11. SEISMIC VELOCITY MEASUREMENTS OF BASEMENTS ROCKS FROM DSDP LEG 37[1]

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ABSTRACT

The seismic compressional and shear wave velocities have been measured up to 2 kbar confining pressure for a large collection of basalts and a few gabbros and serpentinized peridotites recovered on DSDP Leg 37. The mean compressional velocity for 79 basalts is 5.94 km/sec. These results and the drilling record explain the low velocity upper crustal layer 2a sometimes outlined by seismic refraction measurements. In these areas, there is an upper layer of highly fractured low density volcanic material, flow breccia, drained pillows, and perhaps lava tubes with extensive voids and some intercalated sediments. The results also explain why the refraction velocities for layer 2 are in general so much lower (5.0 km/sec) and more variable than the velocities of little-weathered sea-floor basalts measured in the laboratory (6.0 km/sec). The refraction velocity depends on the amount of fracturing, voids, and sediment and not on a downward change in general rock composition or metamorphic grade.

Poisson's ratio for little-weathered basalts is found to decrease systematically with decreasing velocity. The relation predicts a Poisson's ratio of 0.28 for a layer 2 refraction compressional velocity of 5.0 km/sec and 0.24 for a layer 2a velocity of 2.8 km/sec in good agreement with the values observed. Poisson's ratio from refraction measurements should distinguish between low velocity fractured basalt and similar velocity sediments since the latter should have high Poisson's ratios.

One hole penetrated a complex section of gabbros, serpentinized peridotites, and breccias. The gabbros have a mean velocity of 7.21 km/sec, appropriate to the upper part of crustal layer 3 (i.e., 3a) if a small amount of fracturing or low velocity material is present. If the ultramafics in the section were little serpentinized before being brought to near the surface, such a complex at the base of the crust would explain the basal layer (3b) that has sometimes been observed by refraction measurements with velocities between those of oceanic layer 3 and the mantle.

INTRODUCTION

Seismic refraction measurements provide the most important presently available information on the structure of the oceanic crust. The interpretation of these measurements in terms of the rock compositions that are present in the crust requires a comparison of the refraction velocities with velocities measured in the laboratory for a wide range of rock types. Much important information has been obtained by measurements on dredged sea-floor rocks, but far more representative and less weathered samples from greater depths in the crust are now being obtained by the Deep Sea Drilling Project. Leg 37 provided samples from over 500 meters depth into layer 2, five times the previous maximum. This depth is sufficient for the first time, to compare the velocity-depth profile in layer 2 by refraction measurements over the drill sites with velocities measured on rocks from the drill holes. Unfortunately no in-hole velocity measurements could be made, but laboratory measurements on a large number of samples are reported here.

Laboratory velocities have been measured on a large number of samples previously obtained by dredging and drilling. A summary of the data is provided in the review by Christensen and Salisbury (1975). Details of many of the measurements have been reported in previous volumes of the Initial Reports of the Deep Sea Drilling Project.

Direct sampling by dredging and drilling and correlation with ophiolite complexes have shown that upper crustal layer 2 must consist primarily of extrusive basalt. The mean and standard deviation of seismic

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refraction velocities for layer 2 is 5.04 ±0.69 km/sec (Christensen and Salisbury, 1975; also Raitt, 1963; Ludwig, et al., 1971). Laboratory measurements of basalts give a mean velocity of about 5.5 km/sec (Christensen and Salisbury, 1975) which is much higher than the mean, but within the range of refraction velocities. However, many of the measured samples have undergone extensive sea-floor weathering that has considerably reduced their velocity. The weathering extends only to a shallow depth so these samples are not representative of the major thickness of layer 2. Christensen and Salisbury (1972, 1973) show that the weathering and reduction in velocity increase progressively with age, and Hyndman (1974) and Salisbury and Christensen (1976) showed that the weathering reduction in velocity decreases rapidly with depth. Even in 100-m.y. old sea floor, the reduced velocity extends to a depth of only 50 meters. Thus, only in quite old sea floor is the weathered layer of sufficient thickness to be important in seismic refraction measurements (although the increasing thickness of the weathered layer may explain the small decrease in refraction velocity with age that has been suggested for layer 2, e.g., Christensen and Salisbury, 1972; Hart, 1973). Young sea floor basalts (less than 20 m.y.) and those from deep holes into older sea floor have mean velocity of about 6.0 km/sec (e.g., Christensen and Salisbury, 1975). Thus, there is a major discrepancy between refraction and laboratory velocities that requires large-scale (larger than laboratory samples) fracturing, intercalated sediment, volcanic breccias, or rubble in layer 2. The discrepancy is even larger in some regions such as the Reykjanes Ridge (Talwani et al., 1971) where the upper part of layer 2 (designated layer 2a) has velocities between 2.3 and 3.7 km/sec.

The composition of lower crustal layer 3 is still much debated since probable samples have been obtained only where they have been exposed by tectonic motion such as along fractures. The most probable rocks are gabbro, metagabbro, metabasalt, and possibly amphibolite. All give reasonable agreement with the mean seismic refraction velocity of 6.73 ±0.19 km/sec. Although fresh gabbros have somewhat higher laboratory velocities, the layer velocity may be reduced by fracturing and low velocity material in the same way, although much less, as is apparent for layer 2. The lowering of velocities by fracturing is illustrated by the very low seismic refraction velocities found by Lort and Matthews (1972) in the gabbro section of the Troodos ophiolite complex. Shear velocities from refraction measurements for layer 3 are few but suggest Poisson's ratios from 0.24 to 0.31. The above rocks have laboratory values in this range; gabbro about 0.30 and metabasalt about 0.28. Serpentinites have much higher Poisson's ratios of about 0.37 so they cannot be a major constituent of layer 3 (Christensen, 1972; Christensen and Salisbury, 1975).

VELOCITY MEASUREMENTS

The velocity measurements reported here were made with two different instruments onboard *Glomar Challenger*. Most samples were measured, first at one atmosphere pressure on the Hamilton frame apparatus, then to 2.0 kbar in a high pressure apparatus. The estimated accuracies of the techniques are: Hamilton frame, compressional waves only, ±3%; shipboard measurements to 2.0 kbar, compression ±1%, shear ±2%. Data are given in Table 1.

The Hamilton frame apparatus (Hamilton, 1965; Cernock, 1970) provides a velocity at atmospheric pressure that cannot easily be obtained on the high pressure equipment as well as providing a check on major errors in the high pressure velocities. The apparatus is designed for the rapid measurement of sediments that have low velocity and thus long travel times through the sample. Very good time resolution is not required. The transmitted pulse has a slow rise time and the equipment uses an oscilloscope variable time delay for time measurement which has fairly low accuracy. Also it is difficult to make good acoustic contact with igneous rock. The values given are the means of values with the pulse travel in opposite direction through the length of the minicores.

