and ±0.05; P_p: ±0.2 and ±0.03. The pore fluid system was capable of resolving volume changes of 2×10^{-2} mm^3. Uncertainties in computed permeabilities ranged from about ±10% for $k > 10^{-20}$ m^2 to about ±20% for $k < 10^{-21}$ m^2.

In addition to these permeability measurements, a separate cylinder from the 11.4-km amphibolite core was saturated with 0.1 *M* KCl solution and placed in the pressure vessel to measure electrical resistivity as a function of effective pressure. In this experiment, a 100 Hz sine wave (peak-to-peak amplitude = 1 V) was applied across the sample in series with a precision decade resistor. The voltage drop across the sample and resistor were alternately measured with a high input impedance (>3×10^8 ohm) voltmeter and the resistor adjusted to match the sample resistance. In this way, sample resistivity was measured to an accuracy of ±0.2%.

Matrix Permeability

Permeability of the three Kola cores is plotted as a function of effective confining pressure in Figure 1. For all cores, *k* dropped four orders of magnitude as P_{eff} increased from 10 to 300 MPa. By comparison, the permeability of granite samples from surface outcrops decreases by approximately two orders of magnitude over this same pressure range [*e.g. Brace et al.*, 1968]. The most likely cause of this extreme pressure sensitivity is the growth of microcracks during coring and retrieval of the Kola samples [*e.g. Kremenetsky*, 1990]. As discussed below, proper interpretation of these data requires that this effect be identified and corrected for. Upon unloading, the Kola samples consistently recover about 30% of their initial permeability (Figure 1). Thus, while some irreversible damage has occurred during the laboratory test cycles, a significant portion of the pressure-induced crack closure is recoverable.

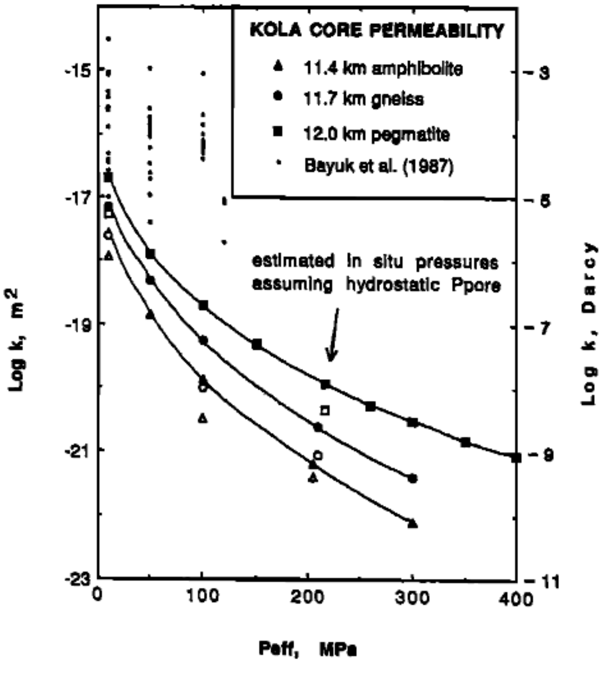

Fig. 1. Permeability, *k*, as a function of effective confining pressure, P_{eff}, for three cores from the Kola Superdeep well. *k* is shown both during loading (filled symbols) and unloading (open symbols); solid curves are fit to data collected during loading. Estimated *in situ* P_{eff} calculated assuming hydrostatic P_p and lithostatic P_c. Also shown is *k* reported by *Bayuk et al.* [1987] for shallower cores from the same well.

Also plotted in Figure 1 are permeability data for samples retrieved from shallower depths (3.8 to 9.9 km) in the Kola well as reported by *Bayuk et al.* [1987]. Their samples also showed a strong pressure sensitivity. However, at P_{eff} = 100 MPa, they reported permeabilities that were 1 to 5 orders of magnitude greater than our determinations. The variation in reported permeabilities may simply result from the different depths from which these two sets of samples were recovered.

