24. LARGE-SCALE ELECTRICAL RESISTIVITY AND BULK POROSITY OF THE OCEANIC CRUST, DEEP SEA DRILLING PROJECT HOLE 504B, COSTA RICA RIFT[1]

Keir Becker, Deep Sea Drilling Project, Scripps Institution of Oceanography[2]

ABSTRACT

A long-spaced, DC electrical resistivity experiment was run successfully during Leg 83, throughout over 1 km of Layer 2 of the oceanic crust at Hole 504B. This experiment responds to *in situ* crustal resistivities over vertical and radial averaging scales of about 5 to 50 m. Apparent crustal resistivities are about 10 ohm-m in about 600 m of pillow lavas, sharply increasing to nearly 500 ohm-m in the underlying dikes. Bulk crustal porosities were approximated by applying Archie's Law to the apparent resistivities. Apparent porosities decrease sharply from about 10% in the pillow lavas to about 2% in the dikes, and the results indicate three porosity layers which seem to correspond to seismic Layers 2A, 2B, and 2C. Comparison of the apparent bulk porosities to shipboard porosity measurements on recovered basalt samples suggests that Layers 2A and 2B have significant open fracture porosity, whereas the dikes of Layer 2C have very little fracture porosity. The sharp increase with depth of apparent resistivity and the order-of-magnitude decrease in apparent bulk porosity are highly consistent with the steep reduction with depth of bulk crustal permeability measured in Hole 504B.

INTRODUCTION

The circulation of seawater through fresh basalt plays a vital role in the development of the chemical and physical nature of the oceanic crust. The modes and effects of circulation are themselves partially controlled by the variable permeability and porosity of the basaltic layer. Since these crustal parameters probably depend on irregular fracturing of unknown scale, they cannot be reliably determined from dredged or cored samples. On the contrary, independent determinations of bulk porosity are essential in relating physical properties measured on recovered samples to the formation properties of the crust. Bulk permeability and porosity must be measured *in situ*, preferably from deep boreholes, at averaging scales large enough to escape the disturbance of drilling on the surrounding formation, as well as to include the effects of irregular fracture porosity.

We report here the results of such an *in situ* experiment, a large-scale electrical resistivity log in the deepest borehole drilled to date into the oceanic crust, Hole 504B of the Deep Sea Drilling Project (DSDP). Over the temperatures encountered in the basement section (60–160°C), the electrical conductivity of the pore fluid, essentially seawater, is one to four orders of magnitude greater than the intrinsic conductivity of the host basalt. Therefore, our results, although not a direct measurement of porosity, were highly sensitive to the bulk porosity of the crust.

Hole 504B is located about 200 km south of the Costa Rica Rift (Fig. 1), in 5.9-m.y.-old crust under 3460 m of water. It was cored by three DSDP legs, 69, 70, and 83, to a depth of 1350 m beneath the seafloor (BSF), 1075.5 m into basement (Fig. 2), nearly twice the base-

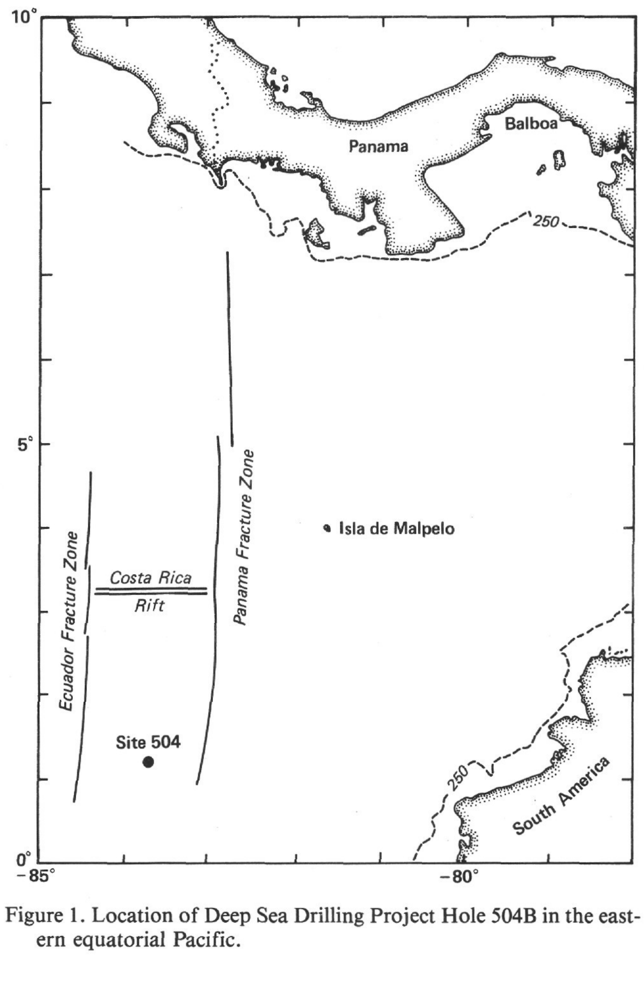

Figure 1. Location of Deep Sea Drilling Project Hole 504B in the eastern equatorial Pacific.

ment penetration of any other oceanic borehole (CRRUST, 1982; Cann, Langseth, Honnorez, Von Herzen, White, et al., 1983; Anderson et al., 1982). Leg 83 clearly penetrated into the sheeted dikes and massive units of Layer 2C (Hole 504B summary chapter, this volume). Be-

[1] Anderson, R. N., Honnorez, J., Becker, K., et al., *Init. Repts. DSDP*, 83: Washington (U.S. Govt. Printing Office).

[2] Address: Deep Sea Drilling Project A031, Scripps Institution of Oceanography, La Jolla CA 92093.

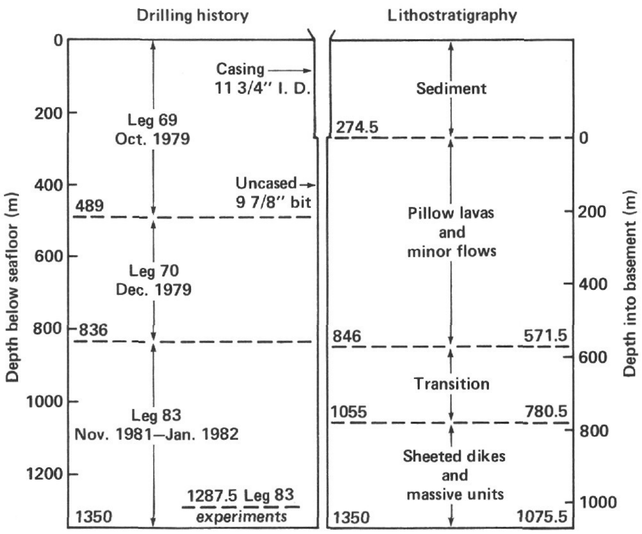

Figure 2. Hole 504B drilling history (left) and generalized lithostratigraphy (right). The latter is based only on the 20% core recovery.

cause of the relatively poor core recovery (about 20%), good geophysical logs were essential to interpret the section and to relate studies of recovered samples to the bulk properties of the crust.