Both compressional and shear wave velocities were measured onboard ship from 0.07 kbar (2500 psi) to 2.07 kbar (30,000 psi) using a method essentially as described by Birch (1960) and Christensen and Shaw (1970). The pressure was applied with a hydraulic fluid medium which is excluded from the sample, using a High Pressure Equipment Ltd, Model LM-I. Isostatic Press pressure chamber with 10-cm inside diameter and pumping unit. The pressure can be measured to ±2% and temperature to ±0.2°C with an internal thermistor. The samples are 2.5 cm diameter and 3 to 5 cm long. The circumference of the sample is jacketed by a thin metal sheet with a soldered joint to exclude the pressure medium. Thus, the confining pressure is close to the external pressure and the pore pressure is small; see comments below about relating laboratory confining pressure to depth in the crust. The ends of the samples are painted with silver-filled epoxy resin to make electrical contact with the pulse transducers and with the jacket. The transducers are 2.54 cm in diameter and about 0.1 cm thick with a resonant frequency of 2.0 mHz from Valpey Fisher Ltd. Barium titanate transducers in compressional mode were used to generate compressional waves and AC cut quartz transducers in transverse mode to generate shear waves. The transducers are fastened with electrically conducting epoxy to 2.60 cm diameter by 4.0 cm long stainless steel electrodes. Gum rubber tubing seals the space between the electrodes and jacketed specimen. Brass cylinders around the whole assembly act as electronic shields. All electrical connections are with shielded cables. A Hewlett-Packard Model 214-A pulse generator is used to generate 0.3 μsec wide pulses to excite the transmitting transducer. Ringing is reduced by using a 50-ohm termination to match the output impedance of the generator. High frequency cross-coupling between input and received pulse lines was reduced by smoothing the output pulse with a 0.004 microfarad capacitance. The pulse transit time through the sample is measured by comparison with a variable mercury-delay-line. The output pulse is split and sent

TABLE 1
Seismic Velocities

Sample (Interval in cm)	Bulk Density (g/cm^3)	P or S or σ	Incr. or Decr. Press.	Ham. Frame	Velocity (km/sec) Pressure (kbar) 0.07	0.17	0.34	0.52	0.69	1.03	1.38	1.72	2.07
Hole 332A													
6-2, 117-120	2.792	P	I	6.09		6.35	6.40	6.40	6.38	6.46	6.48	6.49	6.49
Basalt			D					6.38	6.42	6.44	6.48	6.50	6.50
		S	I					3.39	3.40	3.43	3.46	3.49	3.50
			D				3.34	3.41	3.43	3.47	3.49	3.50	3.50
		σ					0.31	0.30	0.30	0.30	0.30	0.30	0.30
7-1, 66-69	2.810	P	I	6.14	6.57	6.59	6.60	6.59	6.59	6.58	6.57	6.59	6.58
Basalt			D		6.49	6.51	6.52	6.53	6.57	6.59	6.59	6.60	6.58
		S	I			3.38	3.38	3.38	3.38	3.39	3.40	3.41	3.41
			D			3.38	3.39	3.39	3.39	3.39	3.40	3.40	3.40
		σ				0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
7-2, 41-42	2.811	P	I	5.46			5.69	5.69	5.71	5.78	5.80	5.82	5.85
Basalt			D			5.60	5.67	5.71	5.76	5.79	5.82	5.83	5.85
		S	I		3.15	3.16	3.13	3.13	3.14	3.14	3.17	3.18	3.20
			D			3.09	3.10	3.12	3.13	3.16	3.18	3.19	3.20
		σ				0.27	0.28	0.29	0.29	0.29	0.29	0.29	0.29
8-2, 6-9	2.809	P	I	5.42	5.73	5.74	5.76	5.80	5.85	5.93	5.98	6.02	6.05
Basalt			D		5.72	5.75	5.80	5.85	5.90	5.96	6.00	6.03	6.05
		S	I			3.19	3.22	3.22	3.24	3.26	3.27	3.30	3.32
			D		3.15	3.17	3.19	3.22	3.24	3.28	3.30	3.32	3.32
		σ			0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
12-1, 122-125	2.796	P	I	5.37	5.64	5.65	5.67	5.67	5.68	5.69	5.70	5.71	5.72
Basalt			D		5.57	5.59	5.62	5.64	5.66	5.68	5.71	5.73	5.73
		S	I			3.04	3.07	3.08	3.08	3.08	3.09	3.10	3.11
			D			3.07	3.08	3.09	3.10	3.11	3.11	3.11	3.11
		σ				0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
16-1, 33-36	2.719	P	I	5.16	5.40	5.39	5.42	5.45	5.46	5.50	5.52	5.55	5.58
Basalt			D		5.32	5.33	5.40	5.44	5.48	5.51	5.55	5.57	5.58
		S	I		2.86	2.88	2.92	2.94	2.96	3.00	3.01	3.01	3.01
			D		2.88	2.90	2.94	2.96	2.96	2.98			
		σ			0.30	0.30	0.29	0.29	0.29	0.29	0.29	0.29	0.29
21-1, 131-134	2.810	P	I	5.66	5.98	6.01	6.03	6.06	6.06	6.08	6.09	6.09	6.10
Basalt			D		6.02	6.03	6.04	6.06	6.05	6.07	6.08	6.10	6.10
		S	I				3.18	3.20	3.22	3.25	3.27	3.29	3.30
			D			3.19	3.21	3.23	3.25	3.27	3.29	3.30	3.30
		σ				0.30	0.31	0.30	0.30	0.30	0.30	0.29	0.29
27-1, 128-131	2.710	P	I	5.33	5.62	5.62	5.63	5.64	5.66	5.69	5.74	5.75	5.77
Basalt			D		5.52	5.58	5.63	5.65	5.68	5.72	5.75	5.77	5.79
		S	I			2.98	3.02	3.04	3.07	3.11	3.12	3.14	3.15
			D			3.00	3.05	3.07	3.09	3.11	3.13	3.14	3.15
		σ				0.30	0.30	0.29	0.29	0.29	0.29	0.29	0.29
28-1, 83-86	2.790	P	I	5.63	5.72	5.75	5.77	5.79	5.81	5.83	5.85	5.86	5.89
Basalt			D		5.59	5.63	5.70	5.72	5.74	5.78	5.84	5.87	5.88
		S	I			3.14	3.18	3.19	3.20	3.21	3.23	3.23	3.24
			D			3.15	3.18	3.19	3.20	3.22	3.22	3.23	3.23
		σ				0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
28-3, 28-31	2.791	P	I	5.52		5.71	5.73	5.78	5.79	5.80	5.83	5.85	5.87
Basalt			D				5.67	5.72	5.76	5.81	5.84	5.86	5.88
		S	I			3.17	3.19	3.20	3.20	3.21	3.22	3.23	3.23
			D			3.19	3.19	3.20	3.22	3.23	3.23	3.23	3.24
		σ				0.28	0.27	0.28	0.28	0.28	0.28	0.28	0.28
29-1, 74-77	2.846	P	I	5.82	6.06	6.11	6.13	6.15	6.15	6.15	6.16	6.17	6.19
Basalt			D		6.09	6.13	6.12	6.13	6.15	6.17	6.17	6.17	6.19
		S	I			3.30	3.33	3.33	3.33	3.33	3.33	3.33	3.33
			D			3.32	3.33	3.33	3.33	3.33	3.33	3.33	3.33
		σ				0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.30
30-1, 127-130	2.822	P	I	5.83	6.15	6.15	6.15	6.15	6.15	6.15	6.16	6.17	6.17
Basalt			D		6.11	6.11	6.12	6.13	6.13	6.14	6.16	6.17	6.18
		S	I			3.31	3.32	3.33	3.34	3.35	3.36	3.36	3.37
			D			3.33	3.34	3.35	3.35	3.36	3.36	3.36	3.36
		σ				0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29

