Permeability, electrical resistivity and frictional strength of SAFOD fault gouge and damage zone rocks

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Introduction

The San Andreas Fault Observatory at Depth (SAFOD) scientific drillhole near Parkfield, California crosses two actively deforming shear zones at a vertical depth of 2.7 km, referred to as the southwest deforming zone (SDZ) and the central deforming zone (CDZ). Core samples retrieved from these active strands consist of a foliated gouge containing the magnesium-rich clay minerals saponite ± corrensite, with porphyroclasts of serpentine and sedimentary rock. The adjacent damage zones are comprised of fine-grained sandstones, siltstones, and mudstones. We have conducted laboratory tests to measure the permeability, electrical resistivity and frictional strength of these various samples at effective confining pressures, P_{eff}, to 200 MPa to determine how physical properties vary across these two creeping segments. Our goals are to help explain the apparent weakness of the San Andreas fault inferred from heat-flow and stress orientation data, and to understand how pore fluids affect fault behavior.

Experimental Method

Permeability and Electrical Resistivity:

Intact samples of core material were tested at effective confining pressures, P_{eff}, up to 120 MPa using a brine formulated to duplicate the *in situ* formation fluid chemistry. Permeability was determined by using a steady-state fluid flow technique and applying Darcy's Law. Electrical resistance of the samples was measured using a two electrode system. Excitation was provided by a 200 Hz sine-wave generator with nominal peak-to-peak voltage of 3 volts.

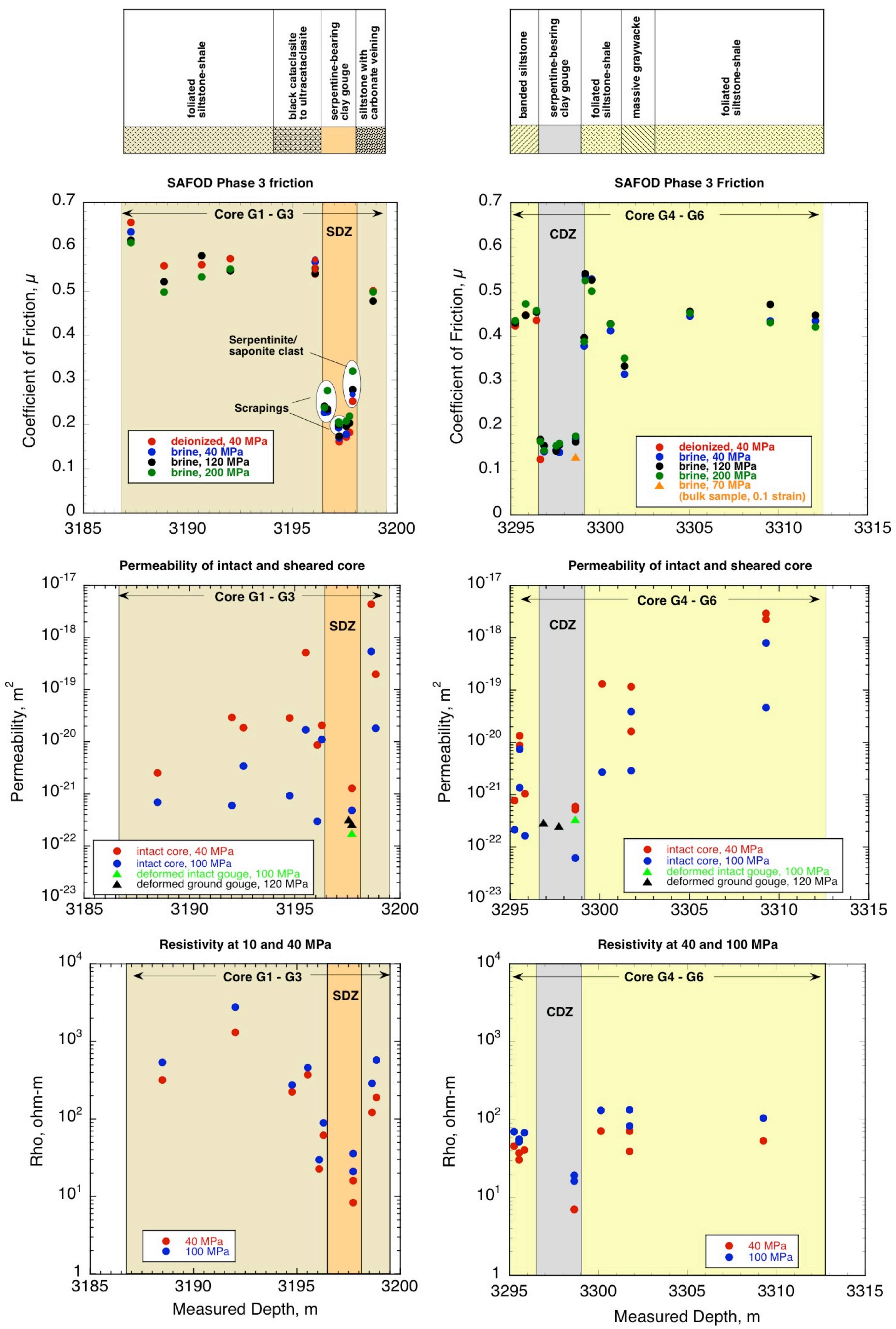
Friction, deformed ground core:

