41. SHIPBOARD PHYSICAL-PROPERTIES MEASUREMENTS OF BASALTS FROM THE COSTA RICA RIFT, DEEP SEA DRILLING PROJECT LEGS 69 AND 70[1]

Shun-ichiro Karato,[2] Ocean Research Institute, University of Tokyo, Minamidai, Nakano, Tokyo 164, Japan
Roy H. Wilkens,[3] Department of Geological Sciences, University of Washington, Seattle, Washington
and
Marcus G. Langseth, Lamont-Doherty Geological Observatory, Palisades, New York

ABSTRACT

Physical properties of basalts from Deep Sea Drilling Project Sites 504 and 505, south of the Costa Rica Rift, including wet-bulk density, water content, sonic velocity, and thermal conductivity, were measured on board D/V *Glomar Challenger* during Legs 69 and 70. The mean wet-bulk density is 2.90 ± 0.06 g/cm^3, porosity $5.0 \pm 2.2\%$, sonic velocity 5.75 ± 0.30 km/s, and thermal conductivity 1.67 ± 0.09 W/m°K.

Basalts from this young ocean crust (5.9 m.y.) have relatively low porosity and consequently high density and sonic velocity, as compared to average DSDP basalts.

Some systematic trends in depth variation of physical properties were found: down to Core 40 in Hole 504B, grain densities were lower than those deeper in the hole, whereas porosity in the upper section was higher. This can be attributed either to differences in the flow type or in the nature of alteration of basalts at the different levels in the hole.

INTRODUCTION

Physical properties of basement rocks play key roles in our understanding of the physical processes that operate in the ocean crust. During DSDP Legs 69 and 70, drilling of basement rocks was tried in young oceanic crust south of the Costa Rica Rift. At Hole 504B (1° 13.6'N, 83°43.8'W) successful drilling was accomplished to 562 meters sub-basement depth. Measurements of the physical properties of the cored samples, including wet-bulk density, water content, sonic velocity, and thermal conductivity, were made on board the *Glomar Challenger*.

Since these physical properties are sensitive to water content, samples selected for physical-properties studies were stored in sea water as soon as possible after the cores had been received on deck. Sonic velocity was measured for mini-core samples 2.5 cm in diameter by 2 to 5 cm in length, which were representative of the core and section from which samples were taken. Gravimetric measurements were made for mini-cores and/or rock chunks taken from the same piece of basalt from which the mini-core was cut. Thermal conductivity was measured for the same basalt piece that supplied the mini-core.

It must be noted that the core recovery in this area is low—about 20 to 30%. Much of the section not cored probably consists of broken and fractured rocks. In addition, the physical-properties measurements could be done only for unfractured materials, although we have attempted to sample all rock types and states of alteration and weathering. Therefore, the mean values of measured physical properties may not be representative of *in situ* properties of the drilled section. This chapter summarizes and discusses the results of shipboard physical-properties measurements. The interpretation of downhole experiments in terms of physical-properties studies is made in Cann and Von Herzen (this volume). Detailed sonic-velocity studies at high pressure are described in Wilkens et al. (this volume), and electrical-resistivity and water-permeability studies in Karato (this volume).

All of the results are given in Table 1 and plotted against depth in Figure 1. Because most of the samples were taken from Hole 504B, the following discussion will be concerned mainly with Hole 504B data. The incorporation of Hole 505B data would not materially alter the conclusions.

Cores 1 to 29 of Hole 504B were drilled during Leg 69, and 32 to 70 during Leg 70. Because the measurements were made by different observers on the different legs, there may be a systematic difference between Leg 69 and Leg 70 results. This must be kept in mind when depth variations of physical properties are discussed.

GRAVIMETRIC MEASUREMENTS

The wet-bulk density of basement rocks was determined by weighing samples first in air, to determine the mass, and then suspended in distilled water, to determine the volume. Water content was determined by weighing samples sea-water saturated and after drying at 110°C for 24 hours. Porosity and grain density were calculated from wet-bulk-density and water-content data. The reproducibility of measurement was about 0.05 g; thus, the accuracy of wet-bulk density and grain density is about $\pm 0.5\%$, and that of porosity $\pm 1\%$.

The wet-bulk density of 115 basalts ranges from 2.73 g/cm^3 for a basalt breccia to 3.02 g/cm^3 for a low-porosity basalt, with a mean of 2.90 ± 0.06 g/cm^3. The

[1] 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).
[2] Present address: Research School of Earth Sciences, The Australian National University, Canberra 2600, Australia.
[3] Present address: Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Table 1. Physical properties of basalts from Holes 504B and 505B.