TABLE 1 – *Continued*

Sample (Interval in cm)	Bulk Density (g/cm^3)	P or S or σ	Incr. or Decr. Press.	Ham. Frame	Velocity (km/sec) Pressure (kbar)								
Hole 332A *Cont.*													
31-2, 32-35	2.732	P	I	5.18	5.61	5.66	5.70	5.71	5.75	5.78	5.82	5.84	5.86
Basalt			D		5.57	5.64	5.69	5.73	5.77	5.80	5.84	5.85	5.86
		S	I			3.00	3.04	3.07	3.09	3.12	3.14	3.15	3.16
			D			3.00	3.05	3.07	3.10	3.13	3.15	3.15	3.16
		σ				0.30	0.30	0.30	0.30	0.29	0.29	0.30	0.29
31-3, 79-82	2.780	P	I	5.44	5.66	5.73	5.78	5.80	5.82	5.83	5.85	5.86	5.88
Basalt			D		5.68	5.74	5.77	5.80	5.81	5.83	5.85	5.86	5.88
		S	I			3.10	3.12	3.13	3.14	3.15	3.16	3.16	3.17
			D			3.10	3.12	3.14	3.14	3.15	3.16	3.17	3.17
		σ				0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.30
33-2, 92-95	2.813	P	I	5.58	5.83	5.86	5.88	5.90	5.90	5.92	5.94	5.93	5.93
Basalt			D		5.87	5.88	5.89	5.90	5.91	5.92	5.92	5.92	5.94
		S	I		3.23	3.24	3.23	3.23	3.24	3.24	3.23	3.23	3.23
			D		3.23	3.22	3.21	3.22	3.22	3.23	3.23	3.23	3.23
		σ			0.28	0.28	0.29	0.29	0.29	0.29	0.29	0.29	0.29
33-2, 128-131	2.855	P	I	5.88	6.14	6.16	6.18	6.19	6.19	6.19	6.20	6.21	6.21
Basalt			D			6.15	6.17	6.17	6.19	6.20	6.20	6.21	6.21
		S	I			3.33	3.33	3.32	3.32	3.33	3.33	3.33	3.33
			D			3.33	3.32	3.31	3.32	3.32	3.33	3.33	3.34
		σ				0.29	0.30	0.30	0.30	0.30	0.30	0.30	0.30
34-1, 88-91	2.816	P	I	5.76	6.07	6.04	6.07	6.09	6.11	6.14	6.17	6.19	6.23
Basalt			D		5.97	5.96	6.03	6.09	6.14	6.17	6.20	6.21	6.23
		S	I			3.20	3.23	3.25	3.27	3.30	3.32	3.34	3.35
			D			3.19	3.24	3.27	3.30	3.32	3.34	3.35	3.35
		σ				0.30	0.30	0.30	0.30	0.30	0.30	0.29	0.30
34-2, 104-107	2.810	P	I	5.37	5.67	5.68	5.76	5.79	5.80	5.83	5.85	5.86	5.88
Basalt			D		5.63	5.72	5.76	5.78	5.80	5.82	5.85	5.86	5.88
		S	I		3.02	3.06	3.09	3.11	3.12	3.14	3.15	3.16	3.17
			D		3.04	3.08	3.09	3.11	3.13	3.14	3.16	3.17	3.17
		σ			0.30	0.30	0.30	0.30	0.30	0.30	0.29	0.29	0.30
36-2, 33-36	2.827	P	I	5.80	6.19	6.21	6.27	6.28	6.27	6.27	6.28	6.29	6.29
Basalt			D		6.23	6.25	6.23	6.23	6.24	6.26	6.27	6.28	6.29
		S	I		3.36	3.36	3.36	3.37	3.37	3.37	3.38	3.38	3.39
			D		3.35	3.36	3.36	3.36	3.37	3.38	3.39	3.39	3.38
		σ			0.29	0.29	0.30	0.30	0.30	0.30	0.29	0.30	0.30
37-1, 116-119	2.818	P	I	5.69	5.88	5.89	5.93	5.92	5.93	5.94	5.95	5.96	5.97
Basalt			D		5.87	5.88	5.89	5.91	5.92	5.93	5.95	5.96	5.97
		S	I			3.23	3.22	3.23	3.22	3.23	3.23	3.22	3.23
			D			3.24	3.23	3.23	3.23	3.23	3.23	3.23	3.23
		σ				0.28	0.29	0.29	0.29	0.29	0.29	0.29	0.29
40-2, 95-98	2.741	P	I	5.15	5.52	5.58	5.92	5.94	5.96	6.03	6.07	6.11	6.13
Basalt			D			5.69	5.87	5.95	6.00	6.01	6.05	6.10	6.12
		S	I			3.05	3.13	3.17	3.19	3.22	3.25	3.27	3.30
			D			3.08	3.16	3.20	3.22	3.26	3.27	3.29	3.30
		σ				0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
40-3, 40-43	2.861	P	I	5.79	6.45	6.46	6.47	6.49	6.48	6.50	6.52	6.52	6.53
Basalt			D		6.45	6.45	6.48	6.49	6.50	6.51	6.52	6.52	6.54
		S	I		3.43	3.43	3.46	3.47	3.49	3.50	3.50	3.51	3.52
			D		3.45	3.46	3.48	3.49	3.49	3.50	3.51	3.51	3.51
		σ			0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Hole 332B													
1-5, 27-30	2.796	P	I	5.79	6.27	6.31	6.33	6.35	6.37	6.41	6.43	6.45	6.48
Basalt			D		6.28	6.33	6.34	6.36	6.38	6.41	6.44	6.46	6.48
		S	I			3.37	3.38	3.32	3.39	3.40	3.42	3.42	3.43
			D			3.39	3.39	3.39	3.41	3.41	3.42	3.42	3.43
		σ				0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.31
1-5, 120-123	2.812	P	I	5.63		6.09	6.17	6.21	6.23	6.31	6.34	6.37	6.38
Basalt			D			6.08	6.22	6.26	6.27	6.31	6.34	6.36	6.38
		S	I		3.05	3.15	3.23	3.26	3.30	3.34	3.37	3.39	3.40
			D		3.04	3.18	3.28	3.31	3.34	3.37	3.39	3.40	3.40
		σ				0.31	0.31	0.31	0.30	0.30	0.30	0.30	0.30

