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Permeability of Deep Drillhole Core Samples

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ABSTRACT

The permeability of fault zone material is key to understanding fluid circulation and its role in earthquake generation. In this paper, permeability results from four different scientific drillholes are discussed in relation to recent studies on core samples from the Nojima Fault. This comparison illustrates the advantages and limitations of laboratory studies on extracted core samples. We observe that matrix permeability of core samples is extremely low, suggesting that most fluid flow at depth will occur through discrete joints and faults rather than through the bulk of the rock. The permeability of deep core samples is also more sensitive to pressure than equivalent rocks obtained from surface outcrops. In addition, stress-relief and thermal fractures due to coring and extraction may influence laboratory permeability measurements, most typically for deeper rocks and those containing abundant quartz.

INTRODUCTION

Scientific drillholes through the Nojima Fault by the University Group, the Geological Survey of Japan (GSJ) and the National Research Institute for Earth Science and Disaster Prevention (NIED) provide unique information on the physical properties of rocks in an active fault zone. These drillholes cross the fault at depths of 389 m, 624 m, and below 1140 m respectively, sampling a variety of materials including a clay-rich fault core, a fractured zone adjacent to the fault and intact rock beyond the fracture zone. *Naka et al*. (1998) reported on the permeability and shear strength of core samples extracted from the GSJ and NIED drillholes at various distances from the fault zone. They found that permeability in the shear zone was low (~10^{-18} m^2) due to the presence of the clay minerals; that the fractured zone had a higher permeability of around 10^{-16} m^2; and that the intact zone more distant from the fault had permeability values of less than 10^{-21} m^2. These results suggest that the damaged zone on either side of the fault can act as a conduit for fluids parallel to the fault, but that the low permeability clay-rich shear zone will impede flow across the fault.

The core samples studied provide a picture of conditions in the upper crust adjacent to an active fault. However, because earthquakes can be generated at great depths and in many different environments, we are also interested in how the physical properties of extracted core samples depend on factors such as depth of burial, *in situ* pressure, rock type, and the effects of weathering and stress-relief fracturing. This paper summarizes the permeability results of core samples from four other scientific drillholes, so that the lessons learned can be applied to the Nojima Fault studies. These drillhole sites include Cajon Pass in California, Kola in Russia, KTB in Germany, and Illinois UPH 3. Results show that (a), the matrix permeability of most crystalline rock samples is extremely low due to repeated episodes of hydrothermal healing and sealing, so that the bulk permeability of large rock masses is largely controlled by flow through fractures and joints; (b), weathering of near-surface rocks reduces the pressure sensitivity of permeability, so that permeability behavior determined from near-surface samples cannot be extrapolated to depth; and (c), in many cases, stress-relief fractures introduced during coring and extraction dominate the physical properties of the rocks, particularly for samples that contain quartz.

SUMMARY OF CORE SAMPLE PERMEABILITIES

Cajon Pass, California

At Cajon Pass in Southern California, a hole was drilled to a depth of 3500 m 4 km to the northeast of the San Andreas Fault to investigate the thermomechanical nature of this fault. Rocks selected for laboratory permeability studies included granodiorites, monzogranites and gneisses. Permeability measurements (Figure 1) were made on the core samples at confining and pore pressures that matched the *in situ* pressures for each sample depth (*Morrow and Byerlee*, 1992), so that each data point in Figure 1 represents a different sample. Permeability of unfractured samples (solid symbols, Figure 1) decreased systematically with depth from 10^{-18} to 10^{-22} m^2 at effective pressures of only 5 to 50 MPa, indicating a strong pressure sensitivity of permeability. Values for the relatively few specimens containing visible stress-relief fractures (open symbols, Figure 1) were one to two orders of magnitude higher than the unfractured samples, but still in the comparatively low permeability region of 10^{-19} to 10^{-20} m^2. Petrographic observations indicate that repeated episodes of healing and sealing account for the overall low permeability values, which were several orders of magnitude below bulk downhole measurements. Accordingly, the laboratory measurements should be considered a lower limit to permeability. The results suggest that massive water circulation through the mass of the rock is unlikely as a mechanism for obscuring the heat flow anomaly that would be expected if shear stresses acting on the San Andreas fault to cause slip were high. This finding is consistent with geochemical evidence (*Kharaka et al*., 1988) of little mixing of the pore waters sampled from different sections of the borehole.