The 274.5 m of chert-based sediment have sealed the crust at Hole 504B from open circulation of seawater. Surface heat-flow measurements and downhole temperatures indicate dominantly conductive heat transfer through the drilled section, at a value of 190 $\pm$10 mW/m^2, consistent with predicted plate heat flow (Langseth et al., 1983; Becker et al., 1983a,b; this volume). No direct evidence was found for presently active hydrothermal circulation, although a vigorous, pressure-driven, nonhydrothermal downhole flow of bottom water commenced when Leg 69 penetrated the sediment seal (Anderson and Zoback, 1982). This downhole flow was directed through the cased sediment into the upper 100 m of basement, and the rate of flow decayed significantly over the 3.5 yr. between Legs 69 and 92 (Becker et al., this volume). It had no discernible effect on the crust deeper than 400 m beneath the seafloor.

EXPERIMENTAL PROCEDURE

The large-scale electrical resistivity experiment was first deployed on Leg 69 by Francis (1982), who discussed the methods in detail. It was run twice in Hole 504B, first during Leg 70 to a depth of 836 m BSF (Von Herzen et al., 1983), and again during Leg 83 to 1287.5 m BSF. The experiment is a simple, long-spaced, DC resistivity log, basically an adaptation of the earliest kind of resistivity logging (Schlumberger et al., 1934a,b). The downhole electrode configurations are shown in Figure 3. A large current is passed from the ship down the armored logging cable, through an insulated cable to a steel sinker-bar/current-electrode. It then passes through the formation and sea back to the ship. Francis (1982) showed that, despite the high conductivity of seawater, the long, narrow seawater return path up the borehole is relatively resistive ($\approx$5 kohm/km), so that the current may be taken to return through the formation. He also showed that neither the casing nor the armored logging cable shunt the current return path. Because of the resistivity of the formation, a potential gradient is set up in the hole, and it is sampled with several nonpolarizing Ag/AgCl electrodes.

The experiment was run at discrete, stationary intervals: at each level, current was passed for about 10 s each under positive and reversed voltage. This allowed removal by averaging of any biases between electrodes arising from possible ambient potential gradients in the hole. Currents and potential differences were measured to an estimated 3–5% accuracy on Leg 70, and to a 1–3% accuracy with new equipment on Leg 83. On Leg 70, a 500 V power supply passed currents of about 6 A into the formation, and three potential electrodes were spaced 45, 91, and 183 m (i.e., 50, 100, and 200 yards) above the current source (Fig. 3). Potential differences between the X and Y electrodes and Y and Z electrodes were recorded and the experiment was run at 25 m intervals. During Leg 83, a 300 V power supply was used, currents ranged over 3.5–4.3 A, and four potential electrodes were spaced 10, 20, 40, and 80 m above the current source. The hole was logged at 10 m intervals, with four potential differences recorded: 1–2, 2–3, 3–4, and 1–4. This redundancy showed excellent Leg 83 data quality: at every level, the sum of the smaller interval voltages duplicated the overall voltage to well within 1%. Although the hole was considerably deeper on Leg 83, a shorter electrode spacing was chosen, partly because it was feared that the high temperatures in the hole would melt the 105°C-rated insulated cable (a threat that went unrealized), and partly to bridge the range of resolution to the much shorter spaced, focused, commercial resistivity logs also run.

The basic parameters measured were the potential differences between electrodes that were due to a known power source. For the nine possible electrode pairs, potential differences were measured for six and were obtained arithmetically for the other three. Measured voltages were in the 5–50 mV range in the pillow lavas logged on Leg 70; when the pillows and dikes were logged on Leg 83, voltage differences of 10 mV–10 V were recorded. A 300-m section was repeat-logged on Leg 83; at each repeated depth, measured voltages duplicated within 1%.

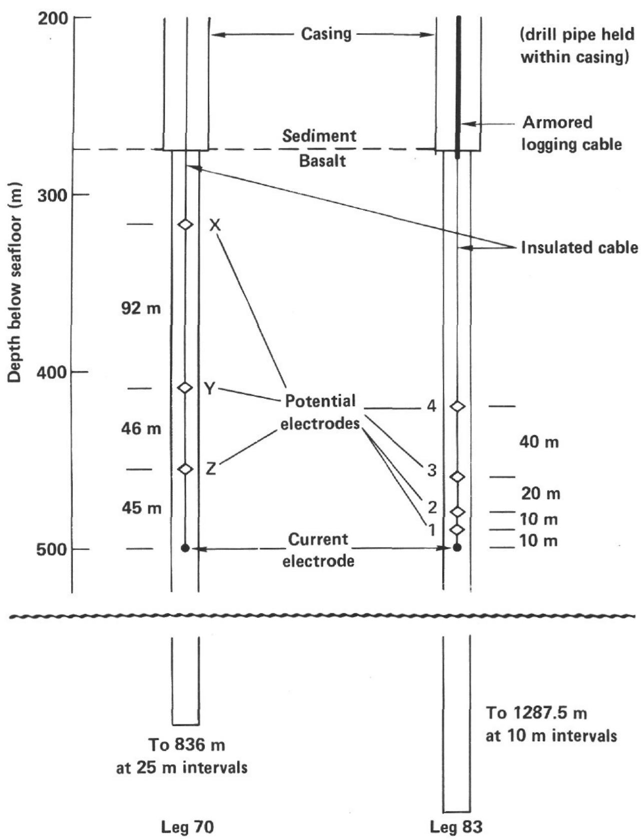

Figure 3. Electrode configurations for the large-scale resistivity experiments in Hole 504B.

APPARENT RESISTIVITY

For a real Earth, with a resistivity varying with depth (and possibly laterally as well), the measured voltage differences are related to the resistivity structure in a complicated, nonlinear fashion. The response of each electrode pair is a function of both the surrounding resistive Earth and the spacings among potential and current electrodes (Dakhnov, 1962; Roy and Dhar, 1971). In effect, each electrode pair averages the Earth's resistivity over a unique radial and vertical scale. Although the scale of investigation of a DC resistivity log is difficult to quantify, the analysis of Roy and Dhar (1971) indicates that the large-scale experiment investigated far enough into the formation (on the order of 5–50 m, depending on the electrode pair) to escape the effects of the disturbed zone near the borehole, where temperature, pressure, and porosity may have been unrepresentative of *in situ* conditions. The large-scale apparent resistivities presented here are thus interpreted as radially and vertically averaged *in situ* resistivities, with the poorly determined averaging scales dependent on the true resistivity structure.

Becker et al. (1982), after Francis (1982), obtained a first approximation to *in situ* resistivities by ignoring the borehole and assuming that the electrodes were embedded in a homogeneous earth of resistivity ρ_a. The apparent resistivities, ρ_a, could then be calculated directly from the measured voltages. With a zero potential assigned to the seafloor, and a current return at the ship, apparent resistivities were obtained by:

$$\rho_a = \frac{2\pi\,\Delta V}{I}\left\{\frac{z_2}{h^2-z_2{}^2} - \frac{z_1}{h^2-z_1{}^2}\right\}^{-1} \tag{1}$$

with h being the depth beneath the seafloor of current source I, and z_1 and z_2 the depths of potential electrodes sensing the voltage difference ΔV ($h > z_2 > z_1$) (see Francis, 1982, for a detailed derivation). In other words, Becker et al. (1982) assumed that the electrode spacings were large enough relative to the hole diameter that no geometric borehole correction was necessary to the measurements. The same assumption is made in analyzing results from somewhat longer spaced versions of a large-scale DC resistivity log (e.g., Runge et al., 1969), but it is questionable with a conductive, seawater-filled borehole and the shorter electrode spacings used in Hole 504B.

