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Nanoscale porosity in SAFOD core samples (San Andreas Fault)

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ABSTRACT

With transmission electron microscopy (TEM) we observed nanometer-sized pores in four ultracataclastic and fractured core samples recovered from different depths of the main bore hole of the San Andreas Fault Observatory at Depth (SAFOD). Cutting of foils with a focused ion beam technique (FIB) allowed identifying porosity down to the nm scale. Between 40 and 50% of all pores could be identified as in-situ pores without any damage related to sample preparation. The total porosity estimated from TEM micrographs (1–5%) is comparable to the connected fault rock porosity (2.8–6.7%) estimated by pressure-induced injection of mercury. Permeability estimates for cataclastic fault rocks are 10^{-21}–10^{-19} m^2 and 10^{-17} m^2 for the fractured fault rock. Porosity and permeability are independent of sample depth. TEM images reveal that the porosity is intimately linked to fault rock composition and associated with deformation. The TEM-estimated porosity of the samples increases with increasing clay content. The highest porosity was estimated in the vicinity of an active fault trace. The largest pores with an equivalent radius > 200 nm occur around large quartz and feldspar grains or grain-fragments while the smallest pores (equivalent radius < 50 nm) are typically observed in the extremely fine-grained matrix (grain size < 1 μm). Based on pore morphology we distinguish different pore types varying with fault rock fabric and alteration. The pores were probably filled with formation water and/or hydrothermal fluids at elevated pore fluid pressure, preventing pore collapse. The pore geometry derived from TEM observations and BET (**B**runauer, **E**mmett and **T**eller) gas adsorption/desorption hysteresis curves indicates pore blocking effects in the fine-grained matrix. Observations of isolated pores in TEM micrographs and high pore body to pore throat ratios inferred from mercury injection suggest elevated pore fluid pressure in the low permeability cataclasites, reducing shear strength of the fault.

1. Introduction

The mechanical behavior of faults depends strongly on the interplay of fluids and damaged fault rocks (Hickman, 1991; Hubbert and Rubey, 1959). Local variation of porosity and fault zone permeability may influence fluid flow and effective pressure, affecting fault mechanics (e.g. Blanpied et al., 1992; Byerlee, 1993; Janssen et al., 2004; Rice, 1992; Schulz and Evans, 1998; Sibson et al., 1975). Laboratory studies and observations of exhumed fault zone rocks indicate that porosity and permeability reduction by compaction or fracture healing may induce high pore fluid pressure, influencing faulting and fault stability (e. g. Faulkner and Rutter, 2001; Hickman et al., 2007; Rice, 1992). Although studies of exposed fault rocks continue to provide important results about the interaction between porosity, fluid flow and fluid pressure, the available information is limited because exhumed fault rocks were altered during exhumation, obscuring fault-related mineral assemblages and textures (Solum and van der Pluijm, 2004).

Core samples from the San Andreas Fault Observatory at Depth (SAFOD) borehole provide a unique possibility to study the microstructures of fresh fault rocks of an active plate-bounding fault from seismogenic depth. A first microstructural study of SAFOD core samples yielded porosity values of 0–18%, with an average porosity of 3% for less deformed shale (Blackburn et al., 2009). Unfortunately, the interpretation of pore origin remains difficult because the applied methods (SEM combined with image-processing, using thresholding techniques) did not allow to distinguish between porosity formed in-situ and pore space formed during core recovery and sample preparation (see also Desbois et al., 2009). To our knowledge permeability data of SAFOD core samples is not yet available.

Here, we present an analysis of submicron pores. Since pores with diameters < 1 μm are not visible in optical thin sections we used transmission electron microscopy (TEM) imaging. In addition, common techniques of porosity determination, such as mercury porosimetry or the BET gas adsorption methods, were used to measure the connected rock porosity, pore volume and pore surface areas of our samples. Porosity data were used to estimate permeability. Different pore types

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are related to sample mineralogy and fabric. Porosity, permeability and pore structure data (i.e. surface area, pore size distribution and pore volume) are used to characterize pore spaces. We discuss the results in terms of fault evolution and compare our observations with those on core material from the Chelungpu Fault drilling Project (TCDP) in Taiwan (e.g. Song et al., 2007) and the Nojima Fault drilling program in Japan (e.g. Shimamoto et al., 2001).

2. Geological setting

The San Andreas Fault (SAF) is a 1.300 km-long transform fault forming the boundary between the northwestward moving western Pacific plate and the eastern North American Plate (Fig. 1). The SAFOD drill site is located in central California at the transition between the creeping segment of the SAF to the North and the Parkfield segment (Fig. 1a). The geology of the SAFOD drill site (Fig. 1b) is characterized by the presence of arkosic sedimentary rocks on the southwestern side of the fault and the presence of Great Valley sedimentary rocks northeast of the fault (Springer et al., 2009). Based on modal content, Bradbury et al. (2007) identified at least four major geological units in the SAFOD drill holes (Fig. 1c). After passing through near-surface Quaternary and Tertiary sediments and the subjacent Salinian granite, arkosic sediments were encountered beneath the Buzzard Canyon fault (Fig. 1b–c). Further east (approximately 1200 m NE of the drill site), the lithology changes abruptly from arkosic sediments of the Salinian terrane (Pacific plate) to claystones and siltstones of the Great Valley/Franciscan terrane (North American plate). The lithological boundary possibly marks an ancestral trace of the SAF (Zoback et al., 2007a). Multiple faults were crossed during drilling, including two actively creeping strands of the SAF, revealed by casing deformation at measured depths of 3192 m and 3302 m (Bradbury et al., 2007). These active fault traces are referred to as the southwest deforming zone (SDZ) and central deforming zone (CDZ), respectively. They were the principal targets for coring during Phase 3 in 2007 (Zoback et al., 2010).

