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PERMEABILITY AND STRENGTH OF SAN ANDREAS FAULT GOUGE UNDER HIGH PRESSURE

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Abstract. The permeability and strength of San Andreas fault gouge from the Cienega Valley was measured under confining pressures up to 2 kbar. The gouge was composed almost entirely of clay minerals, predominantly montmorillonite and mixed-layer clays. Permeabilities ranged between 1 and 10 nanodarcies for confining pressures of a few hundred bars to 1 kbar, and less than 1 nanodarcy for pressures greater than 1 kbar. Permeability was sensitive to confining pressure and differential stress, but did not depend significantly on accumulated strain.

The low strength of saturated clay is often attributed to the buildup of excess pore pressure as the clay is stressed. These experiments, performed under drained conditions where excess pore pressure was not created, suggest that loosely bonded interlayer water in the hydrated clays can generate a pseudo-pore pressure that serves to lower the strength of the gouge.

Introduction

Models of fault dynamics show that a wide variety of fault behavior is possible, depending on parameters that are not well determined to date, such as fault zone thickness and permeability [Bredehoeft and Hanshaw, 1968; Lachenbruch, 1980] . In particular, the permeability of fault gouge has been shown to be intimately related to the extent of frictional heating, anomalous pore fluid pressures, and shear strength of a fault. This inter-relationship is exemplified by Raleigh's [1977] model of fault gouge behavior in which frictional heating causes the dehydration of gouge clays. The released water serves to lower the strength of the fault if excess pore pressures are maintained by a low-permeability gouge. Zoback [personal communication, 1980] found high-pressure gas trappped in San Andreas fault gouge clays at a depth of only 183 m, suggesting that these clays are indeed highly impermeable.

Fault gouge varies widely in composition [Wu, 1978 , but usually contains appreciable amounts of clay. This clay has been observed at depths up to a few kilometers, [Brekke and Howard, 1973] and may persist to depths as low as 10-15 km, based on the stability fields of various clays, and the interpretation of velocity and gravity profiles of fault zones. Fault gouge may therefore be a controlling factor in the flow of water through fault regions.

The permeability of clay and clay-rich sand at pressures lower than 100 bars typically ranges between 10^{-6} and 10^{-2} darcies [Lambe, 1954; Michaels and Lin, 1954; Lambe and Whitman, 1969]. The permeability of fault gouge at high pressure has not even been determined to an order of magnitude, but is clearly of paramount importance when discussing the behavior of faults where *in situ* confining pressures are high. For this reason, a number of experiments were performed to study the permeability of clay gouge under both hydrostatic and triaxial conditions at high confining pressures.

Gouge Description

The gouge used in this study was taken from the 402 m level of a hole drilled into the San Andreas fault at Cienega Valley near Hollister, California. The material consisted almost entirely of clay, with some quartz and feldspar grains. X-ray analysis of the clay size fraction showed it to be composed of 31% montmorillonite, 32% mixed-layer clays, 17% illite, 16% kaolinite and 4% chlorite. The analytical method was after Schultz [1964]. Although the permeability depends in part on clay type and pore fluid chemistry [Lutz and Kember, 1959; Mitchell, 1976], this mixed-composition clay gouge seemed appropriate for establishing a representative permeability in naturally occurring material. Also, in conforming the clay gouge to our experimental apparatus, the *in situ* grain fabric was not preserved. This could produce some discrepancies between natural and laboratory measured permeabilities, however, during our shearing experiments, grain fabric may be developed that mimics the naturally sheared state.

Experimental Method

Cylindrical samples of Berea sandstone, 2.54 cm in diameter and 6.35 cm long, were cut in half along a plane oriented at an angle of 30° to the axis (Figure 1). The sandstone halves were separated by a 1.0 mm thick layer of San Andreas fault gouge along the saw cut. The gouge was saturated with distilled water, using the same volume of water and the same procedure each time. A 0.13 mm thick copper sleeve held the two pieces together. The entire assembly was then jacketed in polyurethane to isolate the confining and pore pressures, allowing both the pore pressure and confining pressure to be varied independently. The confining pressure and inlet pore pressure were held constant by a computer-controlled servo-mechanism. Pore pressure was maintained at either 10 or 20 bars at the inlet side and atmospheric pressure at the outlet, creating a gradient through which the distilled water flowed. The flow rate of water through the gouge was measured by recording the volume of the pore fluid reservoir at 2 second intervals, giving

$$\frac{dV}{dt} = q$$

q was measured over an average of 8 hours after the flow rate had come to equilibrium.