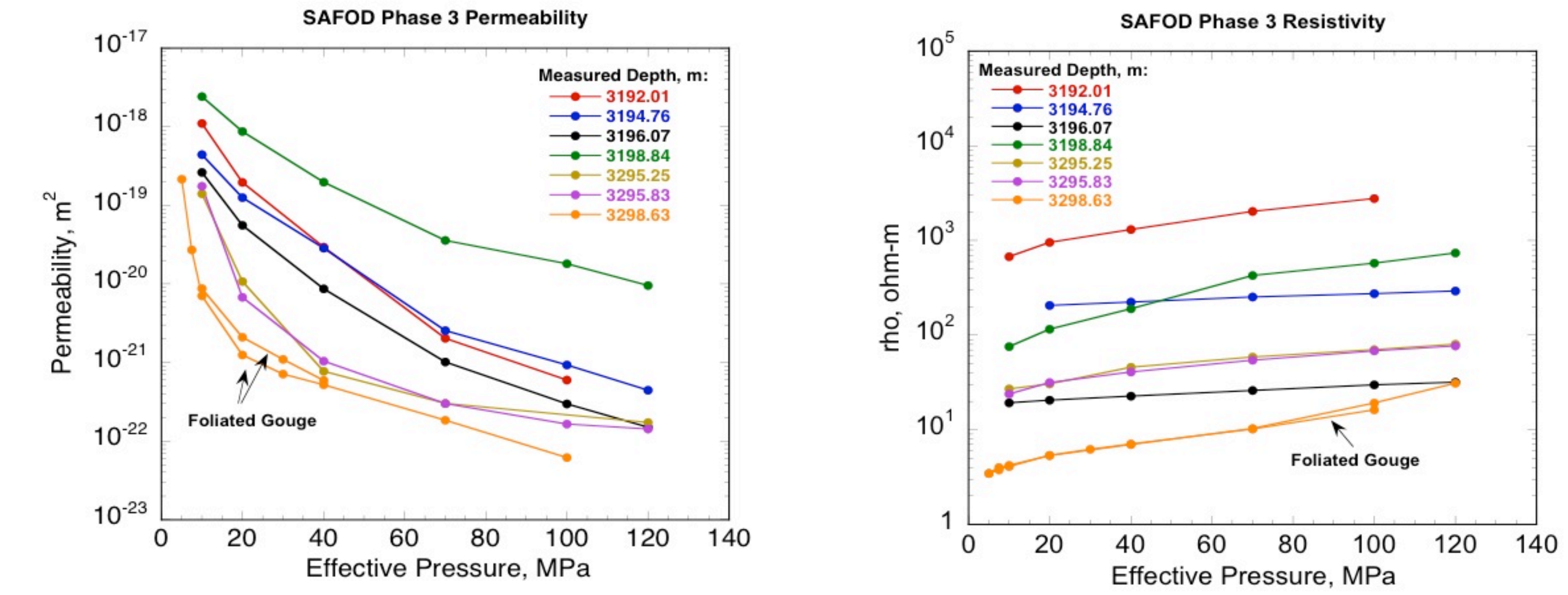
The core material was crushed and sieved to <150 µm. The resulting powder was then saturated with brine and applied in a 1-mm layer between saw-cut sliding blocks containing a 30° sawcut. Each sample assemblage was sheared at constant pore fluid pressure of 1 MPa and effective normal stress of 40, 120 and 200 MPa. Sliding proceeded at 1 µm/sec to 9 mm of axial shortening. In some experiments, permeability was measured during shearing.

Strength, deformed intact core:

Saturated, intact samples were deformed to 10% strain at 1 µm/sec and P_{eff} = 100 MPa. Sliding was halted at various displacements to measure permeability.