Sample (interval in cm)	Wet-Bulk Density, ϱ_b (g/cm^3)	Grain Density, ϱ_g (g/cm^3)	Porosity, ϕ (%)	Sonic Velocity, V_p (km/s)	Thermal Conductivity, K (W/m°K)
504B-4-2, 102–104	2.91	2.96	2.7	6.21	1.83
4-3, 123–125	2.83	2.98	7.8	5.77	—
4-4, 42–44	2.85	3.00	7.2	5.56	1.66
4-5, 125–127	2.88	2.98	5.0	5.72	—
5-1, 57–59	2.90	3.03	6.6	5.67	—
5-2, 41–43	2.88	2.98	4.9	5.65	1.78
6-1, 54–56	2.81	2.95	7.1	5.67	1.64
6-2, 40–42	2.88	3.00	6.0	5.72	—
7-1, 33–35	2.88	2.96	4.4	6.26	—
7-2, 99–101	2.91	2.97	2.7	5.83	1.56
7-3, 127–129	2.90	2.98	4.4	5.77	1.82
7-4, 35–37	2.90	2.98	4.2	6.04	—
7-5, 2–4	2.91	2.98	3.3	5.71	—
8-1, 63–65	2.92	3.00	4.3	5.94	—
8-2, 86–88	2.91	3.01	5.2	5.77	1.68
8-3, 72–74	2.84	2.98	7.3	5.77	—
8-4, 58–60	2.87	3.01	6.8	5.69	1.69
9-1, 51–53	2.89	2.95	3.4	6.04	1.72
9-2, 73–75	2.87	2.99	6.2	5.62	1.65
10-2, 11–13	2.85	2.98	7.0	5.59	1.66
10-3, 83–85	—	—	—	—	1.10*
11-1, 19–21	2.92	3.01	4.3	6.04	1.70
11-2, 76–78	2.87	2.98	5.9	5.89	—
11-3, 27–29	2.85	2.97	6.5	5.86	—
12-1, 50–52	2.81	2.99	9.2	5.67	—
12-2, 107–109	2.94	3.01	3.6	6.01	—
13-1, 140–142	2.84	2.98	7.2	5.43	—
13-2, 99–101	2.85	2.97	6.3	5.67	1.76
13-3, 71–73	2.88	2.99	5.8	5.73	—
13-4, 15–17	2.86	2.99	6.7	5.66	1.70
14-1, 39–41	2.81	2.98	8.9	5.55	1.67
15-1, 140–142	—	—	—	—	1.71
15-2, 27–29	2.88	2.99	5.4	5.80	—
15-3, 138–140	2.91	3.00	4.5	5.79	1.71
15-4, 130–132	2.94	3.01	3.5	6.22	—
15-5, 52–54	2.83	2.99	8.5	5.38	—
16-1, 20–22	2.87	3.00	6.6	5.57	1.70
16-2, 6–8	2.85	2.97	6.5	5.32	—
16-3, 66–68	2.92	3.01	4.7	5.89	—
16-3, 134–136	2.90	2.99	4.5	5.88	1.77
16-4, 103–105	2.86	2.98	6.0	5.88	—
17-1, 96–98	2.91	2.98	4.0	5.98	—
17-2, 104–106	2.89	3.01	6.0	5.86	1.58
18-1, 71–73	2.73	2.95	11.5	5.11	1.60
19-1, 103–105	2.84	2.94	5.3	5.86	—
19-2, 88–90	2.95	3.03	4.1	6.27	1.67
20-1, 116–118	2.88	2.97	4.8	5.59	—
21-1, 137–139	2.85	2.98	6.8	5.55	—
21-2, 59–61	2.85	2.97	6.3	5.67	1.66
21-3, 123–125	2.90	2.98	4.4	5.74	—
21-4, 136–138	2.86	2.98	6.2	5.83	1.57
22-1, 62–64	2.87	2.98	5.5	5.94	1.67
23-1, 90–92	2.92	3.01	4.1	6.19	1.65
24-1, 102–104	2.86	2.97	5.6	5.67	—
24-2, 64–66	2.90	3.00	5.1	5.78	1.65
24-3, 77–79	2.94	3.01	3.3	6.00	—
25-2, 83–85	2.88	2.99	5.4	5.88	1.69
27-1, 109–111	2.89	2.98	4.9	5.75	1.63
27-2, 106–108	2.74	2.95	10.9	5.11	—
28-1, 95–97	2.89	2.99	5.0	5.84	—
28-3, 56–58	2.92	3.00	3.8	5.82	—
28-4, 123–125	2.87	2.97	5.2	5.60	—
29-1, 5–7	2.73	2.94	10.9	5.11	—
29-1, 15–17	—	—	—	—	1.35**
(Note: the foregoing are Leg 69 cores and measurements, the following are from Leg 70.)					
32-1, 145–147	2.95	3.02	3.5	5.95	—
32-2, 102–104	2.90	3.00	4.9	5.58	—
33-1, 130–132	2.92	2.99	3.6	5.74	—
33-2, 71–73	2.89	2.98	4.4	5.86	1.52
34-1, 10–12	2.95	3.01	3.3	5.85	—
34-2, 58–60	2.81	2.92	5.8	5.32	—
35-1, 115–117	2.83	2.95	6.5	5.70	—
36-2, 84–86	2.96	3.01	2.8	5.95	1.64
36-3, 15–17	2.88	2.97	4.8	5.56	—
37-1, 11–13	2.94	3.00	3.2	5.72	—
38-1, 83–85	2.98	3.02	1.6	6.35	—
38-2, 109–111	2.97	3.04	3.7	5.74	1.65
39-1, 103–105	2.90	3.02	6.1	5.50	—
39-2, 117–119	2.94	2.98	2.3	6.07	1.63
40-1, 93–95	2.96	2.99	1.5	6.33	1.60
40-3, 35–37	2.92	2.97	2.6	6.07	—
40-4, 61–63	2.95	2.98	1.4	5.95	—
41-1, 112–114	2.95	2.98	1.7	6.10	1.70
41-2, 96–98	2.96	2.98	1.3	6.17	—
41-3, 104–106	2.98	3.05	3.3	5.96	—
42-1, 31–33	2.88	2.98	5.3	5.50	1.78
42-2, 79–81	2.94	3.02	4.0	5.43	—
43-1, 9–11	2.96	3.04	3.8	5.78	1.78
43-2, 3–5	3.02	3.06	1.8	5.98	—
44-1, 79–81	2.96	3.03	3.6	5.74	1.63