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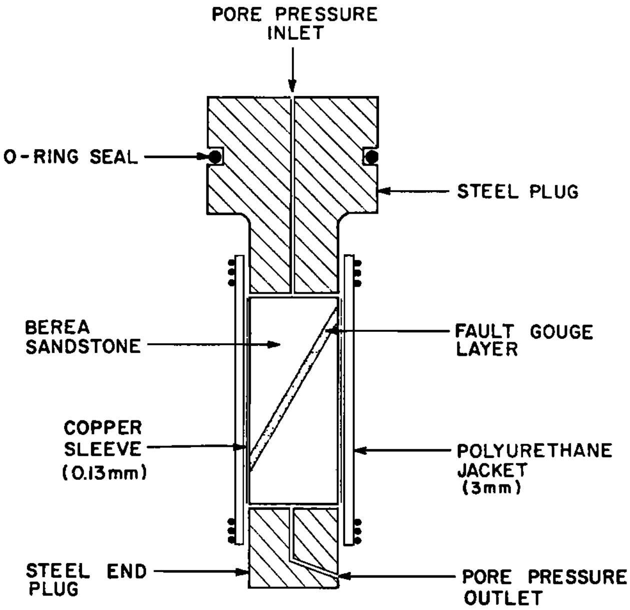

Fig. 1. Sample assembly.

Experiments were performed at a controlled temperature of 27° ±.5 C to allow accurate measurement of pore volumes.

From the flow rate measurements, permeability of the gouge may be calculated from Darcy's law:

$$k = \frac{q\mu}{A} \left(\frac{dP}{dx}\right)^{-1}$$

where q is the volumetric flow rate per unit area of gouge, μ is the dynamic viscosity of water, A is the cross-sectional area normal to the direction of flow, and dP/dx is the pressure gradient across the fault.

The permeability of Berea sandstone ranges from 140 to 180 millidarcies measured parallel to the bedding plane [Zoback and Byerlee, 1975]. This is significantly higher than the expected permeability of the fault gouge. Therefore, the pore pressure drop must occur primarily across the gouge, and the effects due to the sandstone can be neglected in the permeability calculations. Uncertainties in the measurements of the Cienega Valley gouge (particularly due to the undetermined amount of elastic compaction under pressure) could lead to errors of as much as 20% in the absolute permeability. However, relative changes in permeability are accurate to within ±5%, and all values represent an upper limit.

A series of experiments were run to highlight various aspects of the gouge behavior. First, permeability was measured under hydrostatic conditions at confining pressures up to 2 kbars during loading and unloading. This is done with different combinations of gouge thickness and pore pressure to determine whether these parameters would affect permeability. The next experiments showed the effects of shearing and differential stress on flow through the gouge. Permeability was measured on the same sample after 0.5, 1.0, 3.0, 5.0, 7.0, and 9.0 mm of sliding with 2 kbar confining pressure. The axial load was removed for each measurement. Thus, the permeability could be determined as a function of strain without the added effect of differential stress. The sample strain rate (axial shortening) of 10^{-6} s^{-1} corresponded to a slip rate along the clay layer of 7.33 X 10^{-5} mm/s. In a similar experiment, a saturated sample was strained to 3 mm of axial displacement at a strain rate of 10^{-6} s^{-1}. The axial stress was then held constant and the sample allowed to creep. This was done to observe the direction of fluid flow while under an axial load, and thus determine whether the sample was drained.