TABLE 1 – *Continued*

Sample (Interval in cm)	Bulk Density (g/cm^3)	P or S or σ	Incr. or Decr. Press.	Ham. Frame	Velocity (km/sec) Pressure (kbar) 0.07	0.17	0.34	0.52	0.69	1.03	1.38	1.72	2.07
Hole 332B *Cont.*													
2-1, 60-63	2.780	P	I	5.94	6.39	6.50	6.55	6.58	6.60	6.61	6.63	6.65	6.67
Basalt			D		6.43	6.54	6.57	6.59	6.59	6.61	6.63	6.65	6.67
		S	I		3.29	3.31	3.32	3.33	3.34	3.36	3.36	3.37	3.37
			D			3.32	3.33	3.34	3.35	3.36	3.36	3.37	3.37
		σ			0.32	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
2-2, 86-89	2.841	P	I	5.76	6.16	6.24	6.32	6.35	6.36	6.39	6.42	6.44	6.45
			D		6.25	6.28	6.32	6.35	6.37	6.39	6.41	6.43	6.46
		S	I			3.39	3.39	3.41	3.42	3.42	3.44	3.44	3.45
			D			3.41	3.41	3.42	3.43	3.43	3.44	3.44	3.44
						0.29	0.30	0.30	0.30	0.30	0.30	0.30	0.30
2-5, 69-72	2.750	P	I	5.91	6.46	6.52	6.54	6.55	6.56	6.60	6.62	6.65	6.66
Basalt			D			6.43	6.51	6.55	6.58	6.60	6.61	6.63	6.65
		S	I		3.55	3.58	3.61	3.63	3.64	3.64	3.65	3.66	3.66
			D			3.61	3.62	3.62	3.62	3.63	3.64	3.64	3.65
		σ			0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
2-5, 115-117	2.833	P	I	6.03		6.54	6.56	6.59	6.61	6.65	6.64	6.65	6.64
Basalt			D				6.61	6.61	6.59	6.59	6.61	6.63	6.64
		S	I		3.47	3.50	3.52	3.52	3.53	3.53	3.53	3.53	3.53
			D		3.51	3.52	3.53	3.52	3.52	3.51	3.52	3.52	3.52
		σ				0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
3-2, 116-119	2.746	P	I	5.91	6.08	6.12	6.13	6.12	6.14	6.16	6.17	6.19	6.20
Basalt			D		6.08	6.09	6.11	6.14	6.15	6.17	6.18	6.20	6.21
		S	I		3.29	3.31	3.32	3.33	3.33	3.33	3.34	3.35	3.35
			D		3.27	3.31	3.31	3.32	3.33	3.34	3.35	3.35	3.35
		σ			0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
3-4, 10-13	2.814	P	I	6.09		6.48	6.49	6.52	6.54	6.57	6.58	6.60	6.60
Basalt			D			6.39	6.48	6.51	6.55	6.56	6.58	6.59	6.61
3-4, 7-20	2.891	P	I	6.13	6.42	6.43	6.46	6.46	6.49	6.51	6.53	6.54	6.57
Basalt			D			6.41	6.47	6.48	6.50	6.53	6.55	6.56	6.58
6-1, 100-103	2.843	P	I	5.89	5.94	6.03	5.99	6.00	6.00	6.02	6.04	6.07	6.08
			D		5.92	5.96	5.96	5.98	6.00	6.03	6.05	6.07	6.09
		S	I		3.18	3.19	3.20	3.21	3.23	3.25	3.26	3.27	3.29
			D			3.22	3.24	3.25	3.26	3.28	3.28	3.29	3.29
		σ			0.30	0.30	0.29	0.30	0.29	0.29	0.29	0.29	0.29
6-2, 122-123	2.659	P	I	6.16		5.38	5.45	5.52	5.55	5.60	5.64	5.68	5.70
Basalt			D			5.43	5.49	5.51	5.55	5.61	5.64	6.67	5.70
8-3, 22-24	2.727	P	I	5.40	5.58	5.74	5.82	5.83	5.90	5.98	5.95	5.97	5.99
Basalt			D			5.60	5.87	5.90	5.92	5.91	5.95	5.97	6.00
9-1, 112-115	2.806	P	I	5.25	5.43	5.48	5.56	5.62	5.63	5.69	5.74	5.77	5.79
Basalt			D			5.54	5.58	5.63	5.69	5.73	5.76	5.77	5.79
		S			2.91	2.96	3.00	3.03	3.05	3.07	3.08	3.10	3.11
					2.95	2.99	3.03	3.05	3.06	3.08	3.09	3.10	3.11
		σ			0.29	0.29	0.29	0.29	0.29	0.30	0.30	0.30	0.30
9-2, 104-106	2.796	P	I	4.99	5.40	5.48	5.55	5.59	5.62	5.69	5.73	5.76	5.79
Basalt			D		5.43	5.48	5.57	5.60	5.65	5.70	5.74	5.78	5.80
9-3, 80-82	2.873	P	I	5.89	6.31	6.42	6.41	6.43	6.43	6.43	6.44	6.45	6.47
Basalt			D		6.35	6.40	6.42	6.44	6.45	6.45	6.46	6.47	6.47
		S	I				3.22	3.23	3.26	3.32	3.33	3.35	3.35
			D				3.24	3.27	3.32	3.33	3.33	3.33	3.34
		σ					0.33	0.33	0.32	0.32	0.32	0.32	0.32
10-2, 125-128	2.839	P	I	5.08	5.69	5.67	5.74	5.77	5.81	5.81	5.84	5.86	5.90
Basalt			D		5.68	5.64	5.67	5.70	5.75	5.82	5.86	5.88	5.91
14-2, 81-83	2.693	P	I	4.83	5.41	5.46	5.49	5.52	5.56	5.59	5.62	5.63	5.63
Basalt			D							5.56	5.58	5.61	5.63
15-1, 129-131	2.880	P	I	5.69	5.98	5.96	5.98	6.01	6.04	6.06	6.08	6.11	6.12
Basalt			D		5.79	5.92	5.98	6.01	6.04	6.07	6.09	6.10	6.12
		S	I		3.24	3.25	3.27	3.29	3.29	3.30	3.31	3.32	3.33
			D		3.25	3.26	3.27	3.29	3.30	3.31	3.32	3.32	3.33
		σ			0.28	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29

TABLE 1 – *Continued*

Sample (Interval in cm)	Bulk Density (g/cm^3)	P or S or σ	Incr. or Decr. Press.	Ham. Frame	Velocity (km/sec) Pressure (kbar) 0.07	0.17	0.34	0.52	0.69	1.03	1.38	1.72	2.07
Hole 332B *Cont.*													
19-1, 104-107	2.871	P	I	5.41	5.62	5.61	5.74	5.81	5.84	5.90	5.92	5.95	5.97
Basalt			D		5.64	5.71	5.81	5.83	5.86	5.90	5.93	5.97	5.99
20-1, 56-59	2.832	P	I	5.31	5.38	5.45	5.53	5.58	5.61	5.67	5.72	5.74	5.76
Basalt			D					5.51	5.54	5.56	5.67	5.75	5.79
21-1, 99-102	2.900	P	I	5.57	5.72	5.77	5.80	5.82	5.84	5.87	5.90	5.92	5.95
Basalt			D		5.73	5.74	5.79	5.83	5.85	5.90	5.92	5.95	5.96
22-1, 57-60	2.850	P	I	5.68	5.89	5.91	5.95	5.97	5.98	5.98	6.00	6.00	6.03
Basalt			D		5.84	5.88	5.93	5.93	5.96	5.97	5.98	6.01	6.02
22-2, 140-142	2.614	P	I	4.40	4.68	4.78	4.89	5.02	5.09	5.13	5.17	5.21	5.23
Basalt			D		4.81	4.88	5.00	5.09	5.12	5.14	5.16	5.21	5.23
22-3. 39-41	2.862	P	I	5.62	5.76	5.84	5.94	5.97	6.03	6.09	6.12	6.15	6.16
Basalt			D		5.84	5.89	5.99	6.02	6.05	6.09	6.13	6.15	6.16
22-4, 11-13	2.877	P	I	5.87	6.13	6.18	6.21	6.23	6.25	6.27	6.28	6.30	6.31
Basalt			D		6.19	6.21	6.23	6.23	6.25	6.27	6.29	6.30	6.30
24-1, 125-127	2.731	P	I	5.27	5.53	5.60	5.66	5.76	5.76	5.84	5.86	5.91	5.94
Basalt			D			5.60	5.68	5.75	5.80	5.84	5.87	5.92	5.93
25-2, 91-93	2.876	P	I	5.43	5.49	5.52	5.57	5.58	5.62	5.66	5.70	5.76	5.81
Basalt			D		5.53	5.56	5.61	5.62	5.67	5.72	5.76	5.80	5.82
25-4, 47-49	2.829	P	I	5.48	5.82	5.80	5.84	5.86	5.90	5.95	5.99	6.03	6.06
Basalt			D		5.72	5.75	5.84	5.89	5.93	5.95	6.00	6.03	6.06
27-2, 93-95	2.841	P	I	5.75	5.89	5.99	6.01	6.03	6.07	6.11	6.13	6.11	6.10
Basalt			D			5.95	6.06	6.07	6.08	6.10	6.10	6.11	6.10
28-2, 23-26	2.829	P	I	5.40	5.51	5.54	5.56	5.61	5.63	5.65	5.66	5.69	5.71
Basalt			D		5.39	5.46	5.57	5.63	5.65	5.66	5.68	5.70	5.71
29-1, 86-89	2.879	P	I	5.28	5.75	5.83	5.90	5.95	5.96	6.02	6.04	6.06	6.09
Basalt			D			5.89	5.94	5.96	6.00	6.00	6.04	6.07	6.09
31-1, 108-111	2.736	P	I	5.00	5.31	5.36	5.43	5.46	5.47	5.49	5.51	5.53	5.54
			D			5.33	5.41	5.44	5.48	5.50	5.52	5.53	5.54
33-1, 62-65	2.835	P	I	5.37		5.89	5.94	5.93	5.94	5.99	6.02	6.05	6.07
			D			5.87	5.93	5.97	6.01	6.02	6.03	6.05	6.07
35-1, 66	2.813	P	I	5.61		5.88	6.24	6.44	6.52	6.59	6.64	6.67	6.70
Basalt			D			6.15	6.48	6.57	6.60	6.62	6.65	6.65	6.70
36-1, 77-79	2.788	P	I	5.61	5.73	5.82	5.88	5.92	5.95	5.99	6.01	6.03	6.05
Basalt			D			5.87	5.90	5.94	5.96	6.00	6.02	6.04	6.05
36-3, 76-78	2.780	P	I	5.14	5.54	5.81	5.92	5.93	5.94	5.98	6.01	6.02	6.03
Basalt			D				5.90	5.95	5.95	5.98	6.00	6.01	6.02
36-3, 143-145	2.809	P	I	5.37		5.80	5.88	5.90	5.95	5.98	6.00	6.03	6.04
Basalt			D			5.82	5.86	5.92	5.93	5.97	5.98	6.01	6.03
36-4, 131-133	2.696	P	I	4.98	5.30	5.45	5.51	5.53	5.54	5.55	5.58	5.59	5.60
Basalt			D		5.42	5.51	5.52	5.53	5.54	5.56	5.56	5.58	5.59
36-5, 40-42	2.783	P	I	5.44	5.72	5.74	5.75	5.78	5.78	5.82	5.85	5.87	5.91
Basalt			D			5.62	5.70	5.75	5.78	5.85	5.88	5.90	5.92
36-6, 44-46	2.866	P	I	5.64		6.12	6.08	6.15	6.18	6.23	6.28	6.33	6.34
Basalt			D			6.05	6.16	6.20	6.23	6.25	6.29	6.32	6.34
37-3, 54-56	2.883	P	I	5.35	5.70	5.68	5.78	5.83	5.86	5.93	5.98	6.03	6.04
Basalt			D		5.71	5.73	5.82	5.85	5.90	5.94	5.97	6.01	6.03
44-1, 75-77	2.609	P	I	5.07	4.72	5.04	5.13	5.19	5.23	5.29	5.30	5.33	5.35
Basalt			D		5.04	5.11	5.19	5.24	5.26	5.31	5.34	5.36	5.37
47-2, 145-147	2.888	P	I	5.91	5.64	5.68	5.71	5.74	5.81	5.84	5.86	5.89	5.92
Basalt			D		5.64	5.66	5.72	5.79	5.84	5.86	5.88	5.90	5.92