Table 1. (Continued).

Sample (interval in cm)	Wet-Bulk Density, ϱ_b (g/cm^3)	Grain Density, ϱ_g (g/cm^3)	Porosity, ϕ (%)	Sonic Velocity, V_p (km/s)	Thermal Conductivity, K (W/m°K)
504B-45-1, 9–11	2.88	3.01	6.7	5.48	1.55
46-1, 74–76	3.00	3.04	2.2	6.14	1.78
47-3, 7–9	2.95	3.02	3.5	5.92	—
47-4, 98–100	2.97	3.03	2.9	5.94	1.87
48-2, 8–10	2.94	3.03	4.5	5.66	1.66
49-2, 58–60	2.74	3.01	13.3	5.00	1.59
50-1, 27–29	2.96	3.01	2.5	6.20	1.50
51-1, 105–107	2.95	3.01	2.8	6.21	1.50
52-1, 69–71	2.93	3.00	3.2	5.83	1.56
52-2, 29–31	2.94	3.01	3.5	5.75	—
54-1, 129–131	2.88	3.01	6.9	5.39	1.56
55-2, 24–26	2.89	3.01	6.3	5.43	1.47
56-2, 64–66	2.91	3.01	5.4	5.77	1.59
57-1, 39–41	2.90	3.02	6.1	5.37	—
57-2, 134–136	2.98	3.07	4.5	5.91	1.87
58-1, 110–112	2.94	3.05	5.5	5.83	—
58-3, 109–111	2.96	3.02	3.4	5.60	1.74
60-1, 65–67	2.97	3.04	3.5	5.96	1.70
61-2, 79–81	2.94	3.00	3.3	5.84	—
62-1, 106–108	2.91	2.97	2.9	5.44	1.56
63-2, 130–132	2.95	3.01	3.0	5.47	—
63-4, 77–79	2.95	3.01	2.7	5.85	1.70
64-2, 2–4	2.94	3.01	3.3	5.61	1.74
65-1, 57–59	2.98	3.04	3.0	5.57	1.70
66-2, 84–86	2.99	3.05	2.7	5.85	1.56
68-1, 0–2	2.84	2.98	7.1	5.13	1.63
69-1, 54–56	2.95	3.08	6.0	5.76	1.63
70-1, 19–21	2.77	3.03	12.8	4.40	—
70-2, 22–24	2.94	3.04	4.9	5.96	1.63
505B-2-1, 120–122	2.83	2.96	6.7	5.85	1.70
2-2, 140–142	—	—	—	—	1.81
3-1, 108–110	2.86	2.99	6.8	5.87	1.77
3-2, 76–78	2.89	2.98	4.5	5.94	—
5-1, 45–47	2.84	2.99	7.6	5.91	1.69
6-1, 106–108	2.90	3.01	5.6	5.68	—

* Smectite breccia.

** Average of five measurements of breccias.

grain density ranges from 2.92 to 3.08 g/cm^3, with a mean of 3.00 ± 0.03 g/cm^3. The porosity of the basalts ranges from 1.3% for a fresh basalt to 13.3% for a basalt breccia, with a mean of 5.0 ± 2.2%.

The relationship of porosity to wet-bulk density is shown in Figure 2. The average grain density of basalts from this area is higher than that of basalts from older ocean crust (2.91 g/cm^3; e.g., Legs 51 to 53, Atlantic ocean floor about 100 m.y. old. [Hamano, 1979]). The porosity is slightly lower or comparable to that of Legs 51 to 53 (Hamano, 1979), and consequently the wet-bulk density is significantly higher than that for Legs 51 to 53 (2.79 g/cm^3). The high grain and wet-bulk densities of the basalts may be a result of their freshness, because alteration and/or weathering may increase their porosity and decrease grain density by replacement of olivine and/or plagioclase with light clay minerals.

