Nanocoatings of clay and creep of the San Andreas fault at Parkfield, California

A.M. Schleicher[1], B.A. van der Pluijm[1], and L.N. Warr[2]

[1]Department of Geological Sciences, University of Michigan, 1100 North University Avenue, Ann Arbor, Michigan 48109, USA

[2]Ernst-Moritz-Arndt Universität Institut für Geographie und Geologie, F. Ludwig-Jahn-Strasse 17A, D-17487 Greifswald, Germany

ABSTRACT

Mudrock samples were investigated from two fault zones at ~3066 m and ~3296 m measured depth (MD) located outside and within the main damage zone of the San Andreas Fault Observatory at Depth (SAFOD) drillhole at Parkfield, California. All studied fault rocks show features typical of those reported across creep zones with variably spaced and interconnected networks of polished displacement surfaces coated by abundant polished films and occasional striations. Electron microscopy and X-ray diffraction study of the surfaces reveal the occurrence of neocrystallized thin film clay coatings containing illite-smectite (I-S) and chlorite-smectite (C-S) minerals. $^{40}Ar/^{39}Ar$ dating of the illitic mix-layered coatings demonstrated Miocene to Pliocene crystallization and revealed an older fault strand (8 ± 1.3 Ma) at 3066 m MD, and a probably younger fault strand (4 ± 4.9 Ma) at 3296 m MD. Today, the younger strand is the site of active creep behavior, reflecting a possible (re)activation of these clay-weakened zones. We propose that the majority of slow fault creep is controlled by the high density of thin (<100 nm thick) nanocoatings on fracture surfaces, which are sufficiently smectite-rich and interconnected at low angles to accommodate slip with minimal breakage of stronger matrix clasts. Displacements occur by frictional slip along particle surfaces and hydrated smectitic phases, in combination with intracrystalline deformation of the clay lattice, associated with extensive mineral dissolution, mass transfer, and residual precipitation of expandable layers. The localized concentration of smectite in both I-S and C-S minerals contributes to fault weakening, with fracturing and fluid infiltration creating new nucleation sites for neomineralization on displacement surfaces during continued faulting. The role of newly grown, ultrathin, hydrous clay coatings contrasts with previously proposed scenarios of reworked talc and/or serpentine phases as an explanation for weak fault and creep behavior at these depths.

INTRODUCTION

Fault creep occurs as aseismic slip in the uppermost part of the Earth's crust in the time between large stress-releasing earthquakes on active fault zones. The origin of fault creep has been the subject of intense debate (e.g., Tocher, 1960; King et al., 1973; Rosen et al., 1998), and is mostly attributed to factors including (1) low values of normal stress; (2) elevated pore-fluid pressures; and (3) low frictional strength. Along today's San Andreas fault, California, United States, several fault segments undergo creep behavior, while adjacent segments appear to show little or no creep (Rymer et al., 1984; Rosen et al., 1998). At Parkfield, active deformation of the well casing during Phase II and Phase III drilling at the San Andreas Fault Observatory at Depth (SAFOD) drillhole, together with changes in velocity, resistivity, and negligible temperature elevation at the slipping boundary at ~3.2 and 3.3 km measured depth (MD), suggest creep and characterize recent fault activity at these depths (Zoback et al., 2005; Hickman et al., 2008).

The low frictional strength of fault rock is commonly attributed to the presence of clay minerals with low frictional coefficients (Bird, 1984; Saffer et al., 2001; Morrow et al., 2007). A diverse variety of mechanically weak clay minerals has been identified within bulk rock samples recovered from the SAFOD drillhole, including illite, chlorite, illite-smectite (I-S), and chlorite-smectite (C-S) minerals (Solum et al., 2006). The occurrence of serpentine and fragments of talc has also been reported, and led to the suggestion that the formation of talc could explain the low frictional strength of this section of the San Andreas fault (Moore and Rymer, 2007; Wibberley, 2007). Localized smectitic clay mineralization has been recognized as thin film (nano) coatings on the fault rock-chip surfaces of drill cuttings and on equivalent surfaces in recovered core (Schleicher et al., 2006). These coatings are associated with polished or striated, and occasionally fibrous, fracture surfaces, features that have also been reported in other fault zones around the world (e.g., Jefferies et al., 2006; Dellisanti et al., 2008). Geochemical investigations of these mineralized SAFOD fault rocks indicate that extensive fluid-rock interaction and mass transfer occurred at these sites (Schleicher et al., 2009b), although current analyses of noble gas extracted from drilling mud indicate that the fault is currently not a site of focused fluid flow (Wiersberg and Erzinger, 2008).

In this contribution we demonstrate the specific characteristics of the secondary clay nanocoatings that neocrystallized on faults and fractures, creating a dense network of interconnected displacement surfaces along the San Andreas fault. It is proposed that dissolution-precipitation–assisted slip along microscopic smectitic phase boundaries and distributed deformation along microshear planes are plausible mechanisms to explain the creep behavior of the San Andreas fault at Parkfield and similar settings elsewhere.

GEOLOGICAL SETTING AND SAMPLES

The SAFOD drillhole is located along the creeping section of the San Andreas fault in central California (Fig. 1A). Northwest of the drillhole, the fault has a creep rate of 2.5–3.9 cm/yr (Titus et al., 2006); microearthquakes (Mw 0–2.0) are detected at shallow depths of 2–3 km (Nadeau et al., 2004). Drilling in summer 2005 successfully crossed the active trace of the San Andreas fault at ~3300 m MD with a measured temperature of ~112 °C

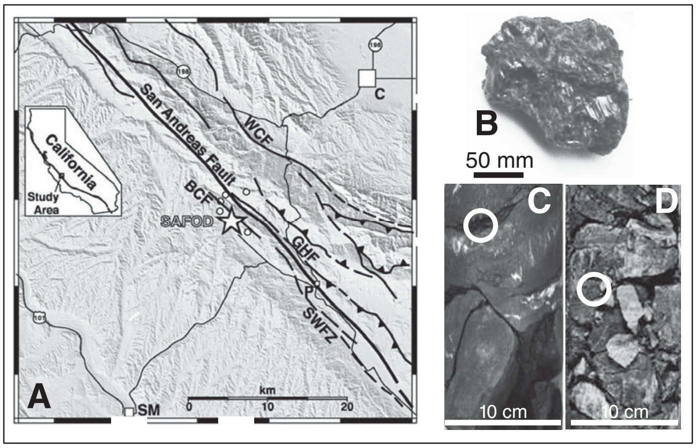

Figure 1. A: Fault map of San Andreas Fault Observatory at Depth (SAFOD) location (after Bradbury et al., 2007). BCF—Buzzard Canyon fault; WCF—Waltham Canyon fault; GHF—Gold Hill fault; SWFZ—Southwest fracture zone; P—Parkfield; SM—San Miguel; C—Coalinga. B: Typical rock chip with polished surfaces and slickensides. C, D: Fault rocks sampled from the 2005 and 2007 cores.