A much better approximation to *in situ* resistivity was obtained in this study by applying the analytic solution for the potential that arises from a point current source in a borehole penetrating a homogeneous medium (e.g., Kunz and Moran, 1958; Gianzero and Rau, 1977). At the center of a seawater-filled borehole of radius a, the potential at a vertical distance z from the current source is given by:

$$V(z) = \frac{I\rho_{sw}}{4\pi}\left\{\frac{1}{z} + \frac{2}{\pi a}\int_0^\infty dx\, A(x)\cos\left(\frac{xz}{a}\right)\right\} \tag{2}$$

$$\text{with } A(x) = \frac{(1-\epsilon)\,K_0(x)\,I_0(x)}{K_0(x)\,I_1(x) + \epsilon\,K_1(x)\,I_0(x)}.$$

Here ρ_{sw} is the resistivity of the seawater in the borehole, ϵ is defined as the ratio of seawater resistivity to earth resistivity, ρ_{sw}/ρ_e, and I_0, I_1, K_0, K_1 are modified Bessel functions of the first and second kind.

Equation (2) cannot be inverted to yield the *in situ* resistivity directly from the measured voltage. To obtain the apparent resistivities reported here, equation (2) was integrated numerically for many values of ϵ, to create arrays of calculated voltage differences appropriate to the various electrode pairs. Given the measured voltage differences, values of ϵ were found by cubic spline interpolation within these arrays. The apparent resistivities were then obtained from the values of ϵ using a temperature-corrected seawater resistivity:

$$\rho_{sw}\ (\text{ohm-m}) = [3 + T(^\circ\text{C})/10]^{-1} \tag{3}$$

(Von Herzen et al., 1983; based on laboratory measurements of Horne and Frysinger, 1963, Quist and Marshall, 1968; and Bradshaw and Schleicher, 1980). Since the potential gradient was more sensitive to resistivity variations where the current density was greater, that is, closer to the current source, the depths assigned to apparent resistivities were those of the deeper potential electrode.

Figure 4 shows apparent resistivities calculated using five of the nine possible electrode pairs. These five pairs shared the same equidimensional ratios of spacings among the current and two potential electrodes (Fig. 3). Thus their averaging characteristics were similar, except that the longer arrays averaged farther into the formation. Indeed the five curves in Figure 4 are increasingly smoothed, left to right, with increasing array length. The greater detail in apparent resistivities from the shorter-spaced Leg 83 electrode pairs probably reflects better resolution of small-scale vertical variations in resistivity; the smoother resistivities from the longer-spaced electrode pairs are probably more representative of the bulk properties of the crust.

The apparent resistivities in Figure 4 are all consistent with bulk crustal resistivities on the order of 10 ohm-m through the ≈ 600 m of pillow lavas cored in Hole 504B. Below this level apparent resistivities sharply increase, approaching 500 ohm-m in the sheeted dikes and massive units of Layer 2C. As occurred with all other geophysical measurements in the hole, the transition in apparent resistivities is much sharper than the lithostratigraphic transition zone of about 209 m (Fig. 2) determined from recovered cores. Finer-scale variations in apparent resistivities (and our later porosity estimates), particularly within the pillow lavas, may be related to the variable degree of alteration (Honnorez et al., 1983; Alt et al., this volume), either by partial filling of pore spaces, or because of the enhanced conductivities of certain alteration products. Comparison of our apparent resistivities with typical values of 5–3000 ohm-m measured on basalt samples (e.g., Hyndman and Drury, 1976; Karato, 1983) suggests a significant fracture porosity in the pillow lavas, sharply decreasing into the dikes below.

Considerably greater detail in apparent resistivities is shown by the much smaller spaced Schlumberger Spherically Focused Laterolog (SFL) run on Leg 83, even when these borehole-corrected readings were averaged over 5