Some systematic trends in depth variation of density and porosity are observed (Fig. 1). This depth variation is not due to systematic experimental errors between legs, since the change in grain density and porosity occurs around the Core 40/41 boundary (Fig. 1). At the upper part of the section drilled during Leg 70 (Cores 32–40), the density and porosity are comparable to values obtained during Leg 69 (Cores 1–29). The average values of physical properties of the upper (Cores 1–40) and lower (Cores 41–70) parts of Hole 504B are given in Table 2.

There are two possible causes for this depth variation of physical properties. One is the change in flow type. Pillows are abundant in the upper part of the hole, and massive flows are more common in the lower part (Fig. 1). Because the porosity of a massive flow is generally smaller than that of pillow basalts, the systematic trend in porosity may be a result of the difference in flow type. However, the difference in grain density may be difficult to attribute to this effect, because it should be related to a difference in chemistry and/or mineralogy of the rocks. The other possible cause, the difference in the nature of alteration, could be responsible for the change in grain density (and/or porosity). This mechanism is consistent with the fact that the change in density occurs near the Core 40/41 boundary (Honnorez et al., this volume).

In addition to this change in density and porosity at the Core 40/41 boundary, there seems to be a general trend of increasing wet-bulk density and decreasing porosity decreases with depth. This may be an intrinsic depth effect, possibly due to a cooling-rate effect or pressure effect on porosity.

THERMAL CONDUCTIVITY

The measurements of thermal conductivity were made on the sawed halves of cores, using the Vacquier flat-plate sensor. This is a needle probe embedded in a piece of microbed brick so that the needle is flush with one surface. It was found necessary to first lap the sawed surface flat and smooth—otherwise the gap between the flat-plate sensor and the sample was large enough to create a large contact resistance, and convection of water in the contact took place.

In order to stabilize temperature prior to measurement, the flat-plate sensor and the sample were submerged in a tank of sea water. By insulating the tank, a

