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Constraints on mineralization, fluid-rock interaction, and mass transfer during faulting at 2–3 km depth from the SAFOD drill hole

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[1] Mineralogical and geochemical changes in mudrock cuttings from two segments of the San Andreas Fault Observatory at Depth (SAFOD) drill hole (3066–3169 and 3292–3368 m measured depth) are analyzed in this study. Bulk rock samples and hand-picked fault-related grains characterized by polished surfaces and slickensides were investigated by X-ray diffraction, electron microscopy, and geochemical analysis. The elemental changes in fault-related grains along the sampled San Andreas Fault are attributed to dissolution of detrital grains (particularly feldspar and quartz) and local precipitation of illite-smectite and/or chlorite-smectite mixed layers in fractures and veins. Assuming ZrO_2 and TiO_2 to be immobile elements, systematic differences in element concentrations show that most of the elements are depleted in the fault-related grains compared to the wall rock lithology. Calculated mass loss between the bulk rock and picked fault rock ranges from 17 to 58% with a greater mass transport in the shallow trace of the sampled fault that marks the upper limit the fault core. The relatively large amount of element transport at temperatures of $\sim$110–114°C recorded throughout the core requires extensive fluid circulation during faulting. Whereas dissolution/precipitation may be partly induced by the disequilibrium between fluids and rocks during diagenetic processes, stress-induced dissolution at grain contacts is proposed as the main mechanism for extensive mineral transformation in the fault rocks and localization of neomineralization along grain interface slip surfaces.

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1. Introduction

[2] Fluids associated with the formation of clay minerals are increasingly recognized as an important factor in shallow crustal faulting at depths of <10 km [*Wu et al.*, 1975; *Carter et al.*, 1990; *Sibson*, 1994; *Vrolijk and van der Pluijm*, 1999]. Their circulation along faults and shear zones can enhance mineral dissolution, element transport, mineral precipitation and rock deformation, depending on the temporal and spatial variations in temperature, pressure and element activities [*Beach*, 1976; *Hulsebosch and Frost*, 1989; *Manatschal et al.*, 2000; *Hayman*, 2006]. At low temperatures, such dynamic changes often lead to the crystallization of hydrous clay minerals in the faulted host rock, which influences permeability and fluid flow, and can transform the fault into a fluid barrier. Potential sources of fluids in shallow faults include meteoric, connate, basinal, metamorphic, and hydrothermal waters [*McCaig*, 1984, 1997; *Forster and Evans*, 1991; *Marquer and Burkhard*, 1992]. Whereas fluids in faults and fractures play a key role in the formation of clay minerals and vice versa [*Dewhurst et al.*, 1999; *Tobin et al.*, 2001; *Crawford et al.*, 2002; *Schleicher et al.*, 2006a], the precise role of fluid-rock interaction and associated clay formation in fault zones is not sufficiently understood [*Chester and Logan*, 1986; *Evans and Chester*, 1995].

[3] This paper presents comprehensive geochemical data from hand-picked, fine-grained fault rock cuttings and equivalent mudrock lithologies of the wall rock, sampled at various depths from the SAFOD drill hole. Data collected in this study demonstrate the extent of mineralization and element transport, and describe the fluid-rock interactions in fault rocks and their host lithologies in the deep San Andreas Fault. Two areas of primary interest were targeted for this study (Figure 1c): a shallow fault trace (fault trace 1) between 3066 m and 3169 m measured depths (MD) and the main trace between 3292 m and 3368 m MD (fault trace 2). The $\sim$100 m wide shallow fault section is interpreted as a fault zone on the basis of rock deformation and alteration features [*Bradbury et al.*, 2007; *Solum et al.*, 2006]. This zone lays $\sim$25 m above a level of active casing deformation located at 3194 m [*Hickman et al.*, 2008]. The $\sim$75 m wide main fault trace includes the active fault recognized by

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