Unfortunately, *in situ* pore pressures at Kola are poorly constrained. If, for the sake of argument, we assume hydrostatic pore pressure and confining pressure equal to the calculated overburden stress (317 to 333 MPa), our measurements provide an upper bound for *in situ* matrix permeabilities. This bound would fall in the range of 5×10^{-22} to 1.2×10^{-20} m^2 (0.5 to 12 nDa) for the three samples that we have studied. However, fluid pressures in the Kola well may be considerably in excess of hydrostatic [*Borevsky et al.*, 1987]. If so, the appropriate *in situ* matrix permeabilities for these samples may be much higher than this.

Inferring the Effects of Stress-Relief Cracking

An important problem that must be addressed in this study is how to determine *in situ* properties from samples that have undergone significant stress-relief (or decompression) cracking during coring. For example, if our estimates of *in situ* pore pressure are correct, then the irreversible stress-relief cracking that appears to have occurred during sample retrieval suggests that the permeabilities we measured are upper bounds to the *in situ* matrix permeabilities. We can expect stress-relief cracking to become more severe as samples are recovered from greater and greater depths, although shallower samples taken from regions subjected to large horizontal compressive stresses may have similar problems. Measurements of porosity and seismic velocity and petrographic observations suggest that stress-relief cracking and core discing are particularly severe in cores recovered from the Kola well below 5 km [*e.g. Kremenetsky*, 1990]. This crack damage may be augmented by cooling of up to 184°C as the cores are retrieved. In the present study, permeabilities were measured at room temperature and no attempt was made to correct for thermal cracking.

Similar problems have been faced in a number of studies on samples from other boreholes. The general strategy has been to assume that the stress-relief cracks have different characteristics (aspect ratio, surface roughness, tortuosity, *etc.*) than the pre-existing *in situ* cracks and thus affect physical properties in different ways. By measuring changes in physical properties of the sample as a function of pressure, it should be possible to identify the effective confining pressure at which the stress-relief cracks have fully closed. An important assumption, and one that has not been adequately tested, is that this closure pressure will be near the *in situ* effective pressure. Further pressurization of the sample should then result in a response due largely to the pre-existing crack population. The physical properties commonly used to infer this transition pressure include linear and volumetric strain [*e.g. Wang and Simmons*, 1978; *Kowallis and Wang*, 1983; *Dey and Kranz*, 1988] and P-wave velocity [*e.g. Kremenetsky*, 1990]. In some cases this transition pressure scales roughly with the depth of sample recovery [*Kremenetsky*, 1990], suggesting that approaches such as these may be valid. However, in other cases, no simple correlation is observed between transition pressure and depth [*Kowallis and Wang*, 1983].

Equivalent Channel Model

We now analyze the Kola data in terms of the Equivalent Channel Model for permeability in an attempt to distinguish between the effects of stress-relief and pre-existing *in situ* cracks. If the pressure at which stress-relief cracks close is approximately equal to the *in situ* effective pressure, then the permeability measured for the core at this P_{eff} should provide an upper bound for *in situ* permeability. We will follow the analysis of *Walsh and Brace* [1984], hereafter referred to as *WB*, in which they derived a number of important relations connecting microscopic pore geometry to macroscopic transport properties of crystalline rocks. In the equivalent channel model, the complex inter-connected pathways responsible for fluid transport in a rock are represented by idealized channels with uniform cross-section, surface roughness and other properties. By assuming that the fluid flow paths for permeability are the same as current flow paths for resistivity, the equivalent channel model makes the important prediction that the characteristic channel aperture is given by the quantity $\sqrt{3kF}$, where the formation factor F is the ratio of resistivities for the rock and electrolyte. By assuming that the surface roughness of the channels is random and can be approximated by an exponential height distribution *WB* have shown that the change in crack aperture with pressure is

$$d(3kF)^{1/2}/d(\ln P_{eff}) = \sqrt{2}\, h \qquad (1)$$

where h is rms surface roughness.

