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Deep permeability of the San Andreas Fault from San Andreas Fault Observatory at Depth (SAFOD) core samples☆

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ABSTRACT

The San Andreas Fault Observatory at Depth (SAFOD) scientific borehole near Parkfield, California crosses two actively creeping shear zones at a depth of 2.7 km. Core samples retrieved from these active strands consist of a foliated, Mg-clay-rich gouge containing porphyroclasts of serpentinite and sedimentary rock. The adjacent damage zone and country rocks are comprised of variably deformed, fine-grained sandstones, siltstones, and mudstones. We conducted laboratory tests to measure the permeability of representative samples from each structural unit at effective confining pressures, P_e up to the maximum estimated *in situ* P_e of 120 MPa. Permeability values of intact samples adjacent to the creeping strands ranged from 10^{-18} to 10^{-21} m^2 at $P_e = 10$ MPa and decreased with applied confining pressure to 10^{-20}–10^{-22} m^2 at 120 MPa. Values for intact foliated gouge samples (10^{-21}–6×10^{-23} m^2 over the same pressure range) were distinctly lower than those for the surrounding rocks due to their fine-grained, clay-rich character. Permeability of both intact and crushed-and-sieved foliated gouge measured during shearing at $P_e \geq 70$ MPa ranged from 2 to 4×10^{-22} m^2 in the direction perpendicular to shearing and was largely insensitive to shear displacement out to a maximum displacement of 10 mm. The weak, actively-deforming foliated gouge zones have ultra-low permeability, making the active strands of the San Andreas Fault effective barriers to cross-fault fluid flow. The low matrix permeability of the San Andreas Fault creeping zones and adjacent rock combined with observations of abundant fractures in the core over a range of scales suggests that fluid flow outside of the actively-deforming gouge zones is probably fracture dominated.

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1. Introduction

Many models have been devised to describe the permeability and fluid flow characteristics of fault zones in an effort to address the long-standing discrepancy between heat-flow measurements, seismic stress drops, and the strength of crustal rocks (Lachenbruch and Sass, 1980, 1992; Hickman, 1991; Brune et al., 1969; Mount and Suppe, 1987; Zoback et al., 1987). For instance, Rice (1992), Byerlee (1990), Sibson (1992), Sleep and Blanpied (1992), Mase and Smith (1987), and Faulkner and Rutter (2001) all invoke low-permeability regions within or adjacent to the actively-deforming fault core and fluid-pressure controlled fault weakening to explain the apparent weakness of the San Andreas Fault. Understanding fault-zone permeability structure is of paramount importance to these efforts. Permeability profiles across the Median Tectonic Line, Japan (Wibberley and Shimamoto, 2003), the Punchbowl fault, California (Chester and Logan, 1987), the Stillwater fault, Nevada (Caine et al., 2010), and the Carboneras fault, Spain (Faulkner et al., 2003) show that many fault zones, especially ones that have evolved with time, are more complex than the simple model of a low-permeability fault core bounded by high-permeability damage zones (e.g., Caine et al., 1996; Lockner et al., 2009).

The San Andreas Fault Observatory at Depth (SAFOD), located NW of the town of Parkfield, California, provides a unique opportunity to investigate the permeability of a seismically active, plate-bounding fault zone sampled at depth (Zoback et al., 2010). At Parkfield, slip on the San Andreas Fault (SAF) has brought

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dissimilar materials into contact. To the west of the fault lie Salinian granites and granodiorites, arkosic sandstones, and conglomerates, while to the east are found Cretaceous Great Valley Formation siltstones, mudstones and shales (Fig. 1a). The SAFOD borehole crossed the fault at a vertical depth of 2.7 km. An