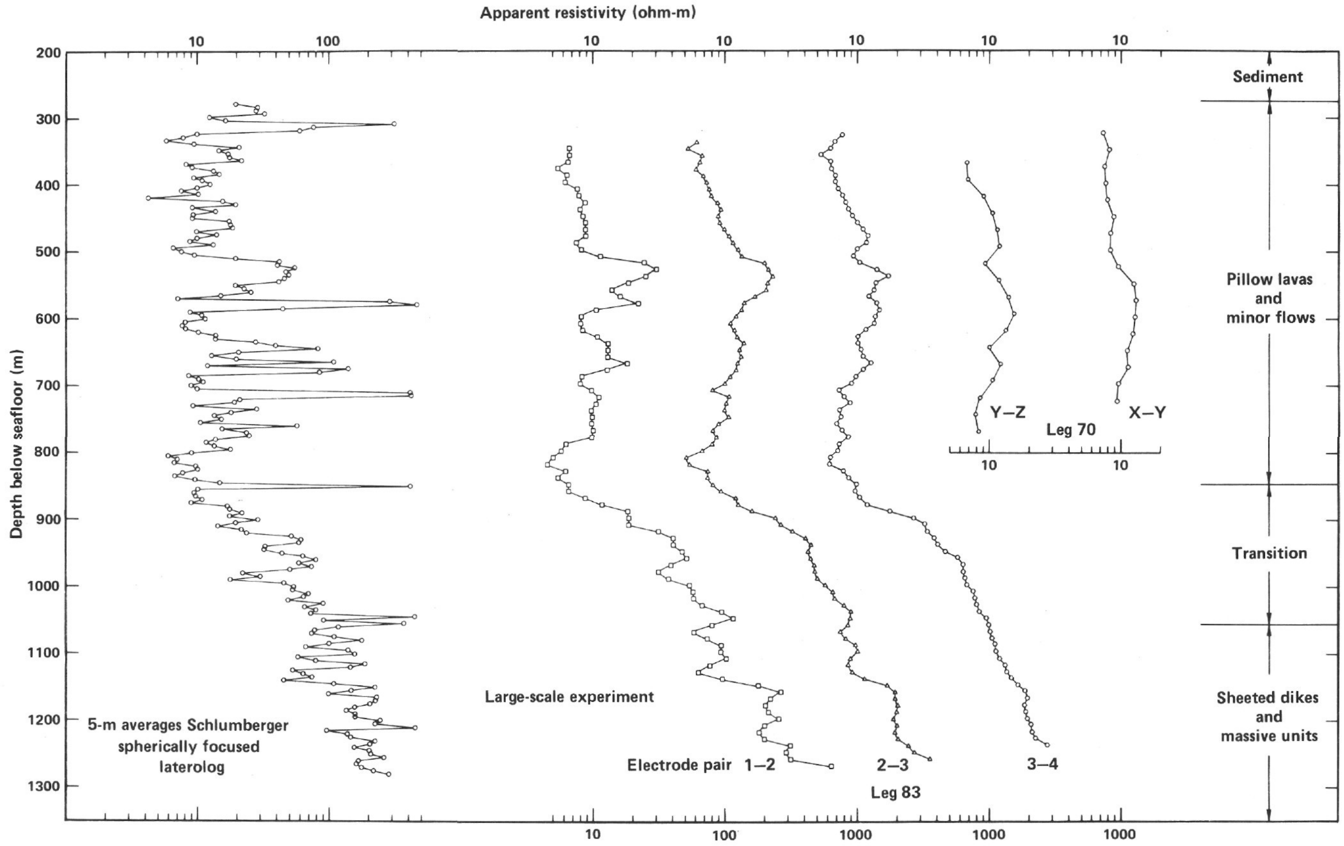

Figure 4. Left to right, 5-m averages of borehole-corrected resistivities measured by Schlumberger logging tool, five sets of apparent resistivities from the large-scale experiment, and generalized lithostratigraphy of Hole 504B. Note that all of the resistivity traces are plotted on equivalent semilogarithmic scales, which have been offset by one decade between traces. Thus all the apparent resistivities are near 10 ohm-m in the pillow lavas and approach 500 ohm-m in the deepest dikes.

m (Fig. 4). Since the radius of investigation of the SFL is relatively small (≈ 0.5 m), some of this apparent detail is not directly representative of *in situ* conditions, but instead reflects some combination of exaggerated tool response at resistivity contrasts and the effect of the disturbed zone near the borehole. Nevertheless, average SFL resistivity values agree quite well with the large-scale values. This contrasts with a disturbing discrepancy (by a factor of up to 2) between large-scale resistivities and Gearhart-Owen laterolog values on both Legs 61 and 70 (Francis, 1982; Von Herzen et al., 1983; Cann and Von Herzen, 1983).

A comparison of the apparent resistivities obtained from equations (1) and (2) indicates that equation (1) is a good approximation for the long-spaced experiment run by Francis (1982) in low-resistivity sediments. Equation (1) is also a reasonable approximation for the experiment of the same spacing run by Von Herzen et al. (1983) during Leg 70 (Fig. 3) in the moderately low resistivity pillow lavas of Hole 504B. However, for the shorter-spaced experiment of Leg 83, equation (1) yields apparent resistivities that are too high by up to 100%, particularly in the high-resistivity dikes, and particularly for the shorter-spaced electrode pairs. Thus, Becker et al. (1982) erroneously argued that the first-order apparent resistivities calculated using equation (1) should be a better approximation to *in situ* resistivities than the values obtained with the Schlumberger SFL. Nevertheless the resistivities vary so strongly in Hole 504B that the basic conclusions of Becker et al. (1982) remain valid.

BULK POROSITY FROM APPARENT RESISTIVITY

In commercial well logging, the porosity, ϕ, is often obtained from the measured resistivity, ρ_m, and the resistivity of the pore fluids ρ_f, by application of the empirical Archie's Law (1942):

$$\frac{\rho_m}{\rho_f} = a\phi^{-m}, \qquad \text{with } a \approx 1,\ m \approx 2.$$

Although this relationship was developed for sedimentary rocks of relatively uniform porosity, it has been applied with reasonable success to samples of both oceanic and continental basement (e.g., Brace et al., 1965; Brace and Orange, 1968; Hyndman and Drury, 1976; Karato, 1983). The application of Archie's Law to *in situ* resistivity measurements in the oceanic crust cannot be rigorously justified, particularly because of the threefold nature of the porosity (Brace, 1971): electrical conduction may be due to vesicular (pore), crack, or fracture porosity. In addition, electrical conductivity may be greatly enhanced by the presence of certain alteration products. The form of the resistivity–porosity relationship probably depends on the nature of the porosity: exponents near or possibly greater than 2 have applied to measurements on basalt samples with dominantly grain-boundary (microcrack) porosity (Brace et al., 1965; Brace and Orange, 1968; Hyndman and Drury, 1976; Karato, 1983) whereas exponents near or possibly less than 2 have applied in interpreting logging measurements in the fractured upper levels of oceanic basement (e.g., Kirkpatrick, 1979; Salisbury et al., 1980; Cann and Von Herzen, 1983). In applying Archie's Law to standard resistivity and neutron porosity logs obtained during Legs 69 and 70 from the upper 561.5 m of basement in Hole 504B, Cann and Von Herzen (1983) obtained a median value of 2.1 for the exponent.

Since Hole 504B clearly penetrated through the highly fractured and partially sealed pillow lavas into relatively unfractured and unevenly altered dikes, a single resistivity-porosity relationship cannot realistically be expected to hold throughout. Nevertheless, bulk crustal porosities at Hole 504B were roughly approximated by applying Archie's Law, compromising on an exponent of about 2. The salinity of the pore fluids closely corresponded to that of seawater (Mottl et al., 1983), so the temperature-sensitive resistivity of seawater was used for that of the pore fluids. The seawater resistivity varies by a factor of 2 over the 60–160° range of equilibrium crustal temperatures in Hole 504B (Equation 3, Fig. 5).

Figure 6 shows apparent bulk porosities calculated using data from the longest-spaced Leg 83 electrode pair, 3–4, which yielded the largest-scale averages of *in situ* resistivity over the complete section. Immediately obvious is a striking, three-layer stratification of porosity, corresponding quite well to Layers 2A, 2B, and 2C, as interpreted from other geophysical measurements in the hole (Anderson et al., 1982; Anderson et al., this volume; Newmark et al., this volume; Salisbury et al., this volume). This stratification in apparent porosities is evident for any reasonable value of the Archie's Law exponent, say 1.5 to 2.5 (Fig. 6). As noted above, there is little rigorous justification for the application of Archie's Law to the ocean crust, much less for the choice of a specific exponent. However, certain theoretical studies (e.g., Sen et al., 1981, and references therein) indicate that Archie's Law can be derived for the resistivity of water-saturated, nonclayey rocks. The analysis in the appendix of Sen et al. (1981) suggests that, for most reasonable geometries of rock porosity (except the extreme cases of oriented, horizontal or vertical, parallel fractures), a fair first approximation to porosity can be obtained using Archie's Law with an exponent equal to 2.

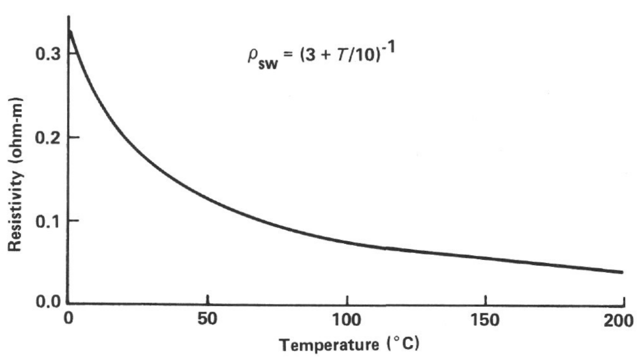

Figure 5. Linearized representation of the variation with temperature of the electrical resistivity of seawater.

