referred to as CUU-W and CUU-WW, respectively).

[8] Cursory inspection of the samples at this stage showed the presence of two contaminants remaining from the drilling process. The first were loss circulation materials (coarse ground nut shells referred to as *nut plugs*) that were added to the drilling fluid to reduce mud loss in case a fissure should open while drilling. The nut plugs were easily separated from the bulk material owing to their density contrast. The second contaminant was metal filings from the drill bit, estimated to be <5 wt. % in most samples. As standard practice adopted for phase 2, a bar-magnet was passed through the samples to remove this small fraction of metal. All samples were then crushed and passed through a 100 mesh sieve to obtain particles sizes of <149 μm.

[9] Triaxial sliding experiments were conducted at room temperature on cylindrical (2.54 cm diameter) granite/sandstone forcing blocks containing saw-cuts inclined at 30° and filled with 1 mm-thick sample gouge layers following the procedure detailed by *Morrow et al.* [1992]. To approximately duplicate the in situ effective stress tests were run at constant normal stresses of 11.0 and 41.0 MPa, and at constant pore pressure of 1.0 MPa. Deionized water was used as the pore fluid and to assure good pore pressure communication between the gouge layer and the external pore pressure system the upper driving block was a porous (20%) Berea sandstone with high permeability. The lower granite driving block had low porosity (<1%) to minimize the generation of pore pressure transients that might result during rapid stress changes.

[10] The samples were sheared up to 9 mm of axial displacement (10.4 mm slip resolved on the saw-cut) at axial displacement rates of 0.01, 0.1 and 1.0 μm s^{-1}. Since the samples typically strain hardened to a steady stress level within 1 to 2 millimeters it was possible to incorporate two pressure steps into a single run doubling the number of analyses. A total of 46 washed and unwashed cuttings samples were tested.

[11] Strength tests were conducted on 5 intact rectangular prisms (1.8 × 1.8 × 4.6 cm) of granodiorite drill core from 1498 m MD in the conventional triaxial configuration at confining pressures of 10 to 160 MPa. The samples were deformed at a constant shortening rate, corresponding to a nominal strain rate of 10^{-5} s^{-1}. With the exception of the granodiorite, the SAFOD core was generally too damaged to obtain intact samples suitable for mechanical testing. As an alternative, frictional sliding tests were carried out on drill core fragments that were crushed to a particle size of <149 μm and deformed in the same manner as the cuttings samples at constant effective normal stresses of 10, 40, and 80 MPa. In all 12 experiments were conducted on core samples from 3058, 3065, 3066, 3067, and 3991 m MD.

3. Results

3.1. Frictional Strength Profile

[12] In Figure 1 we summarize laboratory and logging data as functions of depth for the lower half of the main hole from 1400 to 4000 m MD. For reference, a simplified lithology modified from mud logs (available online at http://www.icdp-online.de/contenido/icdp/front_content.php?idcat = 896) is shown in Figure 1a. Figure 1b plots coefficient of friction, μ (defined as the ratio of shear stress to effective normal stress resolved on the saw-cut) for experiments on cuttings (at 4.8 mm and 8.6 mm of axial displacement), and on core (at 8.6 mm of axial displacement). Zones where smectite, illite and chlorite were identified in relatively high concentrations by XRD [*Solum et al.*, 2006] are indicated in Figure 1c. Seismic velocity data from dipole sonic logs for this section of the borehole are also shown in Figure 1d [*Boness and Zoback*, 2006].