TABLE 1 – *Continued*

Sample (Interval in cm)	Bulk Density (g/cm^3)	P or S or σ	Incr. or Decr. Press	Ham. Frame.	Velocity (km/sec) Pressure (kbar) 0.07	0.17	0.34	0.52	0.69	1.03	1.38	1.72	2.07
Hole 333A													
1-3, 74-76	2.849	P	I	5.74	5.37	5.37	5.39	5.42	5.42	5.45	5.48	5.52	5.55
Basalt			D		5.34	5.33	5.35	5.37	5.38	5.45	5.50	5.54	5.55
3-1, 129-131	2.821	P	I	5.55	5.43	5.52	5.61	5.62	5.64	5.67	5.69	5.72	5.75
Basalt			D		5.44	5.55	5.58	5.61	5.64	5.67	5.71	5.73	5.75
6-2, 58-61	2.872	P	I	6.06	5.93	5.98	6.00	6.01	6.02	6.06	6.08	6.06	6.08
Basalt			D		5.86	5.89	5.90	5.93	5.96	6.00	6.05	6.06	6.08
8-6, 58-60	2.769	P	I	5.47	5.56	5.58	5.65	5.67	5.70	5.73	5.75	5.77	5.79
Basalt			D		5.62	5.65	5.66	5.67	5.70	5.73	5.75	5.78	5.79
10-2, 112-115	2.763	P	I	5.23	5.12	5.21	5.25	5.27	5.30	5.34	5.38	5.40	5.43
Basalt			D		5.17	5.23	5.26	5.29	5.32	5.35	5.39	5.41	5.43
Site 334													
16-2, 88-91	2.820	P	I	5.80	5.93	5.97	5.98	5.96	5.96	5.97	5.99	6.00	6.01
Basalt			D		5.91	5.92	5.93	5.93	5.93	5.95	5.97	5.98	5.99
		S	I		3.19	3.20	3.20	3.20	3.20	3.21	3.21	3.21	3.21
			D		3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.21	3.21
		σ			0.29	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
16-4, 104-107	2.928	P	I	6.20		6.52	6.50	6.50	6.46	6.46	6.46	6.47	6.46
Basalt			D		6.39	6.42	6.43	6.43	6.44	6.46	6.45	6.45	6.48
		S	I		3.50	3.49	3.49	3.49	3.50	3.50	3.50	3.50	3.50
			D		3.48	3.48	3.48	3.48	3.49	3.49	3.49	3.49	3.50
		σ			0.29	0.30	0.30	0.30	0.29	0.29	0.29	0.29	0.29
18-1, 84-87	2.945	P	I	6.25	6.40	6.40	6.40	6.40	6.41	6.41	6.42	6.43	6.44
Basalt			D		6.39	6.38	6.39	6.40	6.42	6.43	6.43	6.43	6.44
		S	I			3.47	3.47	3.48	3.48	3.48	3.49	3.49	3.49
			D		3.47	3.47	3.47	3.47	3.47	3.48	3.48	3.48	3.49
		σ			0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
18-2, 12-14	2.893	P	I	6.23	6.35	6.35	6.39	6.41	6.41	6.41	6.41	6.41	6.41
Basalt			D		6.32	6.36	6.39	6.39	6.41	6.41	6.42	6.41	
		S	I		3.47	3.47	3.46	3.47	3.47	3.48	3.48	3.48	3.48
			D		3.47	3.46	3.46	3.46	3.46	3.47	3.47	3.47	3.48
		σ			0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
21-1, 39-41	3.002	P	I	7.17		7.29	7.30	7.29	7.29	7.30	7.32	7.33	7.32
Gabbro			D			7.25	7.28	7.29	7.29	7.30	7.30	7.31	7.32
		S	I				3.79	3.79	3.80	3.81	3.82	3.83	3.84
			D			3.80	3.81	3.82	3.82	3.82	3.83	3.83	3.84
		σ				0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
21-1, 78-92	2.969	P	I	7.61	7.12	7.17	7.19	7.16	7.19	7.23	7.27	7.28	7.29
Gabbro			D		6.92	7.09	7.13	7.17	7.17	7.20	7.24	7.28	7.29
		S	I			3.78	3.81	3.85	3.87	3.87	3.88	3.88	3.88
			D				3.84	3.87	3.87	3.87	3.87	3.88	3.88
		σ				0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
22-1, 69-71	3.013	P	I	6.82	6.95	6.92	6.92	6.97	6.97	6.99	7.01	7.02	7.02
Gabbro			D										7.01
		S	I			3.69	3.70	3.71	3.72	3.74	3.74	3.74	3.74
			D			3.67	3.68	3.68	3.70	3.72	3.73	3.74	3.75
		σ				0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
22-2, 43-45	2.836	P	I	6.16	6.15	6.44	6.64	6.76	6.79	6.93	6.94	6.98	6.97
Serpentinite			D			6.52	6.71	6.73	6.89	6.87	6.88	6.93	6.95
		S	I		3.05	3.14	3.19	3.22	3.22	3.21	3.21	3.21	3.21
			D			3.19	3.22	3.22	3.21	3.21	3.21	3.21	3.21
		σ			0.34	0.34	0.35	0.35	0.36	0.36	0.36	0.36	0.36
23-1, 76-78	3.034	P	I	7.13		7.11	7.24	7.24	7.23	7.27	7.25	7.27	7.28
Gabbro			D			7.19	7.22	7.22	7.22	7.23	7.25	7.26	7.27
		S	I		3.84	3.84	3.85	3.85	3.85	3.86	3.86	3.86	3.86
			D		3.83	3.83	3.84	3.85	3.85	3.86	3.86	3.86	3.87
		σ				0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30