Test of Aperture/Pressure Relation

Note that for a given crack population, eq. (1) predicts that a plot of crack aperture *vs* ln P_{eff} will yield a straight line of slope = $\sqrt{2}\, h$. *WB* showed that this was true for a number of rocks obtained from surface outcrops. For the Kola samples, however, we anticipate that surface roughness of stress-relief and *in situ* cracks may differ, resulting in a plot with two linear segments intersecting near the *in situ* P_{eff}. To test this hypothesis, we measured resistivity as a function of P_{eff} for a sample taken from the 11.4-km amphibolite core. *WB* noted that the empirical relation

$$k = c\, F^{-r} \qquad (2)$$

where c and r are constants, is satisfied for many rock types. Due to space limitations, we are do not show the raw data, but the amphibolite data conform to this power law and a least squares fit yields $c = 1.0 - 2.8 \times 10^{-11}$ m^2 and $r = 2.45 \pm 0.06$. When these data are used to generate a plot of aperture *vs* log P_{eff} (Figure 2), a distinct slope change occurs at approximately 100 MPa which we interpret as due to closure of large (rough) stress-relief cracks. According to the *WB* analysis, this slope change represents a decrease in surface roughness from 19×10^{-9} to 7×10^{-9} m. Although these surface roughness estimates are highly model dependent, the decrease in surface roughness by a factor of more than 2.5 appears to be significant. Similar plots for Westerly granite and other rocks obtained from surface outcrops are included in Figure 2. None of these data sets shows a break in slope similar to the Kola sample; all are linear over the entire range investigated.

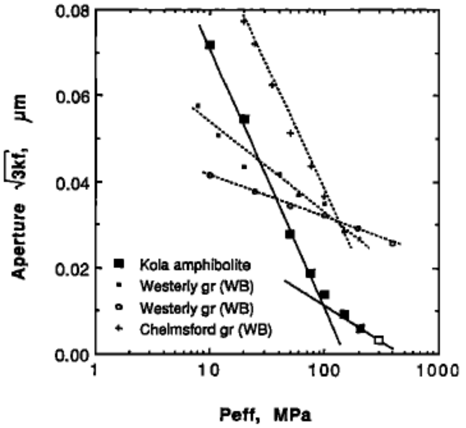

Fig. 2. Crack aperture $\sqrt{3kF}$ plotted *vs* log P_{eff} for amphibolite sample. For open symbol at 300 MPa, F was estimated using eq. (2). Slope ($\propto h$ according to *WB* analysis) changes near 100 MPa. We interpret this transition as indicating the pressure range where stress-relief cracks are closed. Data from two surface granites are also plotted [after *WB*]. These data lack the break in slope observed for the Kola core.

We note in passing that eq (2) can be used to eliminate F from the expression for crack aperture, leading to aperture $\propto k^{(r-1)/2r}$. For the amphibolite sample, where $r = 2.45$, eq. (1) becomes

$$d(k^{0.30})/d(\ln P_{eff}) = \sqrt{2/3}\, h\,. \qquad (3)$$

Thus, once the exponent r is determined for a particular rock, a plot such as Figure 2 can be obtained from k-P_{eff} data alone.

Aperture/Porosity-Reduction Relation

Another relation derived from the equivalent channel model can be used to provide an independent check on stress-relief crack closure. Following *WB*, the definition of hydraulic radius is $m = \phi V/A_s$ where ϕ is porosity, V is total volume and A_s is wetted surface area. *WB* noted that for crack-like fluid channels, the change in crack half-aperture, Δa, is equal to the change in hydraulic radius, Δm. Then, if we express the change in crack porosity as $\Delta v_c/V$, where v_c is crack volume, and use our earlier expression for crack aperture, we have

$$\Delta(3kF)^{1/2} = (\Delta v_c/V)\, V/A_s\,. \qquad (4)$$

WB showed that a number of surface rock samples satisfied this relation. By measuring the amount of water expelled from the sample during increases in P_{eff}, we have a direct measure of Δv_c and can measure the closure of stress-relief cracks. Porosity change is plotted as a function of aperture for the 11.4-km amphibolite core in Figure 3. Once again, a distinct break in slope occurs near 100 MPa, suggesting that at this pressure stress-relief cracks have closed and the remaining cracks contributing to porosity decrease have different surface roughness characteristics. As before, no break in slope was observed in samples obtained from surface outcrops (Figure 3).