Assuming an Archie's Law exponent of 2, bulk porosities in Hole 504B are about 12–14% in the highly permeable reservoir, about 100–150 m thick, identified as a possible thin Layer 2A, 7–10% in the deeper pillows that form Layer 2B, and less than 3% in the dikes and massive units of Layer 2C. These values track with, but are slightly lower (about 3%) than porosity estimates derived from the density and neutron logs, which investigate only the possibly disturbed zone near the borehole. They are also somewhat lower than porosity estimates of 13% or higher obtained by Kirkpatrick (1979) and Salisbury et al. (1980) from standard logs in Layer 2B in DSDP holes in older Atlantic crust. The strong reduction with depth of apparent bulk porosities in Hole 504B is similar to the gradient in porosity inferred by Spudich and Orcutt (1980) from seismic refraction data in 15-m.y.-old eastern Pacific crust.

DISCUSSION: FRACTURE POROSITY, CRUSTAL PERMEABILITY, AND SEISMIC VELOCITY

Shipboard measurements of dominantly grain-boundary porosities of homogeneous basalt samples from Hole 504B yielded mean values of 5% in the pillows of Layer 2A + 2B, 3% for the entire Leg 83 section, and about 1% in the deeper dikes (Karato et al., 1983; Hole 504B summary chapter, this volume). When plotted against depth, these sample porosities seem to fall into three groups, possibly related to Layers 2A, 2B, and 2C (Fig. 7). In Layer 2C, the average sample porosities fall very close to the apparent bulk porosities, whereas in Layers 2A and 2B the bulk porosities are significantly larger than average sample porosities (Fig. 8). The apparent bulk porosities probably reflect some combination of pore, crack, and fracture porosity. Since the latter cannot be represented in recovered basalts, the comparison of bulk and sample porosities (Fig. 8) suggests that Layers 2A and 2B have significant open fracture porosity (partially sealed by alteration products in Layer 2B), whereas Layer 2C has very little fracture porosity. This low fracture porosity in Layer 2C may have resulted from sealing by compression or infilling by alteration products. An alternative possibility must be considered—that the dikes may always have been relatively unfractured, which would probably require that hydrothermal circulation never penetrated pervasively into Layer 2C.

Although there is little rigorous basis for confidence in the actual values of bulk porosity derived from the large-scale resistivities, the porosity stratification revealed by applying Archie's Law is not an artifact of the resistivity-porosity model used. The nearly hundredfold increase of resistivity into the dikes strongly implies a sharp reduction in the bulk porosity, which approaches 1% or lower. This conclusion is completely consistent with the strong decrease of measured permeability with depth in Hole 504B (Fig. 8), confirming the potential of resistivity measurements in assessing crustal permeability (see

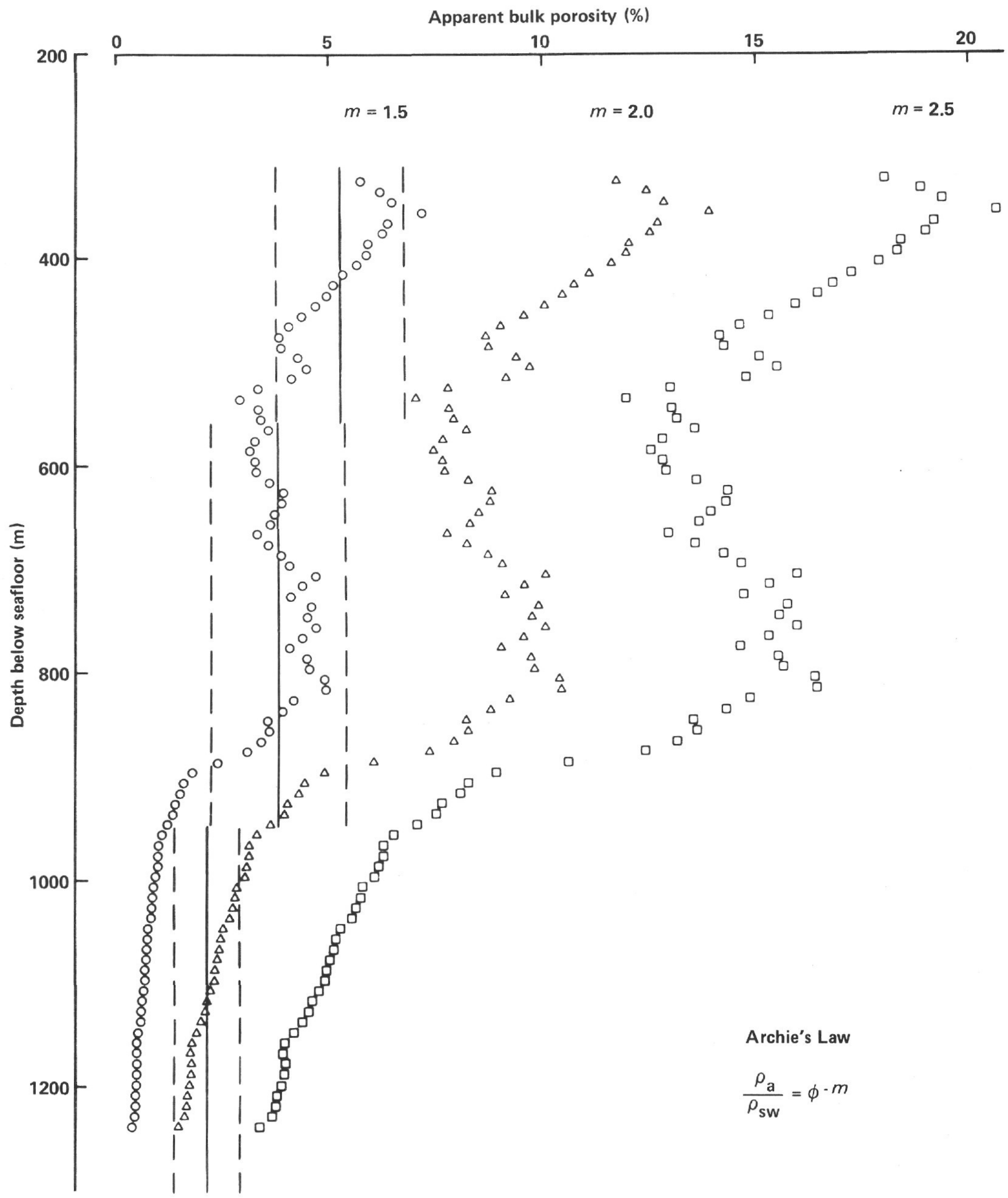

Figure 6. Apparent bulk porosities calculated from apparent resistivities determined from electrode pair 3–4, using Archie's Law with a temperature-corrected seawater resistivity (Fig. 5), for 3 values of the exponent. Solid and dashed vertical lines are mean (±1 S.D.) porosities of basalt samples from Hole 504B (Fig. 7).

Anderson et al., this volume). It is also consistent with the results of a seafloor electromagnetic experiment on the flank of the East Pacific Rise at 21°N (Young and Cox, 1981), which suggests a similar increase of resistivity at a depth of about 1.4 km. In both that experiment and the large-scale resistivity experiment in Hole 504B, the remarkable result was the surprisingly shallow level at which apparent resistivity sharply increases, and, by inference, fracture porosity and permeability to hydrothermal circulation decrease significantly. An important implication of the significant reduction in fracture porosity and permeability with depth in Hole 504B, particularly into the dikes, is that any hydrothermal circulation must presently be limited to shallow crustal levels on the flank of the Costa Rica Rift—about 1 km, or mostly confined to the pillow basalts. It is unclear to what extent hydrothermal circulation may have been so limited closer to the spreading axis.