TABLE 1 – *Continued*

Sample (Interval in cm)	Bulk Density (g/cm^3)	P or S or σ	Incr. or Decr. Press.	Ham. Frame	Velocity (km/sec) Pressure (kbar) 0.07	0.17	0.34	0.52	0.69	1.03	1.38	1.72	2.07
24-1, 63-65	2.871	P	I	7.11	6.92	7.05	7.16	7.23	7.30	7.34	7.36	7.41	7.42
Gabbro			D		6.82	7.02	7.26	7.30	7.32	7.35	7.39	7.42	7.42
		S	I		3.70	3.71	3.72	3.72	3.73	3.73	3.73	3.73	3.74
			D			3.71	3.73	3.71	3.71	3.72	3.73	3.74	3.74
		σ			0.30	0.31	0.32	0.32	0.33	0.33	0.33	0.33	0.33
24-4, 86-88	2.851	P	I	6.39	6.67	6.71	6.77	6.83	6.88	6.91	6.91	6.94	6.92
Gabbro			D		6.74	6.77	6.87	6.87	6.88	6.88	6.89	6.91	6.94
		S	I			3.64	3.64	3.66	3.68	3.67	3.66	3.66	3.67
			D				3.61	3.61	3.62	3.62	3.62	3.63	3.66
		σ				0.29	0.30	0.30	0.30	0.31	0.31	0.31	0.31
Site 335													
5-2, 36-38	2.866	P	I	5.96	6.18	6.17	6.21	6.22	6.24	6.25	6.27	6.29	6.29
Basalt			D		6.17	6.19	6.20	6.22	6.24	6.26	6.27	6.28	6.29
6, cc	2.753	P	I	5.52	5.62	5.70	5.76	5.76	5.78	5.79	5.80	5.80	5.81
Basalt			D		5.64	5.73	5.76	5.76	5.80	5.81	5.82	5.82	5.83
6-1, 5-7	2.822	P	I	5.60	5.80	5.85	5.92	5.94	5.95	5.96	5.97	5.99	5.98
Basalt			D		5.80	5.87	5.93	5.93	5.93	5.94	5.96	5.97	5.97
6-3, 44-49	2.800	P	I	5.58	5.85	5.88	5.87	5.88	5.87	5.88	5.89	5.90	5.90
Basalt			D								5.84	5.89	5.90
6-4, 23-25	2.519	P	I	5.17		5.29	5.35	5.38	5.35	5.37	5.38	5.39	5.40
Basalt			D			5.31	5.32	5.33	5.31	5.33	5.36	5.39	5.40
6-6, 75-77	2.789	P	I	5.67	5.78	5.81	5.88	5.90	5.93	5.93	5.95	5.95	5.95
Basalt			D		5.82	5.86	5.87	5.89	5.91	5.93	5.95	5.95	5.95

through the sample and the delay line and the two received pulses displayed simultaneously on a dual trace Telequipment D-83, 50-mHz oscilloscope. The mercury delay line consists of a column of mercury with one transducer fixed at the base and a second mounted on a screw thread so as to move vertically, changing the length of mercury between the two transducers. The length, measured with a precision dial gage, is adjusted until the two received pulses are superimposed on the oscilloscope. The travel times through the sample and mercury then should be identical. As pointed out by Birch (1960) the mercury-delay-line not only has high precision and stability of about 0.01 μsec, but also, the shape of the received pulse through the mercury is similar to that through the sample. At least the first quarter wavelength of the two pulses can be matched by adjusting the amplitude scales. Thus, the time uncertainty is much less than would result from trying to locate the onset of the received pulse which, because of electrical and mechanical response times, builds up slowly and is followed by damped oscillations. The delay-line was calibrated with a high precision digital time interval unit. A calibration of 6.902 μsec/cm (17.53 μsec/in.) was used, which is identical to the velocity of mercury at 25°C reported by Birch (1960). There is a small temperature dependence of ±0.2% for a range of 19° to 31°C which can be neglected. Good signals can be obtained only above 0.2 kbar pressure and the accuracy increases with increasing pressure as the transducer-sample contact and thus signal improves. The mercury-delay-line reading for zero sample length was determined by extrapolating the pulse travel times of five precision machined steel cylinders 1 to 5 cm in length. They also were used as internal standards for periodic calibration checks. The length of the sample is measured with a precision caliper. The velocity in the rock then is calculated from the length of the sample, the length of the mercury column, and the velocity of the mercury. There are differences in velocity commonly of up to 0.5% between increasing and decreasing pressure, but there appears not to be a systematic difference. The reproducibility for measurement on a single sample is about ±0.4% for compression and ±0.8% for shear, and the values at different pressures for one measurement have a relative accuracy of about ±0.2% for compression and 0.4% for shear. The absolute accuracies at 0.5 kbar and above are estimated to be ±1% for compression and ±2% for shear. This estimated error is about double that of shore measurements largely because of the difficulty in getting the sample ends flat and parallel with the shipboard equipment and because of the high level of electrical and mechanical noise onboard the ship. It still is adequate for most purposes.

Shore-laboratory measurements to 10 kbar made essentially with the same procedure as that described above for onboard ship are reported by Christensen (this volume). The accuracy is about ±0.5% for compression and ±1% for shear. The compressional velocity of six samples was measured both onboard ship and in the shore laboratory. At 0.5 kbar the mean difference of pairs of values is 1.4% with the shipboard velocities having a mean value that is 0.8% higher. This is satisfactory agreement particularly as the sample faces were remachined before the shore measurements. Shear velocity measurements were repeated on only two samples, the shipboard values averaging 3% higher. Thus, there may be a small but barely significant difference in calibration for shear wave velocities in the shipboard and shore laboratories.

The usefulness of laboratory measurement of velocity depends on how well the in situ conditions are simulated, notably the pressure, temperature, extent of water saturation, and the sample orientation if it is anisotropic. There also is the serious problem of how representative the samples are of the complete section or region being investigated. This latter problem is discussed later. The velocities of the sea-floor rocks increase considerably but variably with increasing confining pressure. The measured velocities of Leg 37 samples increase from atmospheric pressure, to 0.5 kbar (upper crust) by about 0.2 km/sec, to 2.0 kbar (lower crust) by about 0.3 km/sec, and to 10.0 kbar by about 0.5 km/sec. Older, more-weathered samples commonly have increases twice those above, particularly at the lower pressures. The prime source of increasing velocity with pressure up to 2.0 kbar is the closing of microcracks and pores. The confining pressure, which is effective in closing such cracks and pores, is equal to the total external pressure minus the internal or pore pressure. In the laboratory the pore pressure is small and the confining pressure close to the external pressure because the pore water usually is allowed to escape as the pressure is increased, and because the compressibility of the pore water is much greater than that of the rock. The total or lithostatic pressure on an in situ rock is equal to the sum of the seawater load, 0.10 kbar per km depth which is 0.18 kbar for Site 332 and the rock load, about 0.20 kbar per km of sediment, and 0.28 kbar per km of basalt. The total pressure at the bottom of the 722-meter deep Hole 332B is about 0.37 kbar. The pore pressure within crustal rocks may vary between close to zero and hydrostatic pressure where all pore spaces are continuously connected with the seawater. If the pores and cracks are not connected, the pore pressure generally will be small because the thermal contraction of the pore water is much greater than that of the rock in cooling from a high temperature of formation since the coefficient of thermal expansion of water is about four times that of basalt and because the compressibility of the water is much greater than that of the rock in going from a shallow depth of formation to subsequent deep burial because the compressibility of water is about 20 times that of basalt. Only in the special but perhaps important situations of increasing temperature or of upward tectonic displacement will the pore pressure of crustal rocks exceed hydrostatic and approach lithostatic pressure so that the confining pressure is small. Thus, the in situ confining pressure generally will range from, (a) the difference between total load or lithostatic pressure and hydrostatic pressure, i.e., 0.12 kbar at the bottom of Hole 332B to (b) lithostatic pressure, i.e., 0.37 kbar at the bottom of Hole 332B.

