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Origin and significance of clay-coated fractures in mudrock fragments of the SAFOD borehole (Parkfield, California)

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[1] The clay mineralogy and texture of rock fragments from the SAFOD borehole at 3067 m and 3436 m measured depth (MD) was investigated by electron microscopy (SEM, TEM) and X-ray-diffraction (XRD). The washed and ultrasonically cleaned samples show slickenfiber striations and thin films of Ca-K bearing smectite that are formed on polished fault surfaces, along freshly opened fractures and within adjacent mineralized veins. The cation composition and hydration behavior of these films differ from the Na-montmorillonite of the fresh bentonite drilling mud, although there is more similarity with circulated mud recovered from 3479 m MD. We propose that these thin film smectite precipitates formed by natural nucleation and crystal growth during fault creep, probably associated with the shallow circulation of low temperature aqueous fluids along this shallow portion of the San Andreas Fault.
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1. Introduction

[2] The San Andreas Fault Observatory at Depth (SAFOD) provides an ideal opportunity to investigate the nature of fault-related clay mineral assemblages along an active portion of a plate boundary [*Wintsch et al.*, 1995; *Scholz*, 1999; *Zoback*, 2000; *Hickman et al.*, 2004]. The occurrence of low layer charged smectitic clays are particularly important because of their ability to swell, exchange cations, and transform at low temperatures [*Ahn and Peacor*, 1986; *Cuadros and Altaner*, 1998]. In addition to their reactive behavior, the combination of a high water content and very low permeability gives the swelling clays their lubricating properties. The occurrence of smectite-bearing fault rock has, therefore, been suggested to contribute to the weakening of faults and is possibly a controlling factor in governing seismic stick-slip versus creep mechanisms [*Wu et al.*, 1975; *Chester et al.*, 1993; *Morrow et al.*, 2000; *Warr and Cox*, 2001; *Bedrosian et al.*, 2004]. Although swelling clay mineral assemblages have been described along the surface trace of the San Andreas Fault [e.g., *Wu et al.*, 1975] and along exhumed portions of the fault system [e.g., *Solum et al.*, 2003], our knowledge on the depth distribution of these minerals along the fault zone is limited.

[3] In this contribution we report the first occurrence of natural smectite-coatings at ca. 3 km depth along polished fractures and mineralized veins within mudrock fragments recovered from the SAFOD drill hole (stars in Figure 1a). Based on a detailed microscopy, microchemical and diffraction study of the well-washed rock fragments, we have been able to distinguish between the natural smectite and that introduced via the drilling mud.

2. Samples and Methods

[4] Rock fragments were collected from a spot-core of a clay-rich shear zone at 3067 m MD (Figure 1a). This part of the bore hole represents a potentially active section of the fault zone, although it is not considered to contain the main fault trace [*Zoback et al.*, 2005; *Ellsworth et al.*, 2005]. The grayish-black, fine-grained fragments are up to 10 mm in average length and show distinct polished surfaces with visible striations. Other rock samples with similar polished surfaces were collected at 3436 m MD from inside a core catcher after a failed coring attempt. The rock fragments were carefully washed and ultrasonically cleaned to remove the bentonite drill-mud from the rock surfaces. Bentonite was used as a drilling fluid during rotary drilling and during the failed coring attempt, whereas a KCl-brine was used during the coring run at 3067 m MD. The nature of rock surfaces and freshly opened fractures were then investigated using scanning electron microscopy after carbon coating.

[5] The fracture-coating and vein filling minerals were investigated by high-resolution transmission electron microscopy (HRTEM) and analytical electron microscopy (AEM) following the analytical procedure outlined in *Warr and Nieto* [1998]. Representative rock chip samples were vacuum impregnated with L.R. White resin to prevent a collapse of the smectite interlayers following the procedure of *Kim et al.* [1995]. Small copper washers (1 mm diameter) were glued onto the prepared thin section, then ion milled and carbon coated. HRTEM-AEM work was undertaken using a Philips CM12 scanning-transmission electron microscope (STEM) with a Kevex Quantum solid-state detector (120 kV/20 mA). This was combined with lattice-fringe imaging and selected area electron diffraction pattern (SAED) study. Qualitative AEM analyses of fixed octahedral and exchangeable cations were obtained using the intensity of dispersed X-rays obtained under consistent measurement conditions.

[6] X-ray diffraction (XRD) study was undertaken on minerals sequentially extracted from polished and striated

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