Phyllosilicate mineral assemblages of the SAFOD Pilot Hole and comparison with an exhumed segment of the San Andreas Fault System

John G. Solum and Ben A. van der Pluijm
Department of Geological Sciences, University of Michigan, Ann Arbor, Michigan, USA

Received 7 March 2004; accepted 24 March 2004; published 24 June 2004.

[1] This paper establishes a reference phyllosilicate data set from the SAFOD Pilot Hole for future SAFOD drilling and presents an application of these data for studies of exhumed fault segments. The chlorite assemblages in cuttings from two intervals of the SAFOD Pilot Hole are separated into two populations based on X-ray diffraction characteristics. The first population is found in granite in both the deeper and shallower interval, whereas the second population occurs only in clastic sedimentary rocks in the shallower interval. The characteristics of the first population match those for protolith and cataclasite of the exhumed Punchbowl Fault, whereas samples from intensely deformed ultracataclasite are most similar to the second. This supports previous findings that the mineral assemblages in the ultracataclasite formed after the cessation of motion along the fault, above a depth of ~2 km, and that mineral assemblages in these exhumed fault rocks have been overprinted by post-faulting alteration.

INDEX TERMS:

1. Introduction
[2] Mechanically weak fault behavior [e.g., Lachenbruch and Sass, 1980; Zoback, 2000], has been attributed to the presence of phyllosilicates in fault zones as neformed clays either directly weaken faults due to low strength [e.g., Wang, 1984] or influence the permeability structure of fault zones [e.g., Morrow et al., 1984; Zhang et al., 1999; Zhang and Cox, 2000; Faulkner and Rutter, 2001]. Chlorite, the dominant phyllosilicate observed in the Pilot Hole, is found in other fault zones, such as the exhumed Punchbowl Fault [e.g., Chester and Logan, 1986; Schulz and Evans, 1998; Solum et al., 2003], and at depth along the active Nojima Fault [e.g., Ohtani et al., 2000]. Exhumed fault zones have been used to study the effectiveness of fault weakening mechanisms [e.g., Chester and Logan, 1986; Evans and Chester, 1995; Vrolijk and van der Pluijm, 1999; Faulkner and Rutter, 2001; Solum et al., 2003], but samples from drilled active faults provide unique opportunities to determine in situ characteristics of fault rocks prior to exhumation. By providing samples from depth, the SAFOD Pilot Hole (SPH) provides the necessary baseline for future studies of fault rocks from the main SAFOD hole, but also permits comparison with exhumed fault segments, such as the Punchbowl Fault (PBF) (Table 1).

[3] The protoliths of the PBF are quartz diorite, quartz monzonite, mica schist, and arkosic fluvial sandstone/siltstone with conglomeratic interlayers, as well as shallow marine arkosic sandstone with conglomerate lenses. This is similar to the rocks of the SPH, consisting of granite and shallow marine coarse sandstones. Thus, it is possible to directly compare characterizations of phyllosilicates from both localities (Figure 1).

2. Experimental Methods
2.1. Sample Description
[4] Cuttings were collected from two intervals from the SPH (488–914 m and 1585–2012 m). These intervals were based on results of point counts (M. Rymer, personal communication, 2004), and were chosen to include the transition from granite to sedimentary cover at ~760 m, as well as zones of chloritic alteration within the granite, including a shear zone at ~1800 m [Boness and Zoback, 2004].

2.2. X-Ray Diffraction
[5] The cuttings were analyzed using oriented and random sample preparations. Oriented preparations were used to enhance the intensities of (00l) peaks, aiding in the identification of phyllosilicate phases. Both bulk and clay (<5 μm) fractions were analyzed for each sample. Oriented samples were prepared by placing a clay-water slurry on a glass slide and allowing it to dry. Random samples were prepared using an end-packing device [Moore and Reynolds, 1997]. Samples of bentonite drilling mud and barite mud additive were analyzed in order to recognize contamination by those materials in the cuttings (Figure 2). Peaks on powder patterns from cuttings that overlap with peaks from drilling mud were not used in samples containing significant traces of drilling mud.

[6] Samples were analyzed using a Scintag X1 0–θ powder diffractometer, with an accelerating voltage of 35.0 kV and a filament current of 20.0 mA. Oriented samples were scanned from 2–30°2θ at a scan rate of 0.25°/min, and random samples from 4–40°2θ at a rate of 1.0°/min.