Lastly, the effect of water on the strength of the gouge was investigated. A vacuum-dried sample of gouge was slid a distance of 5 mm at 2 kbar confining pressure. It was then evacuated to ensure that no pockets of air remained trapped within the sample, and saturated with water while still under confining pressure. In this way, no excess pore pressure was generated as may result in presaturated samples. The sample was slid another 5 mm to compare the wet and dry strengths under drained conditions.

Results

It was necessary to determine whether the gouge had filtered into the sandstone during the course of the experiments. If this were to occur to a substantial degree, the calculated permeabilities could be overestimated or altogether meaningless, and the strength measurements could reflect the shear strength of the sandstone. For this reason, a thin section of a selected sample was examined under the microscope. The gouge layer showed an average of 15% compaction, from 1 to 0.85 mm in thickness. Clay particles protruded less than 0.09 mm into the sandstone to fill pores between the topmost grains. The average grain diameter in the sandstone was 0.41 mm. It

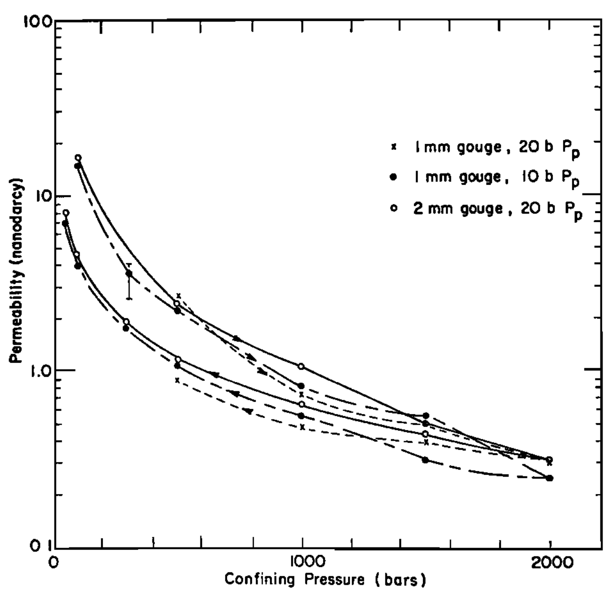

Fig. 2. Permeability of Cienega Valley fault gouge vs. hydrostatic confining pressure, showing loading and unloading paths for different gouge thicknesses, and inlet pore pressures of 10 or 20 bars.

was therefore determined that filtering into the sandstone had not occured to any significant extent.

Permeability

The permeability of Cienega Valley fault gouge under hydrostatic stress is plotted in Figure 2. Upon unloading, the gouge was consistently less permeable than during loading at the same pressure, because the compaction during loading was not completely recoverable. Variations in gouge thickness and pore pressure had little effect on permeability. At confining pressures greater than 1 kbar, the permeability was less than 1 nanodarcy.

Figure 3 (curves A and B) shows the stress-displacement data and associated permeabilities for the sliding experiment. As differential stress was applied (curve A), the sample compacted and the permeability decreased (curve B). Permeability did not vary markedly after the sample began sliding at 1 mm of displacement.

During the sliding-creep experiment (curve C), the strength of the gouge closely followed that of curve A. In the creep segment after 3 mm of displacement, the fluid flow record indicated that water was able to flow into the gouge to maintain the pore pressure differential of 20 bars. Therefore the pore pressure could not have been greater than 20 bars, and the sample was drained. This observation is pertinent to the permeability calculations in which the pressure gradient in the gouge must be known. Permeability remained constant at 0.1 nanodarcy during creep.

Strength

The difference in strength between the wet and dry Cienega Valley gouge is illustrated by curves A and D in Figure 3. The wet gouge (curve A) had a yield strength of 500 bars, whereas the vacuum-dried gouge (curve D) yielded at approximately 1 kbar. The addition of through-flowing water to the dried gouge after 5