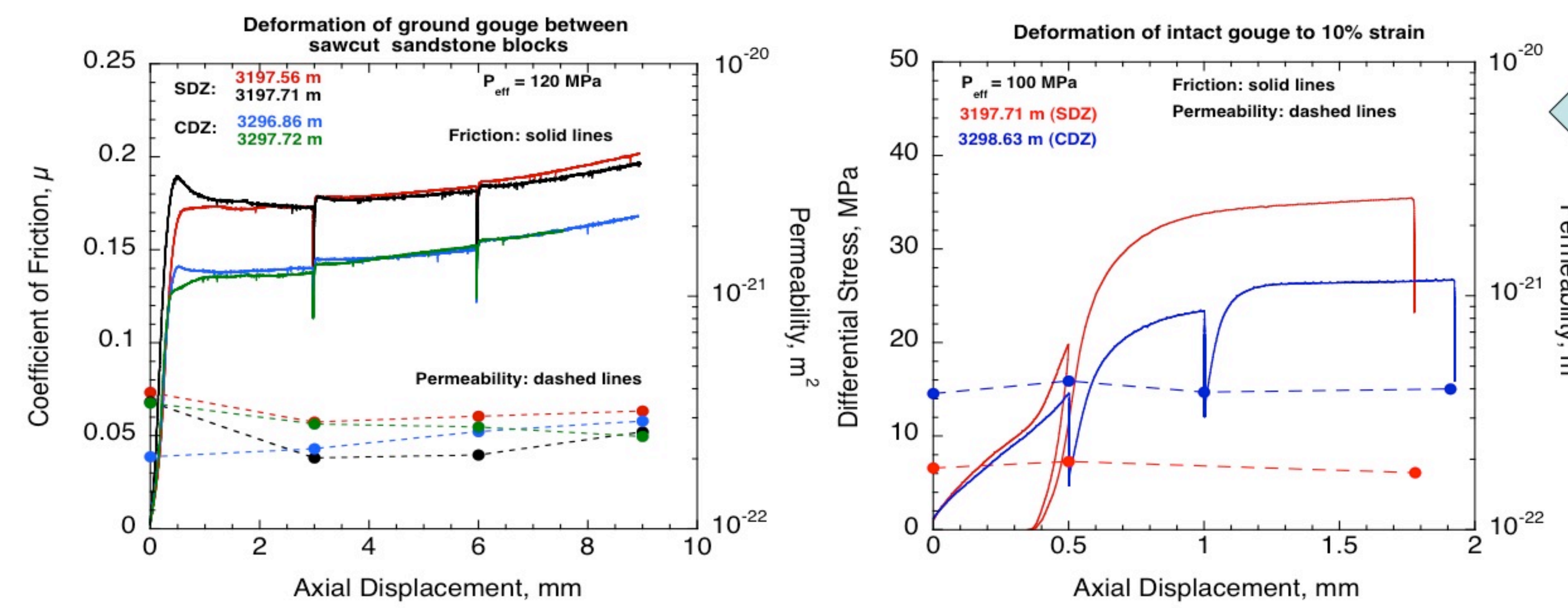
Lithology and Physical Properties of SAFOD Phase 3 Core