Both the aperture/pressure and the aperture/porosity methods suggest that stress-relief cracks in the Kola samples close at P_{eff} = 100 MPa. This value is about 100 MPa lower than our estimates of P_{eff} based on lithostatic P_c and hydrostatic P_p. As such, it suggests that *in situ* pore pressure at 12 km depth in the Kola well may be as much as 100 MPa in excess of hydrostatic fluid pressure. A second and equally valid interpretation would be that fluid pressures are

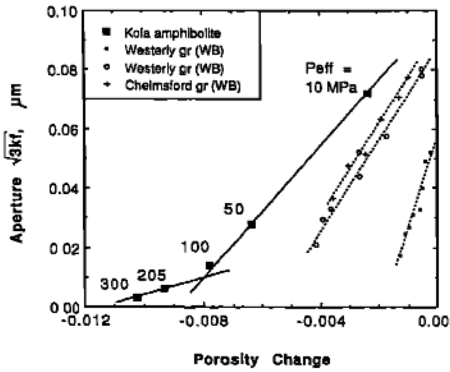

Fig. 3. Crack aperture plotted *vs* crack porosity loss during pressurization of amphibolite sample. According to *WB* analysis, slope $\propto A_s^{-1}$. Change in slope near 100 MPa is further indication of a change in properties of the dominant crack population. Data from surface granite samples [after *WB*] are also plotted and show no break in slope.

hydrostatic while the vertical stress at depth is sub-lithostatic by as much as 100 MPa. The true test of this method for inferring closure pressure will come when samples from different depths, which we have recently obtained, are analyzed. In this case, we expect that the break in slope observed in Figures 2 and 3 will correlate with retrieval depth.

Conclusions

Core samples recovered from depths of 11.4 to 12.0 km in the Kola superdeep well have been tested for matrix permeability over a broad range of pressures up to and exceeding the estimated *in situ* effective pressures. All samples showed an extreme pressure sensitivity of permeability, which we attribute primarily to stress-relief microcrack damage during coring and sample decompression. This pressure sensitivity, combined with uncertainty about *in situ* fluid pressure, makes it difficult to estimate *in situ* matrix permeability. Since stress-relief microcrack damage is irreversible, the crack closure that occurs when samples are repressurized may be incomplete. As a result, permeability measured in the lab can provide only an upper bound to the *in situ* matrix permeability. How important this and related effects due to thermal cracking are in altering permeability remains to be determined.

By assuming that the *in situ* pore pressure follows the hydrostat, and using a confining pressure equal to the calculated overburden stress, our measurements suggest that *in situ* matrix permeabilities of the three samples studied are low; with an upper bound ranging from 5×10^{-22} to 1.2×10^{-20} m^2 (0.5 to 12 nDa). However, application of an equivalent channel model [*Walsh and Brace,* 1984] indicates that a significant change in characteristics of the crack population controlling fluid flow occurred at about 100 MPa effective confining pressure, or about 100 MPa less than our estimates of the *in situ* effective confining pressure. If the *in situ* P_{eff} is this low, it may indicate that fluid pressure at 12 km depth in the well exceeds hydrostat by as much as 100 MPa. Alternatively, the closure pressure observed in the laboratory may indicate that vertical stress at depth in the Kola well is as much as 100 MPa below lithostatic. In either case, if this closure pressure does represent the *in situ* P_{eff}, then the permeability data suggest that *in situ* matrix permeability would be less than 1×10^{-20} to 2×10^{-19} m^2 near the bottom of the well.

We have demonstrated how the equivalent channel model, in conjunction with permeability and resistivity measurements, might be used to distinguish between the effects of stress-relief cracking and those of *in situ* microcracks. This technique may prove useful as an alternative to differential strain analysis and P-wave velocity measurements that are currently employed, but will require confirmation using measurements on samples retrieved from different depths.

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