3. Samples

We analyzed microstructures of four samples from SAFOD phase III cores (S1, S2, S3 and S4; see also Photographic Atlas of the SAFOD Phase 3 Cores 2010, for detailed descriptions of cores). The samples were recovered from different core sections located close to or at some distance to zones of active deformation (Fig. 1c). The mineralogical composition of all samples is documented in Table 1. All depth reported for our samples are measured depth (MD) and be synchronized to the Phase 2 Baker-Atlas Open-hole logs (Zoback et al., 2010; electronic supplement).

Sample S1 (3141 m MD) was taken from a fractured, grayish-red to brownish sandstone (Hole E, Run 1, Section 6), which belongs to a sequence of arkosic sedimentary rocks with interbedded shales and siltstones. The matrix is composed of coarse- to very coarse subrounded grains with visible feldspar and quartz particles (several mm in diameter, Fig. 2a). This section of arkosic rocks is crosscut by several mesoscale faults (Photographic Atlas of the SAFOD Phase 3 cores, 2010; Springer et al., 2009). The sample position is close to a fault-contact between silt- and sandstone but at a distance from the active fault trace (SDZ) of about 50 m.

Samples S2, S3 and S4 belong to the Great Valley sequence (see Bradbury et al., 2007). Sample S2 was collected at 3189 m MD (Hole G, Run 2, Section 4). This position of the core is at 3 m distance to the active SDZ. The strongly foliated shale cataclasite is composed of a brown, fine-grained calcite-bearing clay matrix (grain size < 1 μm) containing quartz and feldspar clasts (Fig. 2b; Photographic Atlas of the SAFOD Phase 3 cores, 2010). Pervasive shearing is defined by dark seams in the matrix and preferred orientation of grains. Abundant pressure solutions seams and authigenic clay minerals indicate extensive fluid–rock interaction and dissolution–precipitation processes (Fig. 2b, see also Gratier et al., 2009; Hickman et al., 2008; Schleicher et al., 2009). The sample contains several calcite vein generations, with the latest one overprinting the fault-related fabric.

Sample S3 is from 3300 m MD (Hole G, Run 4, Section 2), i.e. it roughly coincides with the CDZ and thus represents an actively creeping portion of the SAF. The sample shows a polished slip surface with slickensides. Sample S3 consists of a dark-brown fractured and fine-grained scaly matrix with a higher percentage of illite-smectite (I-S) compared to sample S2 (Fig. 2c). In addition, chlorite is a major mineral constituent of the sample (Table 1). Similar to sample S2, seams of insoluble material (pressure solution relicts) and authigenic clay minerals suggest considerable activity of dissolution–precipitation processes.

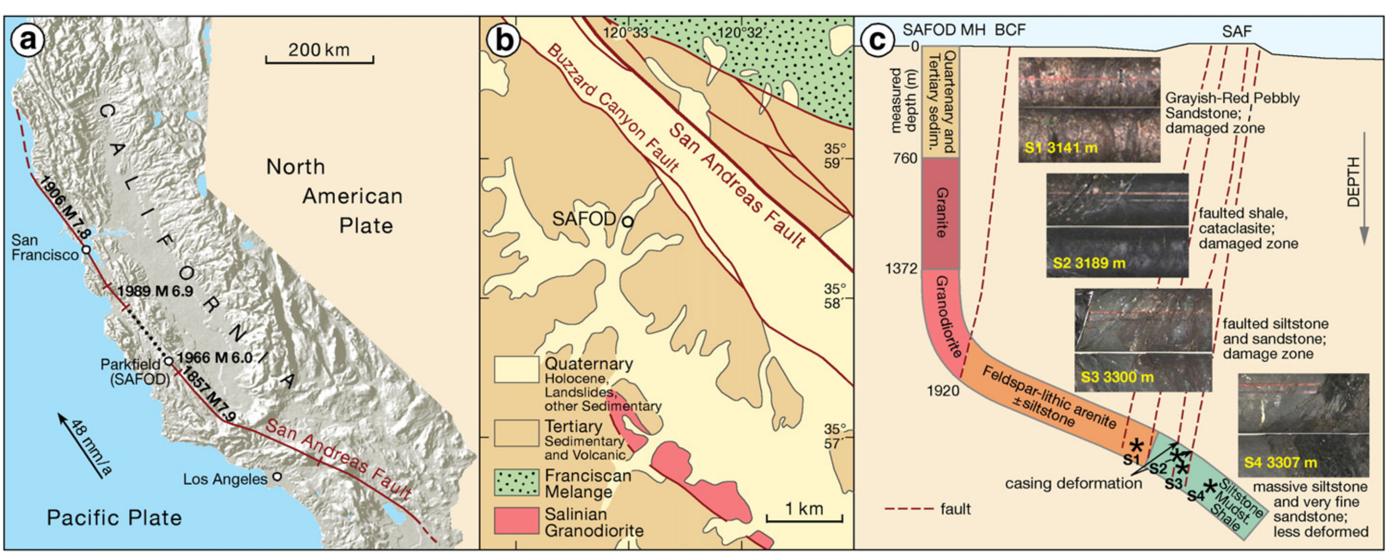

Fig. 1. Location map of the study area. (a) The San Andreas Fault with the SAFOD drill site. The arrow shows the sense of plate movement (Hickmann et al., 2004). Some major historical earthquakes are indicated. The dotted line characterizes the creeping segment. (b) Geological map of the drilling site (modified after Bradbury et al., 2007 and Dibblee et al., 1999). (c) Simplified depth profile of the SAFOD MH (Main Hole) with different rock lithologies and sample positions (synchronized to the Phase 2 Baker-Atlas Open-hole logs). BCF-Buzzard Canyon fault, SAF-San Andreas Fault.