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Permeability differences between surface-derived and deep drillhole core samples

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Abstract. Laboratory tests reveal that the permeability of samples obtained from deep boreholes is often lower and more sensitive to pressure than the permeability of common surface-derived crystalline rocks reported in the literature. We attribute the differences in permeability behavior to the fact that surface rocks have histories of unloading, weathering and retrograde metamorphism which are not comparable to that of the deeper rocks. Weathering products that line cracks and pores of surface rocks and make these openings more difficult to close as pressure increases may account for the relatively low pressure-sensitivity of permeability. Stress-relief cracking in the borehole samples can also reduce the pressure sensitivity. These results have important implications for models that incorporate assumptions about the transport properties of rock at depth, such as models of heat transport or fluid pressure buildup, because many models are based on the properties of common surface-derived rocks. Other physical properties that are controlled by cracks and pores, such as seismic velocity and electrical resistivity, may be similarly affected by differences between surface-derived and deep rocks.

Introduction

Much of our knowledge of the physical properties of crystalline rocks comes from the studies of rock samples obtained from surface quarries. Quarried rocks have long been important for their strength, durability and beauty as building and monument material. More recently, the uniformity and availability of quarry rocks has led to their use in geophysical research. Certain oft-studied quarried granites such as Westerly and Barre Granites have become near standards in the laboratory.

Deep continental drilling has now made available rock samples from great depth, and our knowledge of the physical properties of these rocks is rapidly increasing. In this paper, we compare the permeability of quarry-derived crystalline rocks with the permeability of samples that have been extracted from deep drillholes. These deep sites include the Cajon Pass drillhole in California (3.5 km depth), the KTB pilot hole in Germany (4 km depth), and the Kola superdeep drillhole in Russia (12 km depth). The drillholes penetrate a variety of rock types as well as degrees of deformation and metamorphism.

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Measurement Technique

Laboratory permeability measurements are generally made using the pulse decay method [*Brace et al.*, 1968] or the steady-state flow technique [*Morrow and Byerlee*, 1992]. Regardless of method, permeability values are rarely reported below 10^{-21} m^2 (10^{-9} Darcy) due to the typical range of values of many rocks, the relatively low effective pressures used, and the experimental difficulties in measuring very low permeabilities. However, values as low as 10^{-23} m^2 have been measured with our steady-state flow apparatus by carefully controlling the system temperature and allowing test durations of several days.

Permeabilities of the deep drillhole rocks used in this study were determined at room temperature using intact cylindrical cores 2.54 cm in diameter and 1 to 2 cm in length. Fluid pressure, P_p, (distilled water) and confining pressure, P_c, were increased simultaneously until fluid pressure reached the estimated *in situ* value based on sample depth assuming a normal hydrostatic gradient. Confining pressure was then increased in a stepwise fashion while fluid pressure remained fixed, to produce effective pressures ($P_e = P_c - P_p$) as high as 300 MPa. Fluid flow was driven by a 1 to 2 MPa fluid pressure gradient across the sample and recorded for periods of 1 to 3 days to assure flow rate equilibrium. Permeability was then calculated using Darcy's Law. In many cases the maximum effective pressure was constrained by the permeability measurement threshold of 10^{-23} m^2.

Permeability Results

Surface Samples

Reported permeability measurements of selected surface-quarried granites (Figure 1) typically display a rapid drop as effective pressures increase to 100 MPa, followed by more gradual reductions as pressures continue to rise. Much of the permeability data available in the literature are reported at pressures in the range of tens of MPa and were therefore excluded from this figure. At such low pressures the permeability, k, and pressure, P_e, relation is often approximated as an ex-

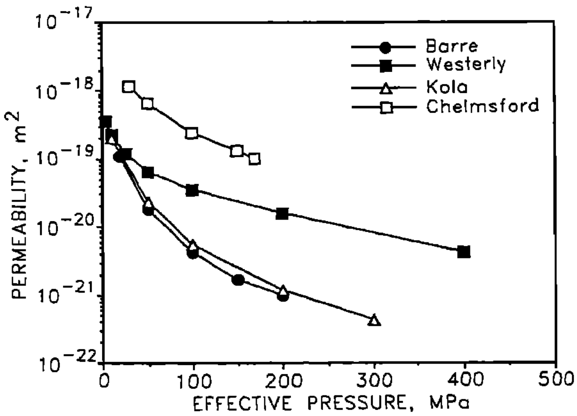

Figure 1. Permeability of surface-quarried granites. Barre: C. Morrow, unpublished data; Westerly: *Brace et al.*, 1968; Kola: *Morrow et al.*, 1994; and *Chelmsford: Bernabe*, 1986.