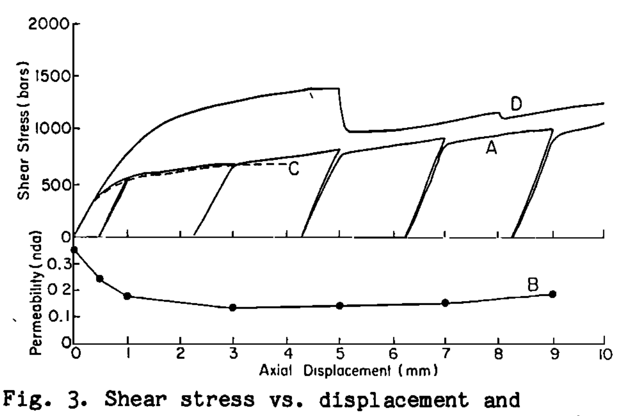

Fig. 3. Shear stress vs. displacement and permeability plot for sliding experiments at 2 kbar confining pressure. (A) Initially saturated sample. The axial load was released for permeability measurements (B). (C) Saturated sample. The axial load was fixed after 3 mm of sliding. (D) Initially dry sample, saturated after 5 mm of sliding.

mm of sliding resulted in an immediate loss of strength of about 500 bars. The low strength of wet clay is often attributed to the presence of excess pore pressure that results as the sample is stressed and unable to drain [Wang et al., 1980]. However, these experiments were performed under drained conditions (implying no excess pore pressure due to free water), and yet the clay still exhibited a low strength, as also observed by Wang and Mao, [1979]. It has been suggested elsewhere, [Summers and Byerlee, 1977; Byerlee, 1978] with dry, expandable clays such as montmorillonite and vermiculite, that loosely bonded interlayer water can produce a pseudo-pore pressure that causes significantly lower strength than the nonexpandable clays. This interlayer water, characteristic of expanding clays, may be a few layers thick when the sample is "dry", and hundreds of layers thick when the sample is saturated. The water is not free to move, and the resulting pressure is intrinsically different than the pore pressure generated by free water around the clay platelets.

These experiments show that the addition of water further decrease the strength from the dried state. Because Cienega Valley gouge contains a large percentage of hydrated clays, this loosely bonded interlayer water may be a factor in the reduction of strength.

Discussion

The absence of a detectable heat flow anomaly along the San Andreas fault was interpreted by Brune et al. [1969] to indicate shear stresses along the fault trace of no more than 100 bars, if the heat transfer is primarily by conduction. On the other hand, Scholz et al. [1979] suggested that frictional stresses along the fault could be on the order of 1 kbar, based on their studies of metamorphism and argon depletion adjacent to the Alpine fault in New Zealand. These higher shear stresses, that are in better accord with laboratory studies of shear stresses [Byerlee, 1978], can be explained if the frictional heat is uniformly dissipated over a broad region by thermally driven ground water convection.

If the permeability of gouge material is on the order of a nanodarcy, as determined in this study, it is difficult to imagine massive water circulation as an effective means of dissipating this extra frictional heat, unless considerable time is allowed. Small local faults are numerous near the San Andreas trace, and would tend to reduce ground water flow in a direction normal to the fault zone if they contain low permeability gouge material. Lachenbruch and Sass [1980] pointed out that hydrologic conditions on either side of the fault are vastly different, and yet the heat flows are similar, suggesting that fluid transport may not account for the observed heat flow distribution.

In order for the heat flow constraint requiring shear stresses of approximately 100 bars to be reconciled with laboratory results (stresses around 1 kbar), fluid pressures must be nearly lithostatic during faulting [Lachenbruch and Sass, 1980]. With clay gouge permeabilities in the nanodarcy range, this condition can certainly be realized. Excess fluid pressures, whether steady-state or transient [Raleigh, 1977], could not be readily dissipated through a fault where clay gouge is present.

Summary of Results

1) The permeability of San Andreas fault gouge from the Cienega Valley is approximately 1 nanodarcy at confining pressures ranging from a few hundred bars to 2 kbars, corresponding to depths of up to 8 km in the earth.
2) The permeability of this fault gouge does not depend significantly on accumulated strain, but does depend on confining pressure and differential stress.
3) The presence of loosely bonded interlayer water in the hydrated clay may serve to lower the strength of the gouge, even when excess pore pressures are not created.

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