Layers 2A, 2B, and 2C have, of course, previously been defined only on the basis of seismic data (e.g., Houtz and Ewing, 1976; Ewing and Houtz, 1979), but the seismic velocities of the basaltic crust should depend strongly on the bulk porosity. The borehole seismic experiments of Stephen (1983), Stephen and Harding (1983), and Little and Stephen (this volume) showed a clear Layer 2B/2C break in Hole 504B, consistent with the sharp change of apparent resistivities and porosities, but it showed no evidence for Layer 2A. However, a 100- to

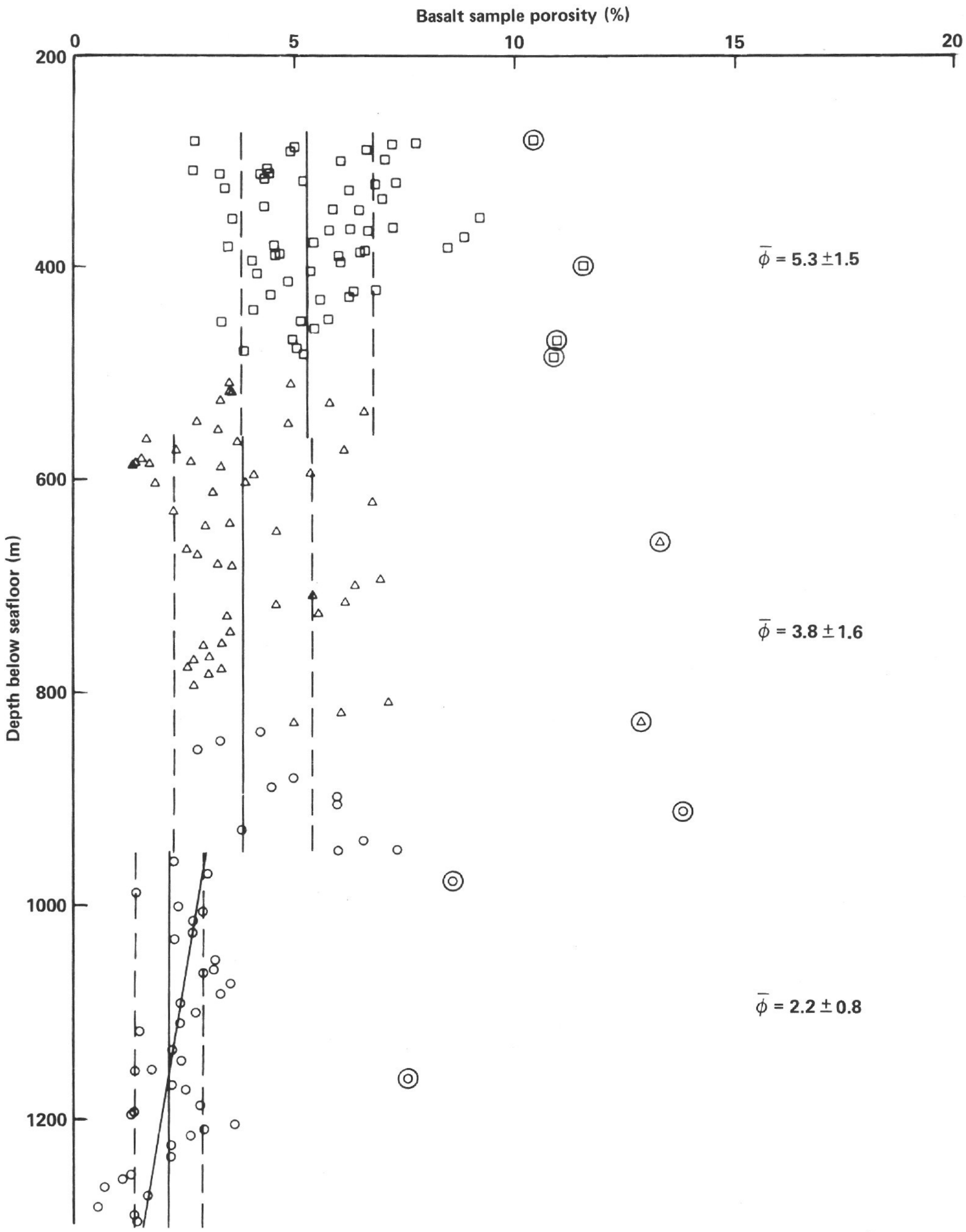

Figure 7. Shipboard measurements of porosities of homogeneous basalt samples from Hole 504B. Squares are from Leg 69, triangles are from Leg 70, and circles are from Leg 83 (Karato et al., 1983; Hole 504B summary chapter, this volume). Solid and dashed vertical lines are mean values ± 1 S.D. (specified on the right) over the vertical intervals spanned, neglecting the 9 circled points.

200-m-thick Layer 2A may be beyond the resolution of both that experiment and conventional refraction techniques, as the seismic wavelengths involved are of greater scale. Salisbury et al. (this volume) and Newmark et al. (this volume) show that the short-wavelength sonic logs are quite consistent with the existence of Layers 2A, 2B, and 2C at Hole 504B. However, they placed the boundaries among these layers somewhat deeper than Becker et al. (1982), who arbitrarily assigned these boundaries to the midpoints of the two zones of steep gradients in apparent bulk porosities (Fig. 8). The analysis of Salisbury et al. (this volume) suggests that a better definition of Layers 2A, 2B, and 2C could have been obtained from the large-scale resistivities and bulk porosities by picking the 2A/2B and 2B/2C boundaries so that the two zones of gradients in bulk porosities were included entirely within the respective overlying layers.

The shipboard physical properties measurements on recovered samples (Hole 504B summary chapter, this volume) and the apparent bulk porosities from the large-scale resistivities indicate that a combination of two important effects may be responsible for the sharp Layer 2B/2C boundary seen in Hole 504B: (1) the nature of the basalt changes across the transition between pillow