[13] The coefficients of friction for washed cuttings and core spanned the range of 0.4 to 0.8 and typically showed a slight increase with effective normal stress. Relatively higher values of μ ($\geq$0.6) corresponded to quartzo-feldspathic rocks derived from granodiorite, arkose, sandstone, and conglomerate facies encountered in the drill hole, and are comparable to the sliding frictional strength measured in the intact granodiorite core samples from 1498 m MD. Lower values of μ (0.40–0.55) were observed at depth

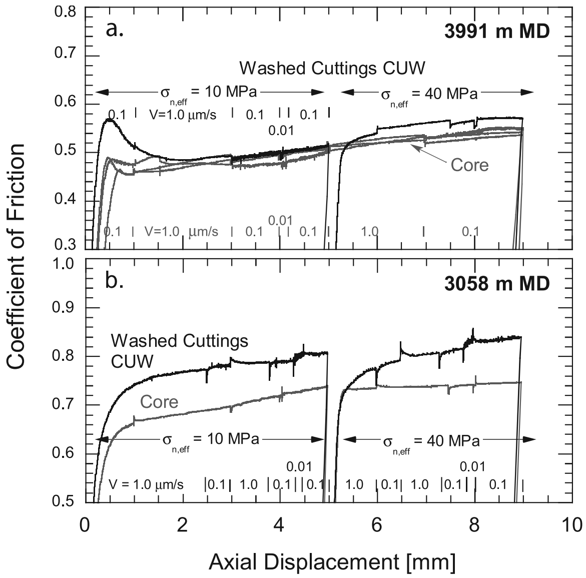

Figure 2. Comparison of friction coefficient versus axial displacement for cuttings and core samples from (a) conglomerate unit at 3058 m MD and (b) siltstone unit at 3991 m MD. Data for drill core samples are plotted in gray and cuttings data are in black.

intervals corresponding to siltstone, shale and claystone units. Of the regions considered to be shear zones because of clay enrichment and reduced seismic velocities, only two shear zones at ~2600 and 3067 m MD, were found to have low strength (μ = 0.4–0.5). The active trace of the San Andreas Fault inferred from borehole casing deformation [*Zoback et al.*, 2006] at 3310–3353 m MD is within a lithological transition zone [*Solum et al.*, 2006] and is manifested in the laboratory data as a modest decrease in frictional strength.

[14] A comparison of unwashed cuttings samples (which should have retained much of their fine grained material) and samples washed following different preparation routines was used to evaluate the loss of fine particles. The various washing procedures for cuttings appear to have little effect on the frictional strength (Figure 1b). In contrast experiments on unwashed cuttings (orange squares) varied greatly in a somewhat unsystematic manner, ranging from values of μ observed for relatively pure bentonite (a major constituent of the drilling mud) to granitic rocks.

3.2. Comparison With Core Samples

[15] To assess the extent to which the cuttings data provide a realistic proxy for actual in situ strength, we compared the results of mechanical deformation experiments on drill core with cuttings for three common facies: granodiorite, conglomerate, and siltstone.

[16] Intact granodiorite core samples (1498 m MD) failed by brittle fracture in strength tests. The coefficient of friction measured during sliding on fracture surfaces formed during these tests is 0.68 ± 0.03, comparable to the friction coefficients obtained for saw-cut experiments of granodiorite drill cuttings at 1890 m MD which typically have μ = 0.7–0.8. As in all of the saw-cut experiments, stable sliding behavior and overall strain hardening were observed, and most samples showed an increase in strength with increasing sliding rate.

[17] A comparison of conglomerate samples from the equivalent depth at 3058 m MD in Figure 2a shows a high friction coefficient (0.75–0.85), as expected. However, the slight difference between cuttings and core suggests biased sampling of the coarse grained rock, or the involvement of contamination from metal filings and perhaps the loss of formation clays in the washed cuttings.

[18] Figure 2b shows μ plotted as a function of axial displacement for core samples obtained from near the bottom of the Phase 2 borehole at 3991 m MD (3070 m TVD). This section of core is from a Great Valley siltstone unit on the NE side of the SAF. Experiments on core samples show steady sliding behavior, strain hardening, and strengthening in response to increasing velocity steps. The cuttings from this depth demonstrate similar behavior.

