Permeability of the oceanic crust based on experimental studies of basalt permeability at elevated pressures

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Abstract

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Permeabilities have been measured as a function of confining pressure at constant temperature for basalt dredge samples from the Juan de Fuca and Tonga-Kermadec regions. Permeabilities at 40 MPa are 1.1×10^{-19} m² for the Juan de Fuca basalt and 7.4×10^{-19} m² for the higher porosity Tonga-Kermadec basalt. Permeabilities decrease significantly with increasing confining pressure. The measured values of permeability are considerably lower than the estimated 10^{-14} to 10^{-15} m² permeabilities of the upper few hundred meters of basement rocks of the oceanic crust, thereby supporting oceanic crustal convection models in which seawater convection occurs largely through macrocracks at relatively shallow depths. Based on our laboratory measurements it is estimated that permeabilities of layer 2C and layer 3 are generally less than 1.0×10^{-19} m². Permeabilities of layers 2A and 2B in young oceanic crust are expected to be anisotropic due to the preferred orientation of fractures. An anisotropic upper crustal model is presented in which layer-2 permeabilities are low parallel to spreading directions.

Introduction

Early oceanic heat flow measurements (e.g., Lister, 1972) provided evidence for a large-scale transport of heat by circulation of seawater within the crust. This process gained support from observations from submersibles, which detected hydrothermal vents on the sea floor (e.g., Corliss et al., 1979). Fractures and rubble zones appear to be common in at least the upper 500 m of the oceanic crust (e.g., Hyndman and Drury, 1976) and in this region the flow of water is primarily controlled by their distribution. The movement of water through intermediate and deeper levels of the oceanic crust is apparently limited to microcracks and in these regions measured permeabilities in laboratory size samples at appropriate pressures become significant.

Most permeability measurements have been made on sedimentary rocks, although a few igneous rocks have been studied (Brace, 1980). Only limited experimental measurements are available on permeability of basalt (Johnson, 1980; Karato, 1983a, b). One purpose of this study is to investigate the permeability of oceanic basalt as a function of hydrostatic pressure. In addition, we examine the nature of permeability at various levels in oceanic crustal layer 2.

Experimental measurement of permeability

Basalt from the Juan de Fuca ridge was cored from the inner portion of a large pillow. Cores from the same sample have provided data on velocities of oceanic basalt (Christensen, 1970) and the effect of pore pressure on basalt velocities

TABLE 1

Modal analyses (vol. %)

	Juan de Fuca basalt	Tonga-Kermadec basalt
Groundmass		
Plagioclase	25.9	9.5
Clinopyroxene	56.7	12.0
Glass	13.7	52.3
Phenocrysts		
Plagioclase	2.4	-
Clinopyroxene	1.3	-
Vesicles	-	26.2

(Christensen, 1984). The Tonga-Kermadec specimen was from a small block of highly vesicular basalt with no apparent structure. Modal analyses are given in Table 1. Porosities measured with a pycnometer are 3.6% for the Juan de Fuca basalt and 32.9% for the Tonga-Kermadec basalt. The relatively high measured porosity for the Tonga-Kermadec specimen, which agrees fairly well with the modal analyses of Table 1, is largely the result of the presence of 1.0 to 0.05 mm diameter vesicles.

Permeabilities were obtained at elevated pressures using a permeameter in which fluid volumetric flow was measured as a function of time for a fixed pressure gradient. The samples were cylindrical, approximately 2 cm in diameter and 1 cm in length with ends cut flat and parallel to within 0.002 cm. A polyurethane sleeve containing the return channel for the permeability fluid isolated the rock specimen from the confining pressure fluid. A hand pump was used to generate the pressure and the samples were seasoned by cycling the pressure several times prior to the permeability measurements. Aluminum cylinders in contact with the rock were grooved for an even distribution of the permeating fluids across the end faces of the rock sample. A large reservoir of distilled water provided a constant head of 0.197 MPa. To assure complete saturation, the sample assemblies with the rock core in place were evacuated before opening the input fluid valve. The pressure vessel was placed in a temperature bath and the measurements were taken at a constant temperature of 20°C. Plots of volumetric



Fig. 1. Volumetric flow versus time at different pressures for the Juan de Fuca basalt.



Fig. 2. Volumetric flow versus time at different pressures for the Tonga-Kermadec basalt.