ponential, corresponding to a linear trend in Figure 1 because the non-linear response at higher pressures is not apparent. In this case, pressure sensitivity, which we define in this paper as minus the slope

$$-\delta \log_{10} k/\delta P_e, \tag{1}$$

is constant. The permeability of Westerly Granite [*Brace et al.*, 1968] is one of the earliest data sets measured to the higher pressures encountered in the mid-crust, and as a result has been frequently used in models of crustal processes. For Westerly, the pressure sensitivity of permeability decreases by an order of magnitude from around 0.030 to 0.002 (decades)/MPa as applied pressure increases to several hundred MPa. The permeability curve of Chelmsford Granite [*Bernabe*, 1986] has a shape similar to that of Westerly Granite but with a higher initial value. Barre Granite (C. Morrow, unpublished data) and the Kola surface gneiss [*Morrow et al.*, 1994], have the same initial permeability but are slightly more sensitive to pressure (Table 1). These four samples are representative of typical quarried rock and the permeabilities and pressure sensitivities are consistent with values reported in *David et al.* [1994].

Table 1. Pressure Sensitivity of Permeability

	$-\delta \log_{10} k/\delta P_e$ (decades)/MPa			
Sample MPa:	0–50	50–100	100–200	>200
Westerly Granite	0.030	0.005	0.003	0.002
Chelmsford Granite	0.013	0.009	0.005	
Barre Granite	0.026	0.012	0.004	
Kola surface granite	0.023	0.012	0.006	0.004
Kola granitic (deep)	0.031	0.020	0.013	0.009
Kola mafic	0.045			
KTB amphibolites	0.040			
Cajon Pass (Fig. 4)‡	0.080			
Cajon Pass (Fig. 5)*	0.055			

‡ depth sensitivity
* average of 1983 and 2887 m cores

Deep Core Samples

Permeabilities of the Kola core samples (Figure 2), cover six orders of magnitude and are ordered according to both rock type and depth due to varying degrees of susceptibility to stress-relief and thermal cracking damage, as discussed in *Morrow et al.* [1994]. The three lower-permeability mafic samples exhibit the greatest and most constant pressure sensitivity, averaging around 0.045 (decades)/MPa. These samples were brought to the surface nearly crack-free, maintaining their low *in situ* porosities of 0.3 to 0.8%, and are very fine-grained, all factors which contribute to the low permeability values. The gneissic samples are generally more permeable and less sensitive to pressure (0.030 (decades)/MPa decreasing to an average of 0.006 (decades)/MPa as pressure is applied) than the mafic samples. The quartz in these samples is more prone to stress-relief and thermal cracking than the mafic minerals [*Nur and Simmons*, 1970], which accounts for the inverse relation between initial permeability and depth. Amphibolites are intermediate in behavior. Petrographic observations of increasing fracture density with depth and quartz content suggest that pressure sensitivity may scale in part with the extent of the stress-relief fractures in these samples, corresponding to the gradual decrease in slope of the permeability data from the very fine-grained and intact to the coarser and more fractured cores. The Kola surface gneiss is by far the least sensitive to pressure, with a permeability curve that flattens out and crosses many of the other curves as pressure increases, contrary to the general trend of the other data. The pressure response of this sample more closely resembles that of Westerly Granite (included for comparison) than the other Kola cores. From this Figure it is clear that both exposure to the surface and stress-relief micro-fracturing affect the permeability-pressure response.

KTB amphibolites [*Morrow et al.*, 1994; Figure 3], sampled along the three principal stress directions at 1252 and 3607 m depth display a low permeability and

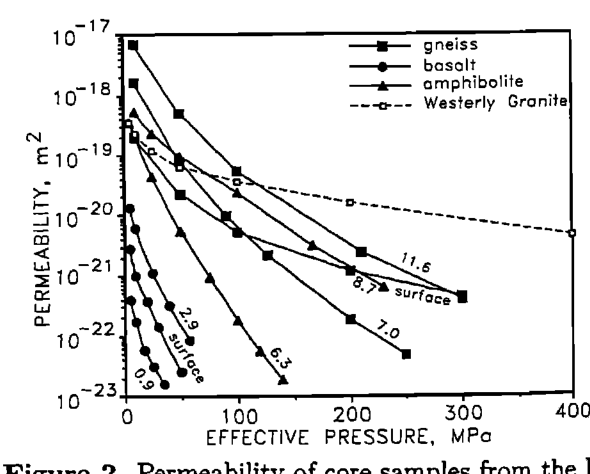

Figure 2. Permeability of core samples from the Kola Superdeep well in Russia [*Morrow et al.*, 1994]. Numbers indicate sample depth in kilometers. Westerly Granite [*Brace et al.*, 1968] included for comparison.