[19] The agreement between strength data obtained from drill cuttings and core supports the feasibility of the method under appropriate conditions which are sensitive to the fraction of weak phases present in the cuttings.

3.3. Dilution of Weak Phases

[20] At the termination of Phase 1 at 3067 m MD the SAFOD borehole had intersected a fracture zone considered to be the southwest strand of the San Andreas [*Hickman et al.*, 2005]. This shear zone is approximately 30 cm thick and is composed of 48–51% illite, 14–18% illite-smectite, 19–22% feldspar, 11–17% quartz, 1% chlorite, and trace amounts of calcite [*Solum et al.*, 2006]. The coefficient of friction of drill core samples shown in Figure 3a was measured to be 0.40–0.45, notably weaker than cuttings (~0.6) tested at this same depth, but similar to the values obtained for other shear zones. We can also surmise based

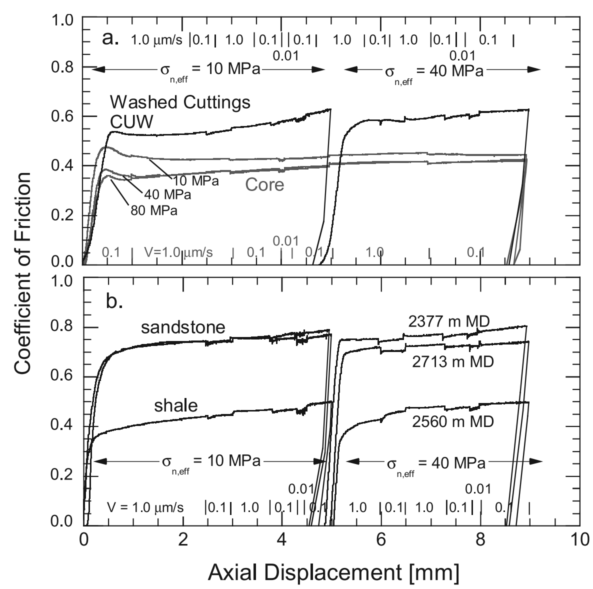

Figure 3. Coefficient of friction versus axial displacement for two shear zones. (a) Narrow shear zone at 3067 m MD. The signal of weaker material is diluted in the cuttings, while in (b) a broad illite clay shear zone at 2560 m MD is easily detected in the cuttings. The stronger samples at 2377 and 2713 m MD are from sandstone units on either side of the fault.

on the sampling interval that for a shear zone to be reliably detected in the cuttings the section would have to be at least 2 to 3 meters thick. Since this layer is narrow and bounded by a conglomerate unit the differences in strength are likely due to mixing of material in the cuttings samples, resulting in the averaging of mechanical properties over an interval of 0.3 m or more. Application of appropriate mixing rules for a polymineralic system would help to define these narrow zones.

[21] While resolving a narrow shear zone in the cuttings may not be straightforward, broad shear zones are readily detected in the cuttings. As an example Figure 3b presents friction data for a thick clay bearing unit at 2560 m MD, interpreted to be a shear zone based on its enrichment in illite and illite-smectite clays, reduced seismic velocities and associated anomalies in downhole geophysical log data (e.g., natural gamma ray, resistivity). This moderately weak layer is bounded by stronger sandstone units at 2377 and 2713 m MD, and the difference in frictional strength is easily discerned.

[22] The quality of the cuttings data may be enhanced further since material from slip surfaces can be recognized in the cuttings by slickensides on grain fragments. Although a tedious process, these grains can be separated from the bulk material and subjected to laboratory testing. We are currently pursuing this approach, and preliminary results from the broad shear zone at ~2560 indicate the plucked material contains ~60 wt% clay relative to a maximum of ~40 wt% in the bulk samples [*Solum et al.*, 2006], and has a friction coefficient of ~0.33 (included in Figure 1b as the black triangle) for 10–40 MPa effective normal stress.