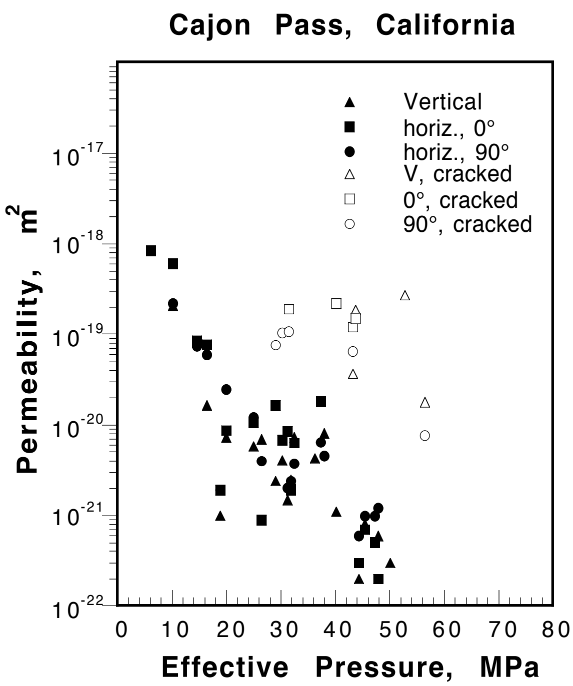

Figure 1. Permeability of intact (closed symbols) and fractured (open symbols) crystalline rock samples from the Cajon Pass drillhole in California under estimated *in situ* effective pressure conditions. Measurements in three mutually perpendicular orientations show the extent of permeability anisotropy.

Kola, Russia

Core samples from the 11 km deep Kola drillhole in Russia included granodiorite gneisses, basalts and amphibolites. Laboratory permeability tests were conducted to determine the pressure sensitivity of permeability and to compare the effects of stress-relief and thermal microcracking on the matrix permeability of different rock types (*Morrow et al*., 1994). Permeability was measured on each sample under a series of increasing confining pressures. The permeability of the basaltic samples (Figure 2) was the lowest and most sensitive to pressure, ranging from 10^{-20} to 10^{-23} m^2 as effective pressure increased from 5 to only 60 MPa. Amphibolites and the granodiorite gneiss samples were more permeable and less sensitive to pressure than the basalts, with permeability values ranging from 10^{-17} to 10^{-22} m^2 as effective pressures increased to 300 MPa. The weathered samples, a surface gneiss and a surface-derived Westerly Granite included for comparison, were the least sensitive of all rocks, with permeability trends that cut across those of the other samples. There was an abundance of microfractures in the quartz-rich rocks, but a relative paucity of cracks in the mafic rocks, suggesting that the observed differences in permeability were based on rock type and depth, and that stress-relief and thermal-cracking damage was correlated with quartz content.

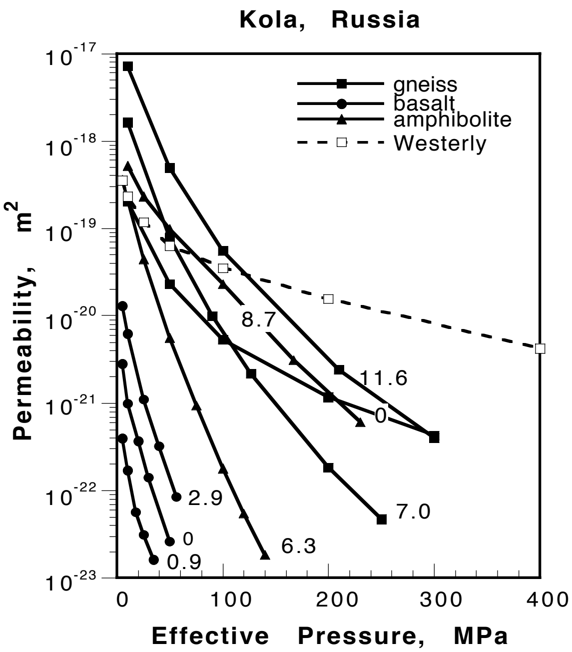

Figure 2. Permeability of core samples from the Kola well in Russia. Numbers indicate sample depth in km. Westerly granite (*Brace et al*., 1968) included for comparison.

KTB, Germany

Amphibolite core samples from the 9 km deep KTB drillhole were tested under increasing confining pressures in mutually perpendicular directions to determine permeability anisotropy (*Morrow et al*., 1994). Permeability values (Figure 3) for samples from 1252 and 3607 m were very low (10^{-19} to 10^{-23} m^2 at pressures from 5 to 60 MPa), similar to the Kola mafic samples. This behavior appears to be due to the paucity of microfractures, either natural or induced through drilling and extraction, again most likely related to the lack of quartz. Permeability anisotropy was over two orders of magnitude. Unlike most of the rocks described in this paper, permeability for many of the KTB samples followed the simple relation $-\log k \propto P_e$, where k is permeability and P_e is effective pressure. However, this may be a result of the limited pressure range over which permeability could be measured.