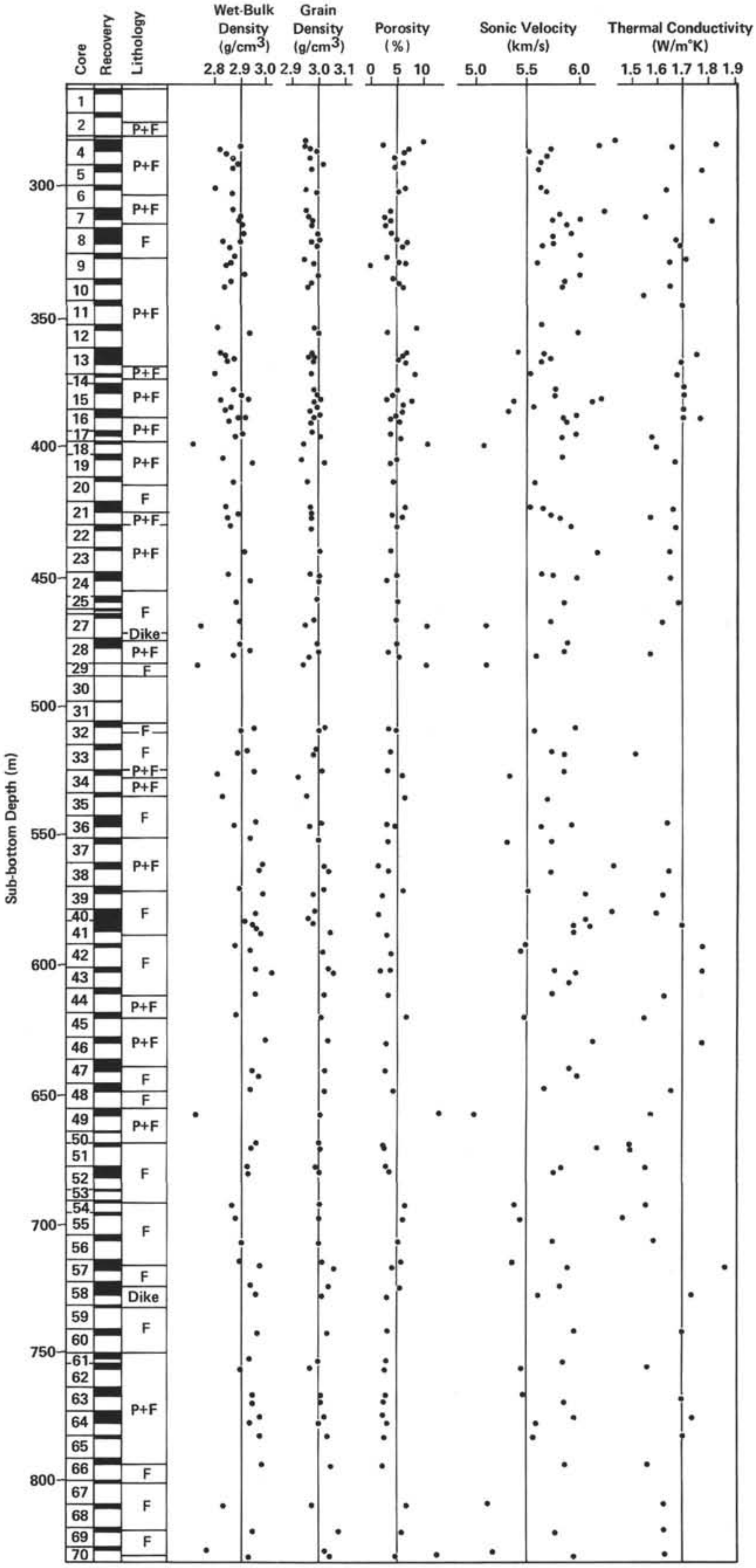

Figure 1. Depth variation of physical properties of basement rocks in Hole 504B. P = pillows, F = flows.

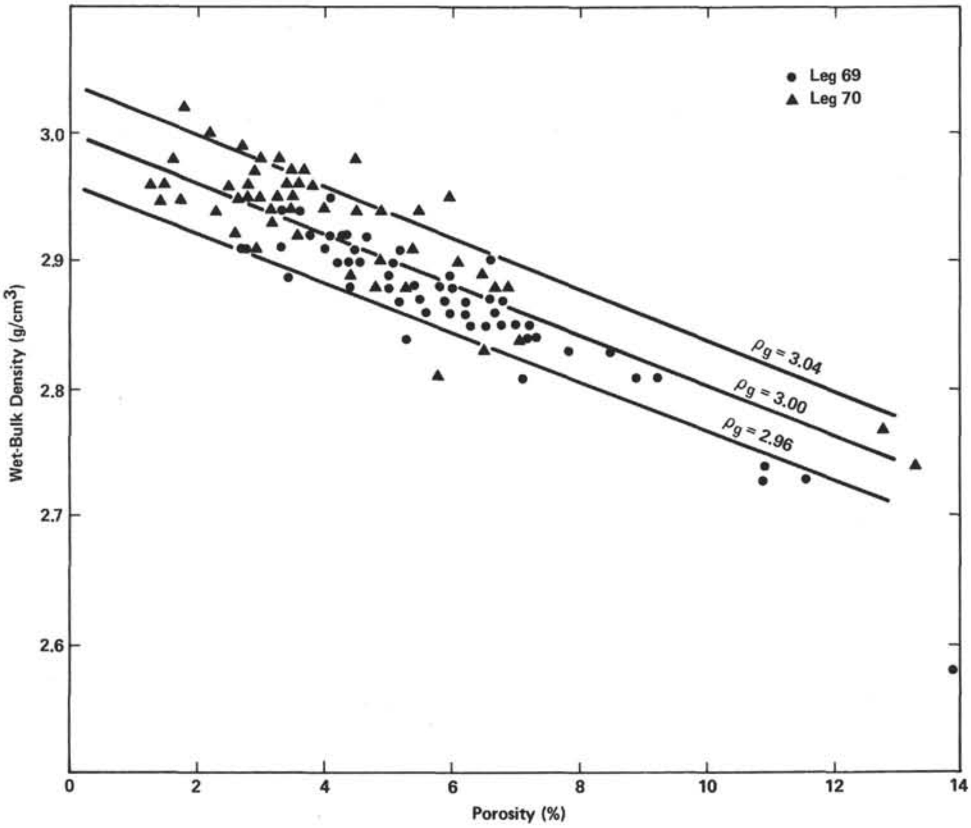

Figure 2. Relationship of wet-bulk density to porosity for basalts from Hole 504B.

stable measurement could be made within 30 minutes or so. Each of the samples was soaked in the salt-water tank prior to measurement. This hastened the equilibration and ensured that the samples were saturated with sea water, their *in situ* condition. The reliability of measurements was checked by measuring the standard granodiorite disks on board, and shown to be about ±5%. The measured values are shown in Table 1 and Figure 1.

The thermal conductivity of 64 basalts ranges from 1.47 to 1.87 W/m°K, with a mean of 1.67±0.09 W/m°K. This result is in agreement with the results of Leg 37 (1.67 W/m°K; Hyndman and Drury, 1976), near the Mid-Atlantic Ridge, but slightly less than the values for basalts from Leg 51 to 53 (1.81 W/m°K; Hamano, 1979), representing Atlantic Ocean floor about 100 m.y. old.