TABLE 2

Measured permeabilities of Juan de Fuca basalt and Tonga-Kermadec basalt at pressures to 40 MPa

Pressure, P (MPa)	Juan de Fuca		Tonga-Kermadec	
	$\frac{1}{k}$ (10 ⁻¹⁹ m ²)	$\frac{\Delta k / \Delta P}{(10^{-21} \text{ m}^2)^2}$	$\frac{k}{(10^{-19} \text{ m}^2)}$	$\frac{\Delta k / \Delta P}{(10^{-21} \text{ m}^2)}$ /MPa)
5	2.79	10.0		
10	1.85	2.1	14.51	25.2
20	1.54	3.I 1.0	10.98	33.3 19.7
30	1.35	1.9	9.11	10.7
40	1.10	2.5	7.42	10.9

flow versus time (Figs. 1 and 2) show a linear relation in accord with Darcy's law:

$$k = q\mu \left(\frac{\Delta P}{\Delta L}\right)^{-1} \tag{1}$$

where q is the volumetric flow rate per unit area, μ is the dynamic viscosity of water, and $\Delta P/\Delta L$ is the pressure gradient across the rock sample. The slopes of the least-squares fitted lines of Figs. 1 and 2 were used to obtain q. Permeabilities at various pressures are given in Table 2 in S.I. units of m² (1 μ darcy = 10⁻¹⁸ m²). The accuracy of k is estimated to be $\pm 5\%$.

Basalt permeability

A few measurements of permeabilities of oceanic basalts have been reported at near atmospheric pressures using constant head-pressure techniques (Johnson, 1980; Karato, 1983a, b). Reported values range from 2.0×10^{-22} to 9.1×10^{-18} m². In addition, Karato (1983a) has measured the effect of confining pressures on permeability for a basalt sample from Deep Sea Drilling Project Hole 504B to about 15 MPa. Permeabilities of the samples we have studied and the measurements of Karato are compared in Fig. 3. As confining pressure is increased, all three basalts show significant decreases in permeability which are expected since the passages for fluid flow are



Fig. 3. Permeability versus pressure for a DSDP basalt from Hole 504B (Karato, 1983a) and for the Juan de Fuca and Tonga-Kermadec basalts.



Fig. 4. Permeabilities of various crystalline rocks. Numbered data are from: (1) Karato (1983a and b); (2) Johnson (1980), (3) Brace (1980), and (4) Trimmer et al. (1980).

likely to be reduced with increasing confining pressure.

The higher permeabilities and pressure derivatives of the Tonga-Kermadec basalt are apparently related to its higher porosity (Table 1). However, it is surprising, in view of the large differences in porosity of the two cores, that their permeabilities are so similar. Perhaps the walls of many of the large vesicles of the Tonga-Kermadec sample are lined with relatively impermeable alteration products or the microcrack geometries within the groundmasses of the two samples are quite different.

In Fig. 4 several permeabilities are compared with the measurements reported in Table 2. The permeabilities of the oceanic basalts are, in general, comparable with permeabilities of other igneous rocks, with the exception of the low-permeability Creighton gabbro and some metamorphics. The permeabilities of these rocks are several orders of magnitude smaller than sandstone permeabilities with similar porosities. This reflects the effect of the geometry of the flow channels which are interconnected cracks in igneous rocks and interconnected pores in sandstones.

Permeability of the oceanic crust

Comparisons of laboratory and downhole logging velocities within the upper kilometer of oceanic layer 2 demonstrate that fracture porosity

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decreases with depth (Salisbury et al., 1985). Below a sub-basement depth of approximately 700 m, the excellent agreement between laboratory and logging velocities suggests that layer 2C is relatively free of macrofractures. Thus the permeability measurements which we have obtained as a function of confining pressure provide estimates for layer 2C permeability.

The permeability measurements in Table 2 were made at elevated confining pressures with minimum pore pressure. Within oceanic layer 2, pore pressure may well be close to or sometimes higher than hydrostatic pressure (Christensen, 1984) and permeability is likely functions of confining and pore pressure. Recent measurements by Bernabe (1987) of granite and sandstone permeabilities while simultaneously cycling confining and pore pressure show that the appropriate "effective pressure" is simply the confining pressure minus the pore pressure. Applying this to the oceanic crust and assuming that the pore pressure is close to hydrostatic, we estimate that a 40 MPa confining pressure, the highest of our measurements, is equivalent to a depth below the ocean floor of approximately 1.5 km. Thus our measurements are likely applicable to much of oceanic layer 2C if pore pressure approaches hydrostatic.