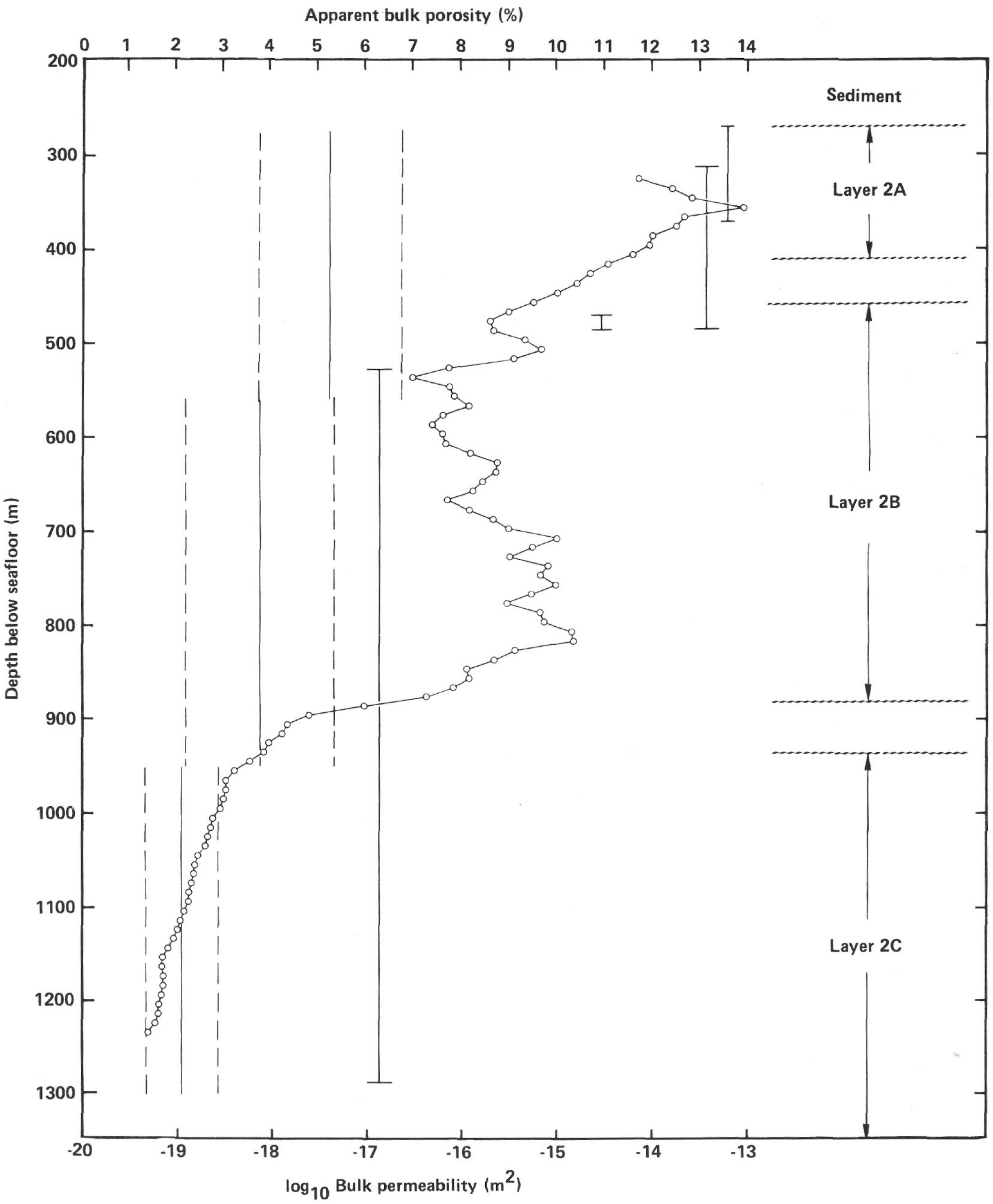

Figure 8. Variation of apparent bulk porosity and measured permeability with depth in Hole 504B. Circles are bulk porosities obtained from the resistivities measured with electrode pair 3–4, using Archie's Law with an exponent of 2. Vertical bars are bulk permeability values averaged over the indicated vertical intervals (Anderson and Zoback, 1982; Becker et al., 1983b, and Anderson et al., this volume). Vertical lines are mean (±1 S.D.) basalt sample porosities from Figure 7. Shown on the right are approximate boundaries between Layers 2A, 2B, and 2C, arbitrarily based only on the gradients in the apparent bulk porosities.

lavas and sheeted dikes, so that laboratory seismic velocities are about 10% higher in the dikes; and (2) the fracture porosity is sharply lower in the dikes, so that *in situ* seismic velocities in Layer 2C are less affected by the porosity and are much closer to the velocities of the host basalt.

ACKNOWLEDGMENTS

The assistance of T. Gustafson, R. Current, and P. Laughlin was invaluable in conducting the resistivity experiments on Legs 70 and 83. The numerical analysis of the resistivity data was accomplished with the generous help of R. L. Parker. M. Salisbury, R. Stephen, and two unnamed reviewers provided constructive comments on an earlier version of this paper. This study was supported by U.S. National Science Foundation grants C-482 and OCE 81-17693.

REFERENCES

Anderson, R. N., Honnorez, J., Becker, K., Adamson, A. C., Alt, J. C., Emmermann, R., Kempton, P. D., Kinoshita, H., Laverne, C., Mottl, M. J., and Newmark, R. L., 1982. DSDP Hole 504B, the first reference section over 1 km through Layer 2 of the oceanic crust. *Nature*, 300:589–594.

Anderson, R. N., and Zoback, M. D., 1982. Permeability, underpressures, and convection in the oceanic crust near the Costa Rica Rift, eastern equatorial Pacific. *J. Geophys. Res.*, 87:2860–2868.

Archie, G. E., 1942. The electrical resistivity log as an aid in determining some reservoir characteristics. *J. Petrol. Tech.*, 5:1–8.

Becker, K., Von Herzen, R. P., Francis, T. J. G., Anderson, R. N., Honnorez, J., Adamson, A. C., Alt, J. C., Emmermann, R., Kempton, P. D., Kinoshita, H., Laverne, C., Mottl, M. J., and Newmark, R. L., 1982. *In situ* electrical resistivity and bulk porosity of the oceanic crust, Costa Rica Rift. *Nature,* 300:594–598.

Becker, K., Langseth, M., and Von Herzen, R. P., 1983 (cited as 1983a). Deep crustal geothermal measurements, Hole 504B, Deep Sea Drilling Project Legs 69 and 70. *In* Cann, J. R., Langseth, M. G., Honnorez, J., Von Herzen, R. P., White, S. M., et al. *Init. Repts. DSDP*, 69: Washington (U.S. Govt. Printing Office), 223–235.

Becker, K., Langseth, M., Von Herzen, R. P., and Anderson, R. N., 1983 (cited as 1983b). Deep crustal geothermal measurements, Hole 504B, Costa Rica Rift. *J. Geophys. Res.*, 88:3447–3457.

Brace, W. F., 1971. Resistivity of saturated crustal rocks to 40 km based on laboratory studies. *In* Heacock, J. G. (Ed.), *The Structure and Physical Properties of the Earth's Crust*: Washington (Am. Geophys. Un.), pp. 243–255.

Brace, W. F., and Orange, A. S., 1968. Further studies of the effects of pressure on electrical resistivity of rocks *J. Geophys. Res.*, 73: 5407–5420.

Brace, W. F., Orange, A. S., and Madden, T. R., 1965. The effect of pressure on the electrical resistivity of water-saturated crystalline rocks. *J. Geophys. Res.*, 70:5669–5678.

Bradshaw, A. L., and Schleicher, K. E., 1980. Electrical conductivity of seawater. *IEEE J. Ocean. Eng.*, OE5:50–62.

Cann, J., Langseth, M. G., Honnorez, J., Von Herzen, R. P., White, S. M., et al., 1983. *Init. Repts. DSDP*, 69: Washington (U.S. Govt. Printing Office).