Measured values of thermal conductivity are plotted against wet-bulk density in Figure 3, and against porosity in Figure 4. No systematic trend can be seen in these figures. This suggests that some factor other than porosity and/or density (e.g., shape of pores, etc.) may control the thermal conductivity, although a systematic trend between porosity and thermal conductivity is observed for a much wider range of porosity (Kono et al., 1980). No systematic depth variation of thermal conductivity is observed within the range of data scatter (Fig. 1; Table 2).

SONIC VELOCITY

Sonic velocity (compressional-wave velocity) was determined with the Hamilton frame velocimeter (400 kHz) from mini-core samples with a 2.5-cm diameter and a 2- to 5-cm length. Prior to measurement, checks were made on the geometry of the frame, and the correction factor, C (defined by C = [true velocity]/[average apparent velocity]) was calculated for the delay time settings of 1 μs/div., 2 μs/div., and 5 μs/div. by measuring the velocity of aluminum and brass standards. The values of C ranged from 1.00 to 1.03, depending on the delay time setting, and on the observer. Reliability of the velocity measurement was checked by repeated measurements of standards and was shown to be about 1%. However, the lack of parallelism of sample cross-sections may give rise to more significant errors, a systematic lower estimation of sonic velocity.

The sonic velocity of 115 basalts ranges from 4.40 km/s for basalt breccia to 6.35 km/s for low-porosity basalt, with a mean of 5.75±0.30 km/s. This average value is comparable to that of Leg 37 basalts (5.94 km/s; Hyndman and Drury, 1976) from the Mid-Atlantic Ridge, but significantly greater than that of Legs 51 to 53 basalts (5.48 km/s; Hamano, 1979) from old (100 m.y.) Atlantic ocean floor, and greater than that of average DSDP basalts (Christensen and Salisbury, 1975). This, no doubt, reflects the relative freshness of basalts from the young ocean floor.

No systematic depth variation is observed (Fig. 1, Table 2). There is a trend suggesting that the sonic velocity of massive flow basalt is slightly higher than that of pillow basalts. The relationship of wet-bulk density to sonic velocity and that of porosity to sonic velocity are shown in Figures 5 and 6, respectively. There are general

Table 2. Mean values of physical properties of basalts from Hole 504B.

Interval	Wet-Bulk Density (g/cm^3)	Grain Density (g/cm^3)	Porosity (%)	Thermal Conductivity (W/m°K)	Sonic Velocity (km/s)
All cores	2.90±0.06 (115)	3.00±0.03 (115)	5.0±2.2 (115)	1.67±0.09 (64)	5.75±0.30 (115)
Upper cores (1–40)	2.88±0.05 (78)	2.99±0.02 (78)	5.3±2.0 (78)	1.67±0.07 (34)	5.78±0.26 (78)
Lower cores (41–70)	2.93±0.06 (37)	3.02±0.03 (37)	4.4±2.6 (37)	1.67±0.11 (30)	5.70±0.36 (37)

Note: Numbers in parentheses are the number of samples.

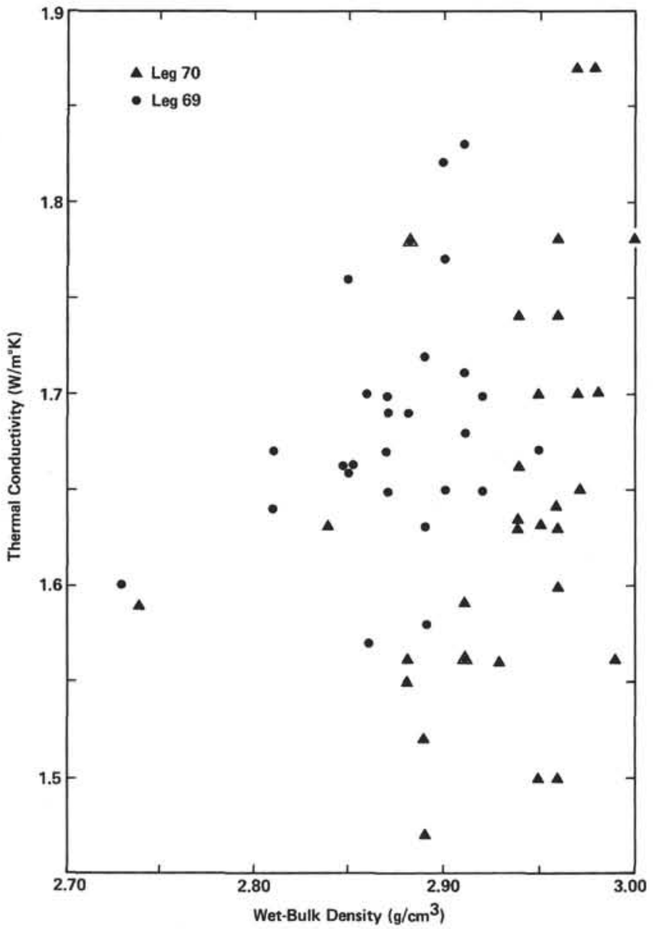

Figure 3. Relationship of thermal conductivity to wet-bulk density for basalts from Hole 504B.