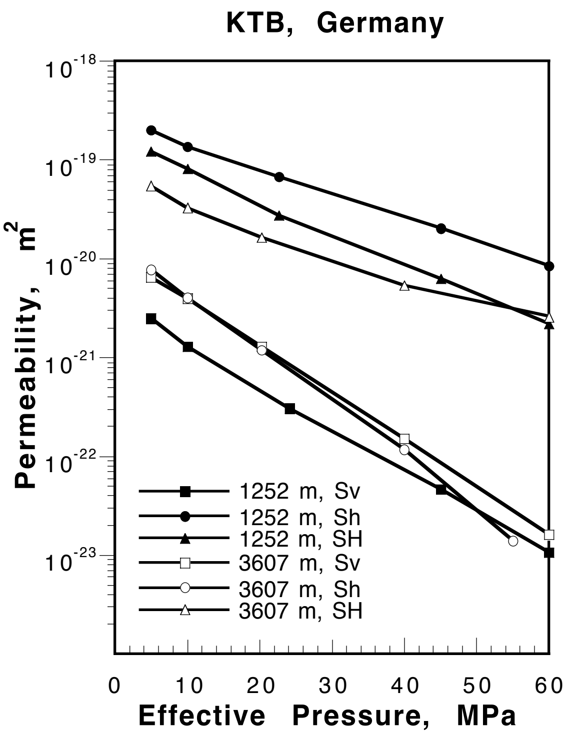

Figure 3. Permeability of amphibolite core samples from the KTB pilot hole in Germany, with cores oriented towards principal stresses.

Illinois UPH 3, Illinois, U.S.A.

Horizontal and vertically oriented granite cores were obtained from depths of 751 to 1605 m in the Illinois UPH 3 drillhole and tested in the laboratory at effective confining pressures from 5 to 100 MPa (*Morrow and Lockner*, 1997). Initial permeabilities (Figure 4) were in the range of 10^{-16} to 10^{-19} m^2 and dropped rapidly with applied pressure to values between 10^{-18} and 10^{-23} m^2, typical of the strong pressure sensitivity of other core samples noted above. However, permeabilities of the Illinois cores were inversely related to sample depth in a systematic way. This suggests that stress-relief and thermal microfractures induced during core retrieval increased with depth and ultimately dominated the laboratory fluid flow measurements. In this case, our measurements give at best an upper bounds on matrix permeability, and do not provide a realistic picture of *in situ* permeability conditions.

DISCUSSION

Crack-dominated fluid flow

The low matrix permeability ($<10^{-16}$ m^2) of core samples from the various drillholes cited above indicates that most fluid flow at depth will occur through discrete joints and faults rather than through the bulk of the rock. In addition, studies of both clay-rich and non-clay fault gouges from various active faults (*Morrow et al.*, 1984) show that gouge permeability is also extremely low (10^{-19} to 10^{-22} m^2) under *in situ* pressure conditions and during shearing. These findings are consistent with the results of *Naka et al.*, (1998) who determined that the fractured rocks adjacent to the Nojima Fault were many orders of magnitude more permeable than either the surrounding intact country rock or the clay-rich fault zone. This allows the damaged zone to serve as a conduit for fluids parallel to the fault in a horizontal or vertical direction but does not allow for free movement of fluids across the fault. This finding has important implications for the modeling of fluid circulation in the vicinity of the Nojima Fault.

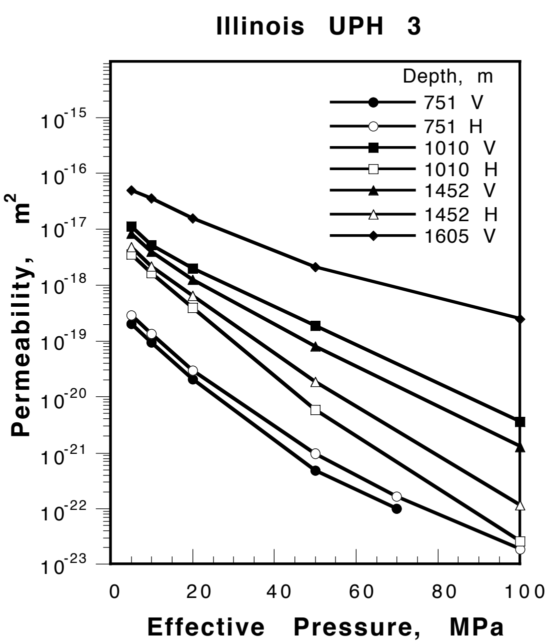

Figure 4. Permeability of granite core samples from the Illinois UPH 3 drillhole. Sample depth in meters for vertical (V) and horizontal (H) cores.

It is important to remember that the permeabilities of fault zone rocks are not fixed parameters with time. Petrographic evidence of repeated crack healing and sealing due to hydrothermal circulation in the various drillhole samples discussed above suggests that these rocks experienced cyclic permeability changes. This is consistent with current models of earthquake generation in which faults undergo repeated episodes of sealing, fluid pressurization, and finally rupture when fluid pressure exceeds the greatest principal stress, as discussed by *Sibson* (1992), *Chester et al.* (1993) and others.