In addition to the pressure effect of the rock as it was on the sea floor, the drilling process and the stresses from rapid reduction in pressure and temperature change at the time of sample recovery probably will cause extensive microcracks and fractures that will reduce the velocities measured at low pressures. They will be closed at about 0.5 kbar pressure. Thus, it is emphasized that laboratory pressure can be related only roughly to equivalent depth beneath the sea floor. The 0.5-kbar velocities are taken to be representative of upper crustal layer 2 and 2.0-kbar velocities to be representative of lower crustal layer 3. The error resulting from incorrectly simulating in situ pressures should be less than 0.1 km/sec or 2% for both compressional and shear waves.

The temperature effect on velocity has not been studied in much detail but is of the order of $-6 \times 10^{-5}°C^{-1}$ (e.g., Birch, 1958) for mafic rocks. Thus, the difference between laboratory temperature of $25 \pm 5°C$ and in situ temperature of about 5° to 100° (Hyndman, et al., this volume) in layer 2 is less than 0.5% and can be neglected. In some regions of layer 2, and more frequently in layer 3 very near a spreading ridge where temperatures reach several hundred degrees, the error may be several percent. The velocities probably will be quite different at temperatures approaching melting.

The importance of the measured samples being water saturated has been emphasized by Dortman and Magid (1969), Nur and Simmons (1969), Christensen (1970), Christensen and Salisbury (1975) for representative compressional velocities. The effect of saturation is small for shear velocities. All of the samples were water saturated before measurement by immersion in seawater following evacuation, then being held at 1.0-kbar pressure in seawater. As discussed in the section on the porosity of basalts (Hyndman and Drury, this volume), even pressure saturation does not completely resaturate these rocks after thorough drying, but the effect on velocity does not appear to be significant. Probably if the sample is nearly saturated, for example 75% or more, the excess water produced with increasing pressure during measurement rapidly fills any unfilled pores and cracks. Also the larger cracks, which are most easily filled, have the greatest effect on velocity. The error from incomplete saturation should be less than 0.5% for compressional velocities up to 1 kbar and negligible above 1 kbar and for shear velocities.

The velocities all have been measured on transverse minicores 2.5 cm diameter $\times$ 3 to 7 cm length taken from most of the major cooling units recovered which are generally equivalent to flows. The orientation of wave propagation thus is horizontal with random azimuth. Previous measurements have indicated a negligible velocity anisotropy in basalts (e.g., Christensen and Shaw, 1970; Christensen and Salisbury, 1972).

VELOCITY RESULTS

Compressional and shear wave velocities along with sample densities and Poisson's ratios are given in Table 1 with a few representative sample results being shown in Figure 1. The mean compressional velocity of basalt

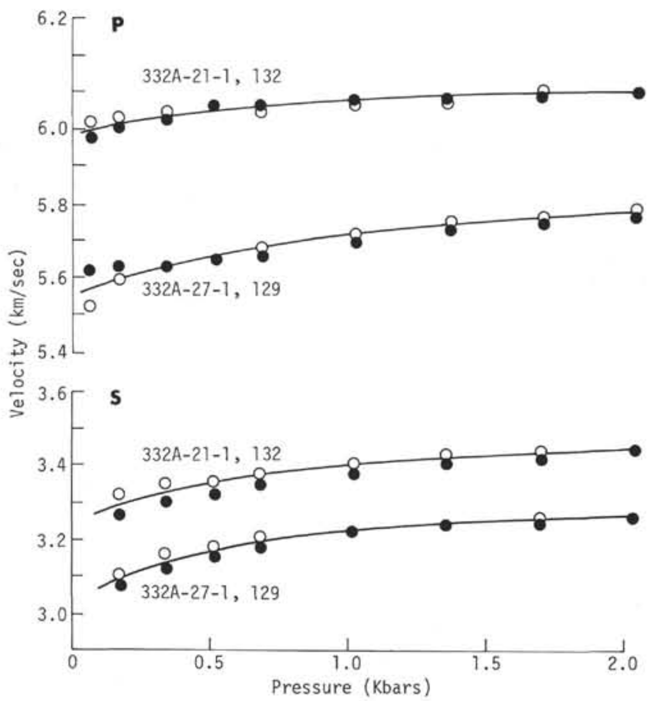

Figure 1. *Examples of compressional and shear wave velocities to 2.0-kbar confining pressure measured onboard* Glomar Challenger. *The solid points are for increasing and open circles decreasing pressure.*

samples does not vary significantly among the five holes, and there is no systematic trend with depth. The mean and standard deviation of individual values of 79 basalt samples, mainly Site 332, at 0.5 kbar corresponding to an upper crustal pressure, measured onboard ship is 5.94 ±0.34 km/sec. The mean shear velocity of 37 samples is 3.26 ±0.16 km/sec. The ratio of compressional to shear velocity is very constant at 1.86 ±0.02 giving a Poisson's ratio of 0.295 ±0.002. The mean bulk density of 101 basalt samples is 2.80 ±0.08 g/cm^3. Histograms of numbers of samples versus compressional and shear velocity and density are shown in Hyndman and Drury, this volume.

The mean values and standard deviations for six gabbros are: at 0.5 kbar, compressional velocity, 7.13 ±0.19 km/sec; shear velocity, 3.76 ±0.07 km/sec; Poisson's ratio 0.31 ±0.01; and density, 2.96 ±0.07 g/cm^3. At the lower crustal pressure of 2.0 kbar the compressional velocity is 7.21 km/sec and shear velocity is 3.79 km/sec.

The mean compressional velocity of three serpentinized peridotites at 2.0 kbar is 6.1 km/sec and for one sample the shear velocity was 2.17 km/sec giving a Poisson's ratio of 0.37. The mean density of three samples is 2.71 g/cm^3.

RELATIONS BETWEEN VELOCITY AND DENSITY AND BETWEEN POISSON'S RATIO AND VELOCITY

The variation of compressional and shear velocity of basalts has previously been shown to be closely and nearly linearly correlated with bulk density (e.g., Christensen and Salisbury, 1975) following the more general empirical relation suggested by Birch (1961). This relation is very useful for relating refraction measurements of velocity and gravity estimates of density. The relation for Leg 37 basalts, gabbros, and serpentinized peridotites is shown in Figure 2. Our basalt velocities are slightly higher or densities lower compared to previous values, but the difference is not significant. Both the gabbros and serpentinized peridotites have significantly higher velocity for a given density compared to the basalts, particularly for compressional velocity. The much higher ratio of compressional to shear velocities, and thus the Poisson ratio, for the serpentinized peridotites compared to the basalts is readily apparent. Note on the same diagram the agreement between the small range of velocities and densities for our basalts and previously measured young unweathered samples with ages less than 20 m.y. The range including older, more-weathered basalt samples is much larger.