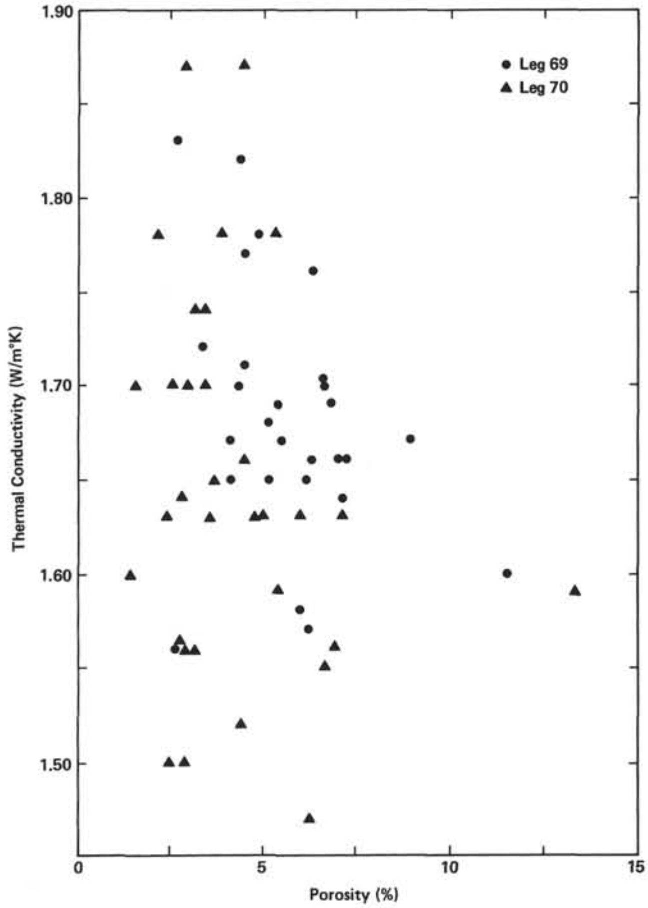

Figure 4. Relationship of thermal conductivity to porosity for basalts from Hole 504B.

trends of sonic-velocity increases with increasing wet-bulk density and with decreasing porosity. The results of linear regression for these relations are summarized in Table 3. Because there seems to be a systematic difference between the results of Legs 69 and 70, a linear regression was calculated for each leg. For a given wet-bulk density, the sonic velocity of Leg 70 basalts is lower than that of Leg 69 basalts (Fig. 5). This can be partly attributed to the higher grain density of the Leg 70 basalts (Table 2). A higher grain density requires a larger porosity for a given bulk density, and porosity appears to exhibit a strong control on velocity. In fact, in the plot of porosity versus sonic velocity (Fig. 6), the difference in legs is less apparent than in the diagram of density versus sonic velocity.

DISCUSSION

Laboratory study of cored samples gives the physical properties of centimeter-scale specimens; it suggests that basalts from this young oceanic crust have relatively high density and high sonic velocity compared to basalt from older ocean floor, although the lower recovery rate in younger ocean crust may bias the sampling toward the denser, higher-velocity rocks. To discuss the nature of the oceanic crust from laboratory data and large-scale seismic experiments, one must note the difference in scale. Because the wavelength of seismic waves is about 0.1 km (for 50 Hz), the velocity of seismic waves should reflect larger-scale porosity than seen in laboratory samples. Laboratory measurements suggest that the average sonic velocity is about 5.75 km/s, considerably