3.4. Preferential Loss of Clay Phases

[23] While frictional strength data from cuttings are inherently limited by the sampling interval, cuttings from a large shear zone may be affected by the loss of fine particles. For example, despite recent indications of a broad actively deforming region from 3310 m to 3353 m MD [*Zoback et al.*, 2006], the strength data for samples in the vicinity of the San Andreas Fault do not reflect the presence of an exceptionally weak shear zone (Figure 1b).

[24] Mineralogical characterization by *Solum et al.* [2006] of washed cuttings from the inferred active trace of the SAF determined the clay content to be between 5–35 % illite, 8–23 % chlorite, 6 % calcite, with trace amounts of serpentine (2 %) and laumontite (<2 %). If the preferential removal of low strength mineral phases from drill cuttings is occurring, then one way of constraining the effect of the lost clay fraction would be from experiments on unwashed cuttings samples. However given the unsystematic variation in mechanical data due to contamination, the results are inconclusive. Another method we are pursuing is to quantify the lost fraction from XRD analyses of unwashed cuttings and drilling fluid separated by the shale shakers in order to reconstruct a sample for laboratory testing that would be better representative of the formation or shear zone.

4. Discussion and Conclusions

[25] Arguments for a weak SAF arising from the absence of a friction-induced surface heat flow anomaly [*Lachenbruch and Sass*, 1980, 1992; *Williams et al.*, 2004] and stress orientation data [*Zoback et al.*, 1987; *Hickman and Zoback*, 2004], suggest a relatively low resolved shear stress (on the order of 10–20 MPa for the upper 15 km of the SAF) and coseismic frictional strength of $\mu = 0.1$ to 0.2, well below the friction coefficient observed for most crustal rocks [e.g., *Byerlee*, 1978]. Low strength minerals are a common constituent of fault gouge and have often been invoked to reconcile field and laboratory observations [*Wu et al.*, 1975]. Accordingly previous studies have focused on clays and phyllosilicates derived from surface and shallow borehole samples [e.g., *Morrow et al.*, 1982], and pure mineral analogs [e.g., *Morrow et al.*, 1992; *Moore et al.*, 1996] to infer mechanical properties of the SAF. Our study of deep, fault-derived materials provides the best San Andreas Fault zone data to date by measuring 63 samples that span a depth range of 2 km. We have established an experimental methodology and demonstrated that meaningful mechanical information can be derived from cuttings despite potential difficulties caused by drilling and sample collection, as evidenced by good agreement between strength of core and cutting samples, XRD analyses and downhole log data.

[26] Two weak shear zones (~2560 and 3067) with friction coefficients ranging from 0.4 to 0.55 were measured in our study and their mechanical data are consistent with fault creep behavior observed in central California down to 4 km depth. The inferred active trace of the SAF at 3310–3353 m MD was found to have a friction coefficient ~0.60 in bulk cuttings samples. If the SAF is indeed unusually weak, then our data demonstrate that the presence of weak alteration minerals would account for a portion of this reduced strength. Other mechanisms such as elevated pore fluid pressure or dynamic weakening processes may be involved in controlling fault strength, although fault-related elevated fluid pressure has yet to be detected in the SAFOD hole [*Zoback et al.*, 2006]. Moreover, to extrapolate to seismogenic conditions we must also consider the role of temperature and the presence of chemically reactive fluids. Studies conducted on heated chrysotile show overall strengthening with increasing effective pressure and temperature [*Moore et al.*, 2004]. Similarly, montmorillonite and illite gouges deformed at high effective pressures [*Morrow et al.*, 1992] strengthen to values well above the heat flow constraint. Nevertheless, many uncertainties remain and more definitive conclusions cannot be drawn partly due to the paucity of core samples retrieved from the initial phases of SAFOD. Fully exploring the constitutive properties and fine structure of the SAF from continuous core available in phase 3 drilling will be critical to resolving the stress-heat flow paradox.

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