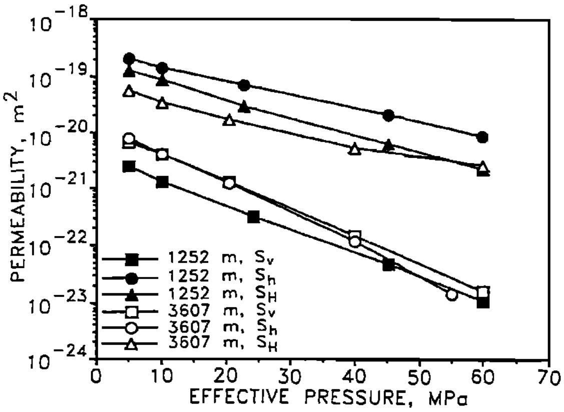

Figure 3. Permeability of amphibolite core samples from the KTB pilot hole in Germany [*Morrow et al.*, 1994]. The three mutually perpendicular directions at each depth correspond to S_v, S_h and S_H.

strong pressure sensitivity averaging 0.040 (decades)/MPa, similar to the mafic Kola samples. The relation of foliation and microcracking to permeability anisotropy is discussed in *Morrow et al.* [1994]. Most of the permeability data are strikingly linear at pressures to 60 MPa (i.e. constant pressure sensitivity); however this trend is difficult to extrapolate to higher pressures because of the extremely low permeability of the samples. These rocks were also brought to the surface relatively crack-free and have particularly low porosities of 0.5 to 0.7%. This data set again shows that the permeability of unfractured deep rocks is strongly pressure-sensitive.

The largest permeability data set consists of 62 Cajon Pass samples of varying mineralogy (Figure 4), each measured at the estimated *in situ* effective pressure for their corresponding depth (*Morrow and Byerlee*, 1988; 1992, unfractured cores only are plotted in Figure 4). Although each data point represents a different sample, taken together these data form a roughly linear permeability trend with a negative slope of around 0.080 (decades)/MPa, which we refer to as "depth sensitivity" because the permeability of each sample was not measured as a function of pressure. Repeated episodes of healing and sealing of natural fractures were found to be responsible for the low permeability values in these intact rocks.

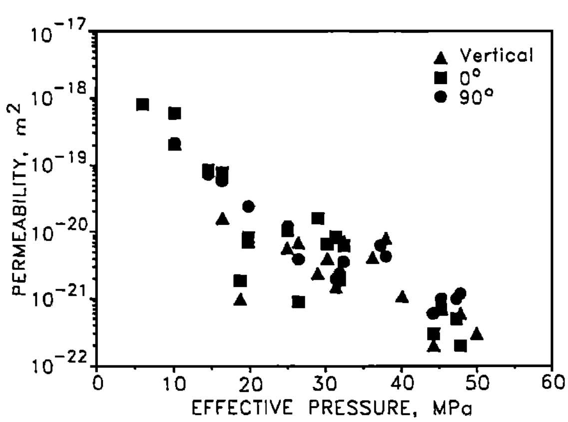

Figure 4. Permeability of samples from the Cajon Pass drillhole in California under the estimated *in situ* pressure conditions [*Morrow and Byerlee*, 1988; 1992]. Core orientation; vertical, or horizontal at 0° or 90° to an arbitrary reference direction, shows extent of anisotropy.

In order to better compare the Cajon Pass samples with the other laboratory data, four granodiorite cores (Figure 5), matched in grain size, fabric and mineral assemblage were selected for measurement; three unfractured and one with a through-going microfracture clear of secondary mineralization. (Note that the presence of fractures is not a strict function of depth in this suite as implied by the Kola drillhole data because of the care taken in sampling the most unfractured sections of the Cajon Pass drill core.) The unfractured core from 745 m depth was situated just below the sediment-granite contact, and although the geologic history of the area is complex [*Silver and James*, 1988], this sample was presumably within the near-surface weathering zone for some time during the geologic past. Unfractured samples at 1983 and 2887 m display a low permeability and a constant pressure sensitivity of around 0.055 (decades)/MPa, whereas the sample near the sediment contact (745 m) and the fractured sample (2604 m) differed in their higher-permeability and more variable pressure sensitivity (0.050 to 0.001 (decades)/MPa with increasing pressure), more closely resembling the Westerly Granite data.