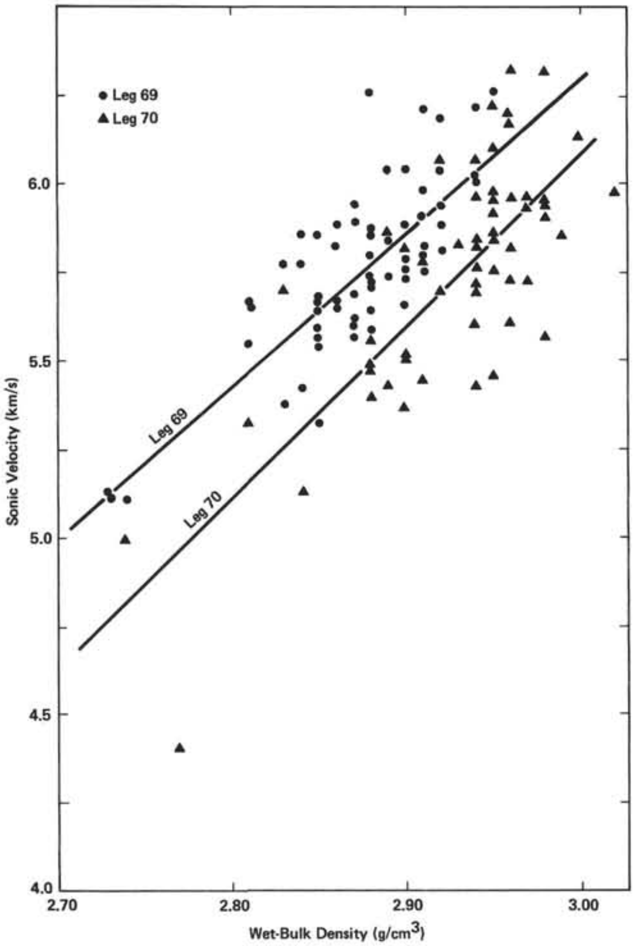

Figure 5. Relationship of sonic velocity to wet-bulk density for basalts from Hole 504B.

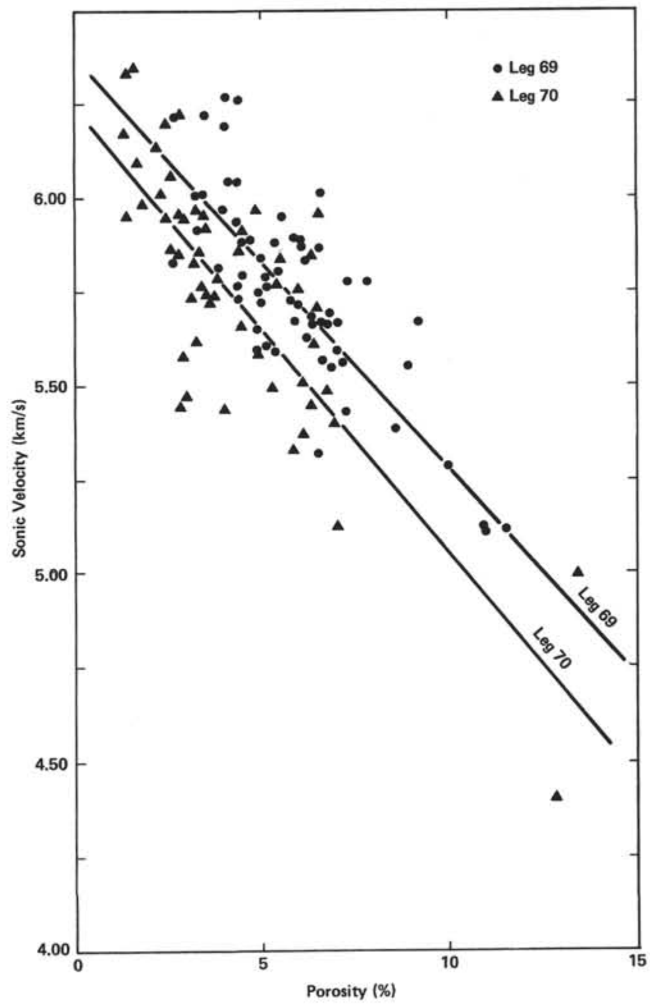

Figure 6. Relationship of sonic velocity to porosity for basalts from Hole 504B.

higher than the seismic velocity measured by oblique seismic experiments (~4–5 km/s; Stephen, this volume). This therefore suggests that there are many large-scale cracks in this young ocean crust, which also is suggested by low recovery and high permeability (Zoback and Anderson, this volume). If the relation of porosity to velocity obtained for laboratory samples could be applied to seismic scale, we would estimate the large scale porosity as 10 to 15%.

Table 3. Regression parameters for the relationship of sonic velocity V_p(km/s) to density ϱ (g/cm^3) and that of V_p to porosity ϕ (%).

$V_p = a + b\varrho$	a (km/s)	b (km•cm^3/g•s)
Leg 69	−6.78	4.36
Leg 70	−8.38	4.82
$V_p = a + b\phi$	a (km/s)	b (km/s • %)
Leg 69	6.38	−0.11
Leg 70	6.25	−0.12

ACKNOWLEDGMENTS

Participation in Leg 69 for R. Wilkens was partly supported by O.N.R. Grant number N0014-80-C-0252 to N.I. Christensen. N. Fujii and S. Lundquist reviewed the manuscript, and their comments are appreciated.

REFERENCES

Christensen, N. I., and Salisbury, M. H., 1975. Structure and constitution of the lower oceanic crust. *Rev. Geophys. Space Phys.*, 13: 57–86.

Hamano, Y., 1980. Physical properties of basalts from Holes 417D and 418A. *In* Robinson, P., Flower, M., Salisbury, M., et al., *Init. Repts. DSDP*, 51, 52, 53, Pt. 2: Washington (U.S. Govt. Printing Office), 1457–1466.

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

Kono, M., Hamano, Y., and Morgan, W. J., 1980. Physical properties of basalts from DSDP Leg 55. *In* Jackson, E. D.,Koizumi, I., et al., *Init. Repts. DSDP*, 55: Washington (U.S. Govt. Printing Office), 715–721.