Cann, J. R. and Von Herzen, R. P., 1983. Downhole logging at Deep Sea Drilling Project Sites 501, 504, and 505, near the Costa Rica Rift. *In* Cann, J. R., Langseth, M. G., Honnorez, J., Von Herzen, R. P., White, S. M., et al., *Init. Repts. DSDP*, 69: Washington (U.S. Govt. Printing Office), 281–299.

CRRUST (Costa Rica Rift United Scientific Team), 1982. Geothermal regions of the Costa Rica Rift, east Pacific, investigated by drilling, DSDP-IPOD Legs 68, 69, and 70. *Geol. Soc. Am. Bull.*, 93: 862–875.

Dakhnov, V. H., 1962. Geophysical well logging. *Q. Colorado Sch. Mines*, 57:1–443.

Ewing, J., and Houtz, R., 1979. Acoustic stratigraphy and structure of the oceanic crust. *In* Talwani, M., Harrison, C. G., and Hayes, D. E. (Eds.), *Deep Drilling Results in the Atlantic Ocean: Ocean Crust*: Washington, D. C. (Am. Geophys. Un.), pp. 1–14.

Francis, T. J. G., 1982. Large-scale resistivity experiment at Deep Sea Drilling Project Hole 459B. *In* Hussong, D. M., Uyeda, S., et al., *Init. Repts. DSDP*, 60: Washington (U.S. Govt. Printing Office), 841–852.

Gianzero, S. C., and Rau, R., 1977. The effect of sonde position in the hole on responses of resistivity tools. *Geophysics*, 42:642–654.

Honnorez, J., Laverne, C., Hubberten, H. -W., Emmermann, R., and Muehlenbachs, K., 1983. Alteration processes in Layer 2 basalts from Deep Sea Drilling Project Hole 504B, Costa Rica Rift. *In* Cann, J. R., Langseth, M. G., Honnorez, J., Von Herzen, R. P., White, S. M., et al., *Init. Repts. DSDP*, 69: Washington (U.S. Govt. Printing Office), 509–546.

Horne, R. A., and Frysinger, G. R., 1963. The effect of pressure on the electrical conductivity of seawater. *J. Geophys. Res.*, 68: 1967–1973.

Houtz, R., and Ewing, J., 1976. Upper crustal structure as a function of plate age. *J. Geophys. Res.*, 81:2490–2498.

Hyndman, R. D., and Drury, M., 1976. The physical properties of oceanic basement rocks from deep drilling on the Mid-Atlantic Ridge. *J. Geophys. Res.*, 81:4042–4052.

Karato, S., 1983. Physical properties of basalts from Deep Sea Drilling Project Hole 504B, Costa Rica Rift. *In* Cann, J. R., Langseth, M. G., Honnorez, J., Von Herzen, R. P., White, S. M., et al., *Init. Repts. DSDP*, 69: Washington (U.S. Govt. Printing Office), 687–695.

Kirkpatrick, R. J., 1979. The physical state of the oceanic crust: results of downhole geophysical logging in the Mid-Atlantic Ridge at 23°N. *J. Geophys. Res.*, 84:178–188.

Kunz, K. S., and Moran, J. H., 1958. Some effects of formation anisotropy on resistivity measurements in boreholes. *Geophysics*, 23: 770–794.

Langseth, M. G., Cann, J. R., Natland, J. H., and Hobart, M., 1983. Geothermal phenomena at the Costa Rica Rift: Background and objectives for drilling at Deep Sea Drilling Project Sites 501, 504, and 505. *In* Cann, J. R., Langseth, M. G., Honnorez, J., Von Herzen, R. P., White, S. M., et al., *Init. Repts. DSDP*, 69: Washington (U.S. Govt. Printing Office), 5–29.

Mottl, M. J., Anderson, R. N., Jenkins, R. N., and Lawrence, J. R., 1983. Chemistry of waters sampled from basaltic basement in Deep Sea Drilling Project Holes 501, 504B, and 505B. *In* Cann, J. R., Langseth, M. G., Honnorez, J., Von Herzen, R. P., White, S. M., et al., *Init. Repts. DSDP*, 69: Washington (U.S. Govt. Printing Office), 475–483.

Quist, A. S., and Marshall, W. L., 1968. Electrical conductances of aqueous sodium chloride solutions from 0 to 800° and at pressures to 4000 bars. *J. Phys. Chem.*, 72:684–703.

Roy, A., and Dhar, R. L., 1971. Radius of investigation in DC resistivity well logging. *Geophysics*, 36:754–760.

Runge, R. J., Worthington, A. E., and Lucas, D. R., 1969. Ultra-long spaced electric log (ULSEL). *Soc. Prof. Well Log Analysts Trans. 10th Ann. Logging Symp.*, H1–H22.

Salisbury, M. H., Stephen, R., Christensen, N. I., Francheteau, J., Hamano, Y., Hobart, M., and Johnson, D., 1980. The physical state of the upper levels of Cretaceous oceanic crust from the results of logging, laboratory studies, and the oblique seismic experiment at Deep Sea Drilling Project Sites 417 and 418. *In* Donnelly, T., Francheteau, J., Bryan, W., Robinson, P., Flower, M., Salisbury, M., et al., *Init. Repts. DSDP*, 51, 52, 53, Pt. 2: Washington (U.S. Govt. Printing Office), 1579–1597.

Schlumberger, C., Schlumberger, M., and Leonardon, E. G., 1934a. Electrical coring; a method of determining bottomhole data by electrical measurements. *Transactions, A.I.M.E.*, 110:237–272.

________, 1934b. A new contribution to subsurface studies by means of electrical measurements in drill holes. *Transactions, A.I.M.E.*, 110:273–288.

Sen, P. N., Scala, C., and Cohen, M. H., 1981. A self-similar model for sedimentary rocks with application to the dielectric constant of fused glass beads. *Geophysics*, 46:781–795.

Spudich, P., and Orcutt, J., 1980. Petrology and porosity of an oceanic crustal site: results from wave form modeling of seismic refraction data. *J. Geophys. Res.*, 85:1409–1433.

Stephen, R., 1983. The oblique seismic experiment on Deep Sea Drilling Project Leg 70. *In* Cann, J. R., Langseth, M. G., Honnorez, J., Von Herzen, R. P., White, S. M., et al., *Init. Repts. DSDP*, 69: Washington (U.S. Govt. Printing Office), 301–308.

Stephen, R. A., and Harding, A. J., 1983. Traveltime analysis of borehole seismic data. *J. Geophys. Res.*, 88:8289–8298.

Von Herzen, R. P., Francis, T. J. G., and Becker, K., 1983. *In situ* large-scale electrical resistivity of ocean crust, Hole 504B. *In* Cann, J. R., Langseth, M. G., Honnorez, J., Von Herzen, R. P., White, S. M., et al., *Init. Repts. DSDP*, 69: Washington (U.S. Govt. Printing Office), 237–244.

Young, P. D., and Cox, C. S., 1981. Electromagnetic active source sounding near the East Pacific Rise. *Geophys. Res. Lett.*, 8: 1043–1046.

Date of Initial Receipt: 15 June 1983
Date of Acceptance: 10 February 1984