Permeability and Electrical Resistivity

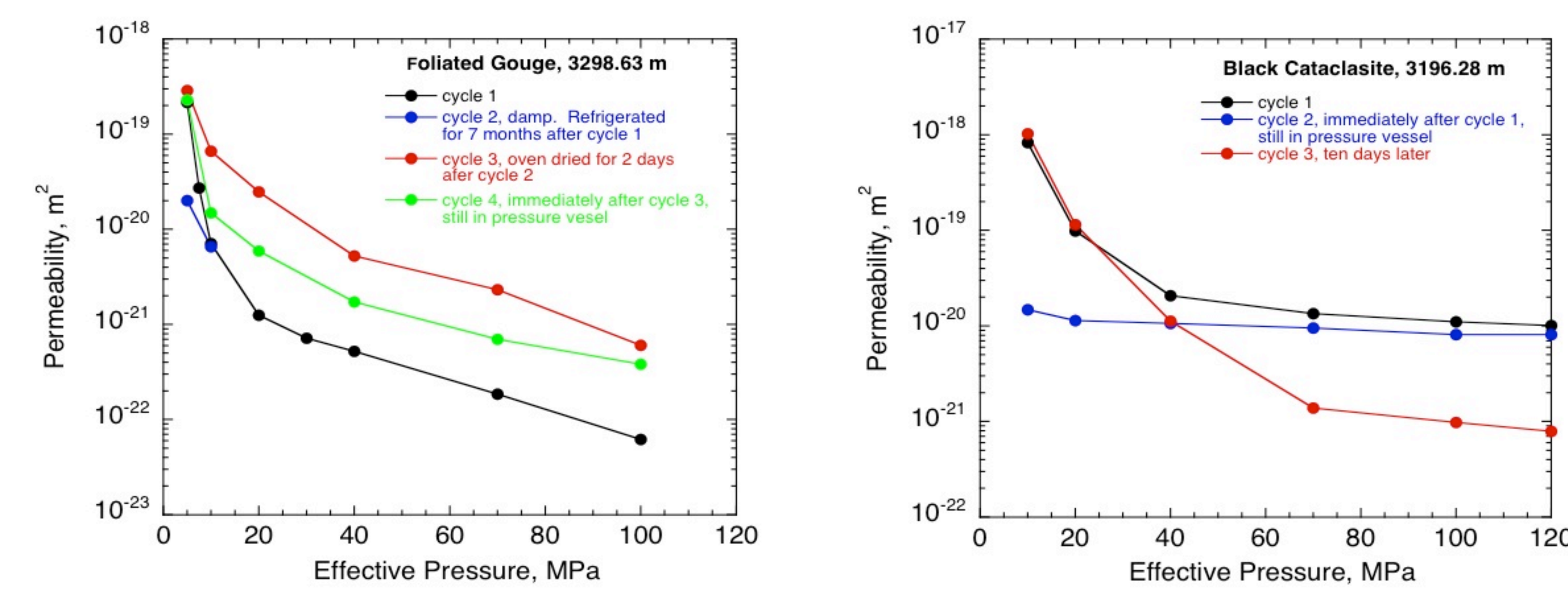
Permeability decreased with applied pressure from around 10^{-18} m^2 at 10 MPa to 10^{-20} to 10^{-22} m^2 at 120 MPa due to porosity reduction. Foliated gouges had the lowest permeability. Associated electrical resistivity increased with pressure, again with foliated gouges having the lowest values (3-30 ohm-m).



Strength and Permeability of Gouge

Deforming zone gouges are weak because the clay mineral saponite (µ~0.05), comprises 60-65% of the volume fraction of the gouge matrix. Corrensite (µ probably greater than saponite) was also found in the SDZ, and that together with the increased quartz content in the SDZ explains why the the frictional strength and differential stresses were marginally higher than the CDZ values.

Permeability was around 2 to 4 x 10^{-22} m^2 and was independent of displacement, indicating that most of the permeability loss occurred during the initial loading of the samples in both sets of experiments.



Pressure Cycling of Samples

Measured permeability values reflect both the *in situ* permeability and the effects of sample retrieval. To determine the susceptibility of permeability to handling, we conducted cycling experiments under a variety of loading and saturation histories. Repeated cycles in the pressure vessel while still saturated showed little permeability recovery. In contrast, samples removed from the vessel and dried showed full recovery upon reloading. Samples removed from the vessel but remaining damp showed partial recovery. Consequently, inferring *in situ* properties in these samples is problematic.

Conclusions

- Permeability values of intact damage zone samples were around 10^{-18} to 10^{-22} m^2 at applied pressures to 120 MPa. Permeability of the foliated gouge was generally lower than the damage-zone rocks (10^{-20} to 10^{-23} m^2 over the same pressure range) due to the fine-grained, clay-rich nature. Such extremely low permeability would constitute a cross-fault barrier to fluid flow at depth, in agreement with mud gas analyses carried out across the San Andreas Fault in SAFOD (*Wiersberg and Erzinger*, 2008).

- Corresponding electrical resistivity values increased with increasing P_{eff}, but were also lower for the foliated gouge (3 to 30 ohm-m) compared to the damage zone rocks (40 to 1000 ohm-m) in agreement with wireline log data.

- The coefficient of friction in the two shear zones (µ = 0.15-0.2) was much lower than that of the damage zone rocks (µ~0.4-0.6) due to the presence of the weak phyllosilicate mineral saponite. Thus, the apparent weakness of the San Andreas Fault, based on stress orientation and heat flow data, can be explained entirely by the rheologic properties of the fault gouge at the SAFOD location without appealing to high fluid pressure, shear heating or other stress reducing mechanisms (*Lockner et al.*, 2011). The actual fault zone pore pressure has not yet been determined from direct borehole observations.

Lockner, et al., Low strength of deep San Andreas fault gouge from SAFOD core, *Nature*, doi:10.1038/nature09927, 2011.

Wiersberg and Erzinger, Origin and spatial distribution of gas at seismogenic depths of the San Andreas fault from drill-mud gas analysis, *Applied Geochemistry*, *23*, 1675-1690, 2008.

Lithology from Bradbury et al., Lithology and internal structure of the San Andreas fault at depth based on characterization of Phase 3 whole-rock core in the…, *Earth Planet. Sci. Lett.*, doi:10.1016/j.epsl.2011.07.020, 2011.