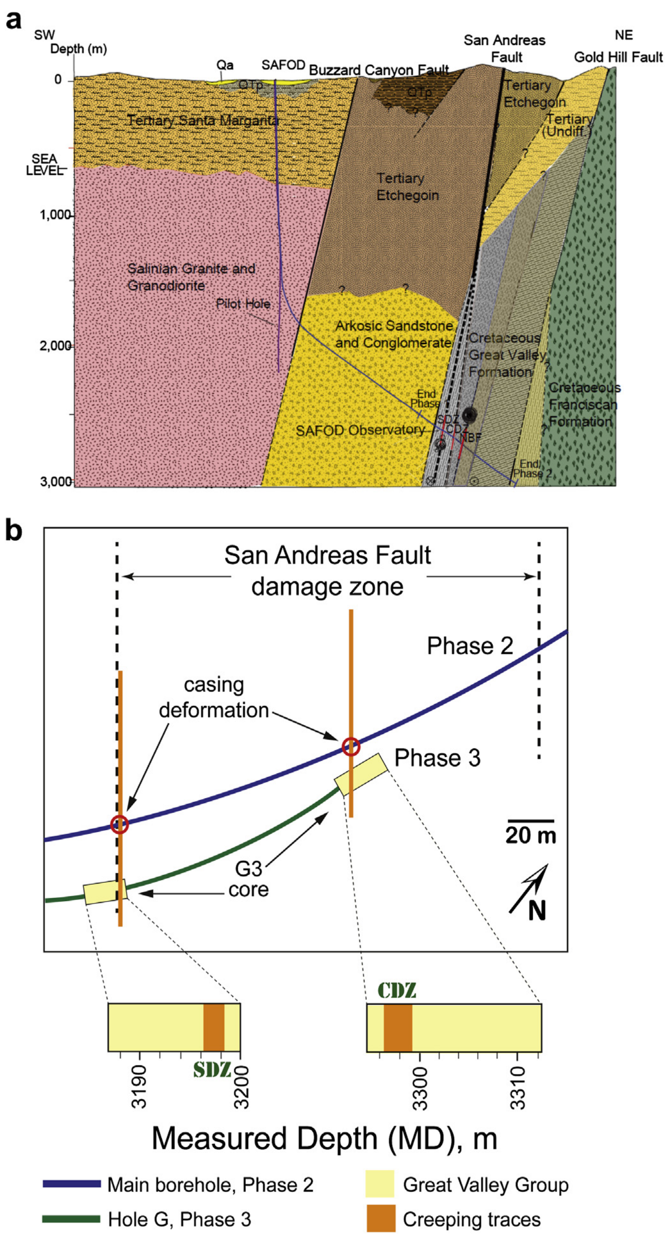

Fig. 1. a) A simplified geologic cross-section along the trajectory of the San Andreas Fault Observatory at Depth (SAFOD) borehole. The three prominent fault strands associated with the San Andreas Fault damage zone are shown in red. The southwest deforming zone (SDZ) and the central deforming zone (CDZ) are actively creeping faults identified through casing deformation. The damage zone is bounded by the SDZ and the northeast boundary fault (NBF). The black circles represent repeating microearthquakes. The depth at which SAFOD observatory instrumentation is deployed is shown. From Zoback et al. (2011). b) Map view of Phase 3 Hole G (green line) relative to the Phase 2 portion of the SAFOD main borehole (blue line). Coring targeted the SDZ and CDZ. Although SAFOD is drilled at a high angle to the San Andreas Fault Zone, the angle between the Hole G core axis and the SDZ and CDZ is not accurately known (see text). Modified from Fig. 1 of Lockner et al. (2011).

approximately 200 m-wide damage zone was encountered within rocks of the North American Plate (northeast side), which is characterized by anomalously low P- and S-wave velocities and low resistivity (Zoback et al., 2010, 2011). Observations of fault-zone guided waves in the SAFOD borehole show that this damage zone is laterally extensive and extends downwards to a depth of at least 7 km (Ellsworth and Malin, 2011). Two narrow, actively-deforming zones were identified within the damage zone based on borehole casing deformation. These actively-deforming zones, at 3192 and 3302 m measured depth (MD, depth as measured along the borehole) in the main Phase 2 borehole were the primary targets for coring during Phase 3 drilling in 2007. Phase 3 Hole G was drilled sub-parallel to the Phase 2 borehole and a total of ~30.7 m of core was recovered across the deforming zones at two depths roughly 100 m apart (Fig. 1b). (See Zoback et al., 2010, supplemental material, for a discussion of the correlation between measured depths in the Phase 2 and Phase 3 boreholes.) Two Mg-clay-rich gouge zones, referred to as the southwest deforming zone (SDZ) and the central deforming zone (CDZ), encountered in Hole G correspond to the two places identified in the Phase 2 borehole using repeat 40-finger caliper logs where the cemented steel casing was being deformed in response to fault creep. The CDZ takes up the majority of this active creep (Zoback et al., 2010). The northeast boundary of the San Andreas damage zone is defined by a narrow zone that has similar geophysical characteristics to the SDZ and CDZ. This zone is referred to as the northeast boundary fault (NBF) and is aligned with locations of the nearby repeating San Francisco and Los Angeles microearthquake clusters (Zoback et al., 2011). However, no casing deformation was detected on the NBF in any of the repeat caliper logs run from 2005 through 2007; thus, if this zone was creeping, it must have been at a relatively low rate. The two observed creeping strands are surrounded by variably deformed sedimentary rocks of the Great Valley Group (Fig. 2). See Bradbury et al. (2011) and Holdsworth et al. (2011) for descriptions of the lithology and internal structure of the recovered core sections.

In this study we present permeability measurements of axially oriented core (fluid flow in a direction parallel to the borehole axis) from the two Hole G cored intervals to relate the overall permeability structure of the SAF to rock type, mineral composition and rock strength. Sample locations and lithology are shown in Fig. 2 and discussed in more detail in Appendix 1. As mentioned above and discussed in more detail below, fault-zone permeability structure is expected to play an important role in determining pore pressure distribution and rates of fluid flow across and within the San Andreas Fault Zone. Our measurements show that, overall, matrix permeability is low throughout the damage zone and extremely low in the clay-rich actively-deforming zones.

2. Samples studied

Seventeen samples oriented parallel to the core axis were selected (black filled circles in Fig. 2), to obtain representative data for all of the major structural units. Measured depths in Hole G of these samples are reported in Table 1. Hole G is oriented at a slightly oblique angle (~80–90°) to the strike of the surface trace of the SAF, at an inclination of 52–62° from vertical at the depths from which the cores used in this study were obtained (see borehole trajectory for all SAFOD phases at http://safod.icdp-online.org). However, the strike and dip of the active strands of the SAF where cored by SAFOD are not well constrained, and the exact orientation of the core relative to the SDZ and CDZ is still a topic of ongoing research. For the purposes of the present study, this uncertainty in relative orientation should not be significant. Indeed, as we discuss