Based on three permeability measurements, Anderson et al. (1985) have proposed that permeability in the vicinity of Deep Sea Drilling Project borehole 504B decreases exponentially with depth (Z) into basement according to:

$$k(Z) = 0.11 \exp(-Z/50) \times 10^{-12} \mathrm{m}^2$$
 (2)

If we assume that pore pressure within layer 2 is close to hydrostatic and the effective pressure law discussed above holds, the permeability for the Juan de Fuca basalt at a depth of 750 m into basement at site 504 would be 1.6×10^{-19} m². Permeability calculated from eqn. 2 at the same depth is 3.4×10^{-20} m². This depth corresponds to approximately 200 m beneath the boundary between layers 2B and 2C where dike rocks have been recovered by drilling.

The agreement between the laboratory measured and calculated permeabilities is surprisingly good, especially considering that permeabilities in the lower portion of hole 504B are poorly constrained. At greater depths eqn. (2) predicts lower permeabilities than we have measured for the lower porosity Juan de Fuca Ridge basalt at appropriate effective pressures. At these depths, metamorphism may be important in reducing porosity as has been observed in many ophiolites at this level (e.g., Christensen and Smewing, 1981). Thus the basalt permeabilities in Table 2 are likely maximum values for an oceanic layer 2C devoid of fractures.

Downhole measurements of permeability are likely a function of the abundance of laterally discontinuous high-porosity pillow units penetrated by drilling. On a larger scale, fracture distributions and hence the overall permeability of the upper portion of basaltic basement corresponding to crustal layers 2A and 2B are poorly constrained. The utility of marine refraction seismology in investigating fracturing in the upper oceanic crust is, however, well demonstrated in the literature. Recent seismic observations have provided detailed information on the acoustic properties of seismic layer 2, which, in turn, have important implications regarding oceanic crustal permeability.

Of particular significance three types of marine seismic observations suggest preferred crack orientation within layer 2 and hence anisotropic permeability. The first is simply a variation of P-wave velocity with azimuth. Azimuthal layer-2 P-wave velocity differences of approximately 0.2 to 0.4 km s^{-1} have been reported in layer 2 at the Mid-Atlantic Ridge (White and Whitmarsh, 1984) and in the southwest Pacific (Shearer and Orcutt, 1985). Second, the direction of particle motion of the P-wave in anisotropic media is not generally parallel with either the group velocity or phase velocity directions. P-wave particle motion deviations of several degrees from the shot-receiver azimuth have been observed in the Atlantic (Stephen, 1981, 1985; White and Whitmarsh, 1984). Third, and perhaps the most convincing evidence for layer 2 anisotropy is shear wave splitting which is clearly illustrated in the particle motion diagrams of Stephen (1981) and White and Whitmarsh (1984).

The most likely cause of layer 2 seismic anisotropy is aligned cracks, since laboratory measurements of velocities in layer-2 basalts show no

significant anisotropy due to preferred mineral orientation (Christensen and Salisbury, 1975). The interpretation of the observed anisotropy in terms of a crack orientation model, which we prefer, requires the presence of randomly spaced vertical fluid filled cracks oriented parallel to ridge crests. This model is consistent with the observed presence of fissures parallel to the spreading axis near active rift zones such as in Iceland (White and Whitmarsh, 1984) and in the inner rift valley on the Mid-Atlantic Ridge (Ballard and Van Andel, 1977) and with sonograph observations of tectonic fabrics of the oceanic floor (Luyendyk and Macdonald, 1977). For this model, permeability in the upper cracked oceanic crust is low parallel to spreading directions and high perpendicular to spreading directions as well as high in a vertical direction. Thus the upper oceanic crust displays a transversely isotropic permeability analogous to seismic "transverse isotropy" with the symmetry axis horizontal and normal to the ridge crest. Symmetry perturbations may arise if subhorizontal fractures are abundant, as has been inferred from borehole televiewer images (Zoback and Anderson, 1982).

Conclusions

Measurements of permeabilities of oceanic basalt as a function of confining pressure provide useful constraints on oceanic crustal permeability. At subbasement pressures corresponding to the upper regions of seismic layer 2C, measured permeabilities are approximately 2×10^{-19} m² in reasonable agreement with predictions based on measurements in DSDP hole 504B. Higher in the crustal section permeabilities are dominated by the presence of fractures.

Anisotropic permeability in young upper oceanic crust likely results from the presence of near vertical fractures with a subparallel orientation. Azimuthal variations of P-wave anisotropy, P-wave particle motion deviations from shot-receiver azimuths and S-wave splitting observations are consistent with the presence of subparallel vertical cracks oriented parallel to ridge crests. The resulting permeability anisotropy has axial symmetry with low permeability parallel to spreading directions.

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