Discussion

The preceding examples illustrate two important points. First, the permeability of intact deep core samples is generally lower and more sensitive to pressure than quarry-derived surface samples. Second, drillhole samples that contain stress-relief microfractures or that may have been at some time subject to weathering tend to have a permeability-pressure behavior similar to surface samples. Weathering is the first obvious difference. Deposition of secondary minerals and partial healing along cracks and voids produced during uplift makes the cracks harder to close under pressure due to crack surface mis-match, and may account for the characteristic reduction in the pressure sensitivity of permeability. Scanning electron micrograph (SEM) observations of quarry-derived crystalline rocks [*Montgomery and Brace*, 1975; *Batzle et al.*, 1980] show abundant evidence for mis-matched crack topography as a result of mineral deposition and dissolution, as well as pitting, mineral bridges that prop cracks open, and healing that transforms open cracks into a network of tubes, isolated pores and finally into filled cracks. This latter process may explain the relative lack of natural open fractures in our deeper samples relative to the surface samples.

The observation that stress-relief fractures tend to reduce permeability pressure-sensitivity may also be related to mis-match in crack closure, but with an entirely different cause. We assume that the rock experiences a triaxial stress state *in situ*, but in the laboratory the core samples are repressurized hydrostati-

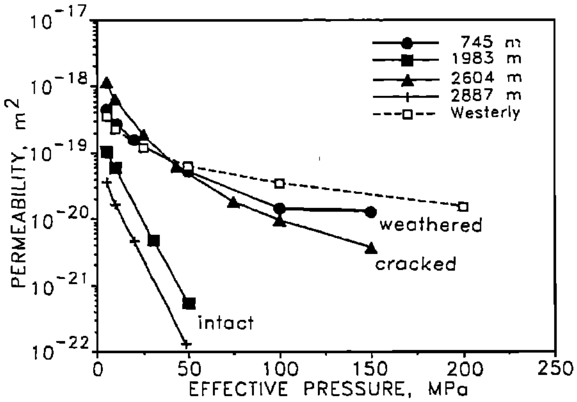

Figure 5. Permeability of selected Cajon Pass core samples as a function of effective pressure. Westerly Granite [*Brace et al.*, 1968)] included for comparison.

cally to the estimated *in situ* S_v based on depth and rock density. The difference between the hydrostatic and *in situ* triaxial stress state should also result in a mismatch in crack closure in the fractured samples, causing the cracks to become propped open as pressure increases. Such a process would not dominate the crack-free samples where stress anisotropy is accommodated elastically. *Durham and Bonner* [1994] find that artificial joints can become propped open by very small shear offsets and remain many orders of magnitude more hydraulically conductive than mated joints even at high stresses. The amount of possible offset upon hydrostatic loading should scale with the size of the cracks, as suggested by the petrographic evidence and gradual trend in the pressure sensitivity of the Kola data from the largely unfractured (most sensitive) to more fractured (least sensitive) samples. The degree of crack mismatch may also be an indication of the extent to which the *in situ* stress state varies from hydrostatic. In the case of the 2604-m Cajon Pass core (Figure 5), the difference between minimum and maximum principal stress was around 40 MPa [*Zoback and Healy*, 1992] and the pressure sensitivity more closely resembled the surface weathered sample than the two intact cores. Although thermal cracking was not isolated from cracking due to elastic moduli differences in the above case, a possible relation between pressure sensitivity and *in situ* stress state in cracked cores will be further explored on a variety of other core samples.

Conclusions

The results of this study show that both surface weathering and stress-relief fracturing have a strong influence on the pressure sensitivity of permeability. Because the vast majority of the permeability data in the literature comes from surface-derived samples, care should be taken when using permeability-pressure data in models of crustal processes such as fluid pressure generation or heat flow because the permeability behavior of surface samples may not be applicable to the deeper crust. Similarly, care should be taken when interpreting laboratory permeability measurements of deep core samples containing stress-relief fractures because the permeability-pressure behavior may not necessarily reflect the true *in situ* condition if principal stresses vary significantly. Since other physical properties such as electrical resistivity, seismic velocity and attenuation are also dependent on crack closure behavior, these parameters may also be sensitive to differences between surface and deep rocks.

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