[7] Bulk samples with oriented preparations were analyzed in order to determine relative mineral concentrations (Figure 3). The area of each relevant peak on an individual powder pattern was measured, and the area of that peak...
Table 1. Relative Mineral Concentrations From the Safod Pilot Hole Based on XRD of Bulk Samples With Oriented Preparations

| Depth (ft) | Depth (m) | i/b/m | hbl | c-s | stilb | chl | al | qtz | kfs | i/m | chl | C-S | stlb | chl | al | qtz |
|-----------|-----------|-------|-----|-----|-------|-----|----|-----|-----|-----|-----|-----|-----|-----|----|-----|-----|
| 1600      | 487.7     | 0.32  | 0   | 0   | 0.31  | 0   | 0.05| 0   | 0.75| 0.78| 0   | 0   | 0   | 0   | 0   | 0   |
| 1700      | 518.2     | 0.52  | 0   | 0   | 0.75  | 0   | 0.09| 0   | 0.63| 0.57| 0   | 0   | 0   | 0   | 0   | 0   |
| 1800      | 548.6     | 0.54  | 0   | 0   | 0.00  | 0   | 0.12| 0   | 0.32| 0.70| 0   | 0   | 0   | 0   | 0   | 0   |
| 1900      | 579.1     | 0.69  | 0   | 0   | 0.66  | 0   | 0.18| 0   | 0.47| 0.54| 0   | 0   | 0   | 0   | 0   | 0   |
| 2000      | 609.6     | 0.31  | 0   | 0   | 0.34  | 0   | 0.21| 0   | 0.34| 1.00| 0   | 0   | 0   | 0   | 0   | 0   |
| 2100      | 640.1     | 0.19  | 0   | 0   | 0.11  | 0   | 1.00| 0   | 0.93| 0.06| 0   | 0   | 0   | 0   | 0   | 0   |
| 2200      | 670.6     | 0.57  | 0   | 0   | 0.44  | 0   | 0   | 0   | 0.44| 0.87| 0   | 0   | 0   | 0   | 0   | 0   |
| 2300      | 701.0     | 0.38  | 0.06 | 0   | 0   | 1.00| 0.63| 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| 2400      | 731.3     | 0.23  | 0.04 | 0   | 0   | 0   | 0.76| 0   | 0.27| 0.37| 0.22| 0   | 0   | 0   | 0   | 0   |
| 2500      | 762.0     | 0.50  | 0.10 | 0   | 0   | 0   | 0.34| 0   | 0.62| 0.03| 0   | 0   | 0   | 0   | 0   | 0   |
| 2600      | 792.5     | 1.00  | 0.13 | 0   | 0   | 1.00| 0.75| 0   | 0.53| 0.28| 0   | 0   | 0   | 0   | 0   | 0   |
| 2700      | 823.0     | 0.23  | 0.49 | 0   | 0   | 0   | 0.49| 0   | 0.49| 0.45| 0   | 0   | 0   | 0   | 0   | 0   |
| 2800      | 853.4     | 0.36  | 0.03 | 0   | 0   | 0   | 0.65| 0   | 0.40| 0.27| 0   | 0   | 0   | 0   | 0   | 0   |
| 2900      | 883.9     | 0.26  | 0.16 | 0   | 0   | 0   | 0.17| 0   | 0.61| 0.64| 0.51| 0   | 0   | 0   | 0   | 0   |
| 3000      | 914.4     | 0.41  | 0.14 | 0   | 0   | 0   | 0.54| 0   | 0.58| 0.58| 0   | 0   | 0   | 0   | 0   | 0   |

The area of each relevant peak on an individual powder pattern was measured, and the area of that peak relative to the sum of the analyzed peaks from that sample was calculated. These relative areas were normalized to the largest relative area for a particular mineral. The phases that were analyzed are undifferentiated illite/biotite/muscovite (i/b/m) (8.8 20), laumontite (limt) (9.3 20), stilbite (stlb) (9.7 20), hornblende (hbl) (10.5 20), mixed layer chlorite-smectite (C-S) (~10.6 20), chlorite (chl) (12.4 20), albite (ab) (13.6 20), quartz (qtz) (20.8 20), K-spar (kfs) (27.5 20), epidote (ep) (15.8 20), and calcite (cal) (29.5 20). All values of 20 are for CuK radiation. The contact between granite and overlying clastic sedimentary rock is ~760 m. Variations in phyllosilicates are discussed below. Tabulated relative mineral concentrations are discussed below. Tabulated relative mineral concentrations from Table 1 are plotted. X-ray diffraction powder patterns for SPH samples are shown in Figure 6a, while results across the PBF are shown for comparison in Figure 6b [Solum et al., 2003]. In the SPH, peaks are narrower in the granite and broader in the shallower sandstone, reflecting the decreasing abundance of smectite interlayers in those samples. Ultracataclasite in the PBF is also characterized by broad peaks, which are due to a large number of smectite interlayers in those samples.
imentary rocks from the SPH. This further supports the interpretation that C-S observed in PBF ultracataclasite formed at a shallower depth than chlorite in the PBF cataclasite and protolith.

3.3. Chlorite and C-S Composition

[11] The populations of chlorite and C-S from the SPH and the PBF can be separated based on characteristics of the powder diffraction patterns. Figure 7a plots the width of the (002) chlorite/C-S peak (crystallinity) against the area of the (002) chlorite/C-S peak over the area of the (001) chlorite/C-S peak (the peak area ratio). Measurements were made using bulk samples with a preferred orientation. The peak area ratio is a function of the chemical composition of chlorite and C-S. The values for the phyllosilicates from the SPH granite overlap with the crystalline and sedimentary protolith and cataclasite from the PBF, both of which were interpreted as pre or synfaulting [Solum et al., 2003]. The values for clays from PBF ultracataclasite do not plot with the SPH granite, and are most similar to the SPH clastic sedimentary rocks, supporting the interpretation that C-S in the exhumed PBF ultracataclasite formed at a shallower depth than the PBF protolith and cataclasite.