Pressure sensitivity

An important finding from these diverse permeability studies is that permeability of deep core samples decreases more rapidly with applied pressure than equivalent surface-derived (quarried) or near-surface granites at comparable effective confining pressures. This is because weathering products in cracks and pores inhibit crack closure with applied pressure. In addition, stress-relief fractures that form from the release of triaxial *in situ* stresses may not completely close under the imposed hydrostatic pressure conditions of the laboratory. Such offset joints can become many orders of magnitude more hydraulically conductive than mated joints even at high stresses. This may explain why the deeper gneissic samples from the Kola well (7.0 and 11.6 km) which contained stress-relief fractures, were not as sensitive to pressure as the shallower (and hence less fractured) quartz-rich samples from Cajon Pass. Similarly, the largely unfractured mafic samples from the Kola and KTB drillholes reaches very low permeability values under only modest applied pressures. Differences in pressure sensitivity are illustrated in Figure 5 for intact, cracked and weathered samples from the Cajon Pass drillhole and also a sample of quarried Westerly Granite, which is often used as a standard in laboratory geophysical testing. The weathered and cracked samples (including weathered Westerly Granite) are more permeable and have a distinctly different pressure response from the intact samples. However, these less pressure-sensitive samples may not be representative of conditions at depth. This result has important implications for geophysical models that assume standard values for the transport properties of rock, such as models of heat transport or fluid pressure buildup. Other physical properties that are controlled by cracks and pores, such as seismic velocity and electrical resistivity, may be similarly affected by differences in pressure sensitivity between surface-derived rocks and deep core samples.

Stress-relief fracturing

While stress-relief fractures may affect the pressure sensitivity of permeability as described

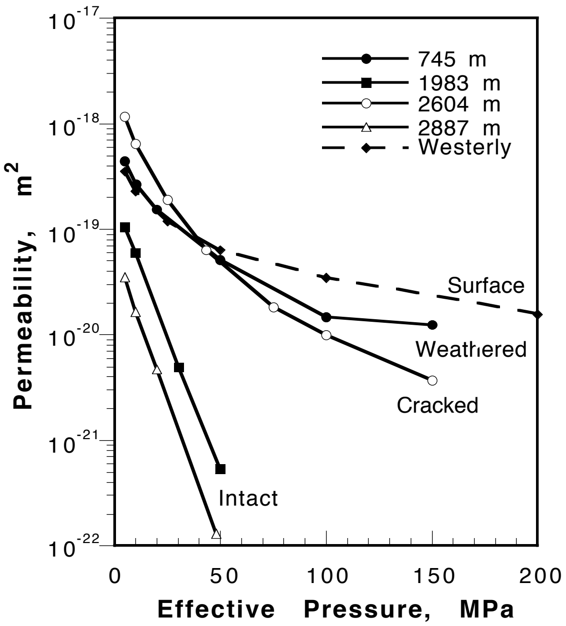

Figure 5. Permeability of selected Cajon Pass core samples showing differences in pressure sensitivity, with Westerly Granite (*Brace et al.*, 1968) included for comparison.

above, the most obvious influence is on the absolute value of permeability. Even on the small scale of these samples, flow in fractured samples was increased by several orders of magnitude. Stress-relief damage was generally more prominent in the quartz-rich rocks and in rocks from greater depths. However, as in the case of the Illinois UPH 3 cores, permeability was entirely dominated by stress-relief cracks even though the samples were from relatively shallow depths. This may result in a substantial overestimate of the *in situ* matrix permeability.

Stress-relief fractures can in some cases be useful for estimating *in situ* pressure conditions. For instance, we can apply the Equivalent Channel Model of *Walsh and Brace* (1984) to the permeability and porosity data to obtain analytical estimates of various parameters such as crack aperture, asperity height, and formation factor. Assuming that the physical characteristics of natural fractures are different than stress-relief fractures, the trend of these parameters with pressure should be different at *in situ* pressures above crack closure than below crack closure. From this change in physical characteristics with applied pressure we can estimate the closure pressure of the stress-relief cracks, and thereby place bounds on the *in situ* effective pressure. This method proved successful for certain quartz-rich samples from the Kola drillhole, where the downhole fluid pressure was not well constrained and *in situ* effective pressures were unknown. However, the use of microcrack closure to estimate *in situ* pressure was not appropriate for the basalt and amphibolite samples from either the Kola or KTB drillholes, because they were relatively crack-free *in situ* (on the scale of our laboratory samples) and remained so even after core retrieval. As a result, their permeabilities were near or below the measurable lower limit of our apparatus at the estimated *in situ* pressures of the rocks, so that permeability measurements could not be made over the necessary spectrum of pressures.

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