[12] X-ray powder diffraction patterns also offer a semi-quantitative estimate of the composition of chlorite, provided that randomly oriented samples are used [Brown and Brindley, 1980]. Figure 7b depicts Y (the total amount of Fe) and D (the symmetry of Fe distribution between the octahedral and hydroxide sheets), using the method of Brown and Brindley [1980]. Only values from the deeper granite samples from the SPH are shown, as it was not possible to accurately measure the peak areas from shallower samples due to contamination by the drilling mud. Analogous to crystallinity data above, the composition of chlorite from the deeper SPH granite generally matches the composition of chlorite from crystalline and sedimentary...

Figure 3. Representative powder patterns from glycolated bulk cutting samples prepared such that clays have a preferred orientation. The peaks are undifferentiated illite/biotite/muscovite (i/b/m), laumontite (lmt), hornblende (hbl), chlorite (chl), albite (alb), quartz (qtz), and K-feldspar (ksp). Unlabeled peaks are unused peaks from the phases mentioned in the preceding sentence, or drilling mud. The depths of the samples are indicated.

Figure 4. Representative powder patterns from the clay size fraction of cuttings prepared with a random orientation. Peak labels are the same as Figure 3, except that the (001) through (005) chlorite peaks are labeled, as these peaks are used to calculate the composition of the chlorite, as discussed in the text.
This is compatible with the earlier interpretation from exhumed ultracataclasite, representing the most intensely of 2–4 km syntectonic clays in the PBF protolith and PBF cataclasite closely resemble the SPH clastic sedimentary rocks. These cataclasite, while clays from PBF ultracataclasite most with PBF crystalline and sedimentary protolith and PBF mineral concentrations, crystallinity, and chlorite composi-

SAFOD drilling, as well as for studies of exhumed fault establish a reference phyllosilicate data set for future studies of exhumed faults, the effects of postfaulting alteration on fault zones.

4. Conclusions

The primary objectives of this short paper are to establish a reference phyllosilicate data set for future SAFOD drilling, as well as for studies of exhumed fault zones, and, secondarily, to offer an application of this data set by comparing it with the Punchbowl Fault. Relative mineral concentrations, crystallinity, and chlorite composition all indicate that clays from the SPH granite correlate with PBF crystalline and sedimentary protolith and PBF cataclasite, while clays from PBF ultracataclasite most closely resemble the SPH clastic sedimentary rocks. These observations are compatible with the idea that the pre and syntectonic clays in the PBF protolith and PBF cataclasite formed while the fault was active, and therefore at a depth of 2–4 km [Chester and Logan, 1986], whereas clays in the exhumed ultracataclasite, representing the most intensely deformed fault rock formed at a shallower depth (<2 km). This is compatible with the earlier interpretation from microstructural work that clays in ultracataclasite are the result of postfaulting alteration [Solum et al., 2003].

The effects of post-faulting alteration limit inferences about fault behavior that can be made from exhumed rocks. Samples from boreholes that collect unaltered fault rocks, therefore, are required to constrain interpretations on the potential role of clays in fault mechanics. The Pilot Hole mineralogical data presented here provide the necessary reference data for comparison between protolith and fault rocks for planned sampling in the next phase of SAFOD, which will include collection of both cuttings and core, allowing for a more thorough characterization of fault-related mineral transformations and, through comparison with exhumed faults, the effects of postfaulting alteration on fault zones.

Acknowledgments. Funding for this study was provided from NSF grant EAR-0230055 (BvdP) and an internship from DOSECC Inc. to Solum. The authors thank Steve Hickman and Jim Evans for their help in obtaining samples from the Pilot Hole and Liz Langenburg and Mike Rymer for providing point counts of the cuttings. Constructive reviews by two anonymous reviewers helped to clarify the presentation and interpretation of the data.

References


Solum, J. G., B. A. van der Pluijm, D. R. Peacor, and L. N. Warr (2003), Mineralogical data presented here provide the necessary reference data for comparison between protolith and fault rocks for planned sampling in the next phase of SAFOD, which will include collection of both cuttings and core, allowing for a more thorough characterization of fault-related mineral transformations and, through comparison with exhumed faults, the effects of postfaulting alteration on fault zones.

Acknowledgments. Funding for this study was provided from NSF grant EAR-0230055 (BvdP) and an internship from DOSECC Inc. to Solum. The authors thank Steve Hickman and Jim Evans for their help in obtaining samples from the Pilot Hole and Liz Langenburg and Mike Rymer for providing point counts of the cuttings. Constructive reviews by two anonymous reviewers helped to clarify the presentation and interpretation of the data.

References


J. G. Solum and B. A. van der Pluijm, Department of Geological Sciences, University of Michigan, 425 E. University Ave., 2534 C. C. Little Bldg., Ann Arbor, MI 48109-1063, USA. (jsolum@umich.edu)