The dependence of Poisson's ratio on compressional velocity for Leg 37 samples measured onboard ship is shown in Figure 3. There is a clear correlation of decreasing Poisson's ratio with decreasing velocity. The regression line for the basalts alone is:

$$\delta = 0.194\ (\pm 0.031) + 0.0167\ (\pm 0.0050)\ V_p$$

The gabbros appear to lie along the same line. The observed trend could be an artifact, the result of a systematic measurement error, particularly in the zero-sample-length mercury-delay-line calibration. However, the error required is about five times the estimated error limits. Also, the comparison of shipboard and shore-laboratory measurements (see above) indicates that if an error exists it is in the shear velocities being too fast. An error in the zero-sample-length calibration that gives shear velocities that are too fast would produce a correlation of Poisson's ratio and velocity the opposite from that observed. Thus, the above correlation is accepted as valid.

Christensen (personal communication) has examined the correlation between Poisson's ratio and compressional velocity for DSDP basalts from many sites of different basement ages. He found a wide scatter, but with a general trend of increasing Poisson's ratio with decreasing velocity, the opposite from that for Leg 37 shipboard measurements. His values of Poisson's ratio are similar for high velocity samples, i.e., 6 km/sec, but tend to much larger values compared to those for Leg 37 basalts for low velocity samples, i.e., 4 km/sec. The different correlation for the two sets of samples may exist because there are different origins for the velocity variation within each set. For Leg 37 basalts, which are very young and little weathered, decrease in velocity comes mainly from increasing vesicular porosity. Vesicular porosity probably affects the compressional more than shear wave velocity, i.e., mainly decreases the bulk modulus. In contrast, the samples examined by Christensen that are generally older probably have decreasing velocity primarily associated with increasing weathering. Weathering affects the shear more than the

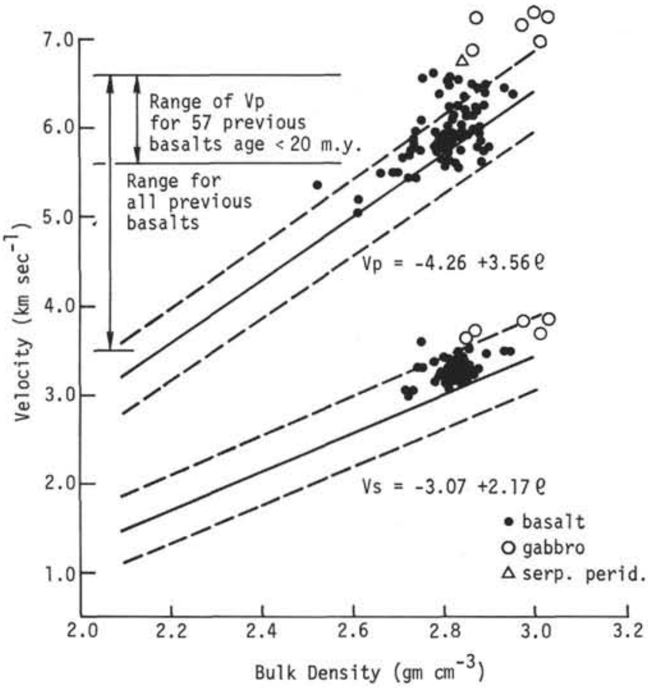

Figure 2. *Variations of compressional and shear wave velocities at 0.5-kbar as a function of bulk density for Leg 37 basement samples. The relations for previous basalts from Christensen and Salisbury (1975) is shown for comparison. Note the good agreement between the small range of velocities for the Leg 37 basalts and previous young unweathered basalts.*

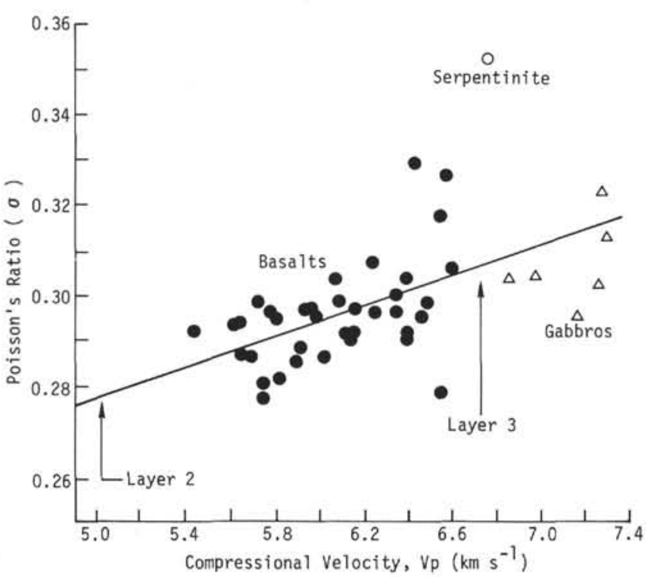

Figure 3. *Relation between Poisson's ratio (δ) and compressional velocity for Leg 37 basement samples. The least-squares regression line for the basalts also is shown.*

compressional velocity, i.e., mainly decreases the shear modulus, so increases Poisson's ratio (see Christensen and Salisbury, 1972, for examples).

The correlation between Poisson's ratio and compressional velocity for the young unweathered Leg 37 basalts is the one appropriate for comparison with refraction measurements since weathering even in old sea floor is limited largely to the upper 50 meters of layer 2 (see above). The large-scale voids and fractures that are responsible for reducing the refraction velocities in layer 2 below that for solid basalt (see discussion below) have dimensions that are about the same fraction of the wavelengths of about 50 meters used as have the vesicles of the laboratory wavelengths of about 0.5 cm. If the assumption that the relation given above applies to layer 2 refraction measurements is correct, the Poisson's ratio predicted for a layer 2a velocity of 2.8 km/sec is 0.24. This relation thus explains why the Poisson's ratio for layer 2 by refraction (see compilation by Christensen and Salisbury, 1975) generally is less than the mean laboratory value of 0.30 for basalts. The relation also suggests the value of measuring shear velocity and thus Poisson's ratio in refraction measurements to distinguish high velocity sediments, i.e., 3 to 4 km/sec, from a low velocity basaltic layer 2. The sediments generally will have Poisson's ratios well above 0.30 and the low velocity layer 2 section values well below 0.30.

CRUSTAL LAYERS 2a AND 2b

As discussed in the introduction, there is a serious discrepancy between the low seismic refraction velocities obtained for layer 2 of 5.0 ±0.7 km/sec and the velocities measured on fresh sea-floor basalts. The high laboratory velocities of young basalts is substantiated by our large collection of 79 basalts with a mean and standard deviation of individual values of 5.94 ±0.34 km/sec. The discrepancy is even larger in some regions such as the Reykjanes Ridge (Talwani et al., 1971) where the upper part of layer 2, designated layer 2a, has velocities between 2.3 and 3.7 km/sec. Where detected, the layer has a thickness of about 1 km, but if the thickness was much less, the layer usually would not be resolved. The layer also usually would not have been detected where there is a significant sedimentary thickness because it then would not produce a first arrival. A few very detailed seismic measurements suggest that actually there may be a gradual rather than stepwise increase in velocity with depth in the upper crust (Sutton et al., 1971; Helmberger and Morris, 1969; Hinz and Moe, 1971). Oceanic basement velocities of less than 4.0 km/sec have been recorded at a number of locations on the Mid-Atlantic Ridge (Le Pichon et al., 1965; Keen and Tramontini, 1970).

R.B. Whitmarsh (personal communication) has obtained a reversed refraction line over the sites of the three deepest holes of Leg 37, Sites 332 and 333, and found a very low velocity upper basement layer. The layer has a velocity of 2.8 km/sec and is about 640 meters thick (his model 1) underlain by 4.9 km/sec material. Most other refraction lines in the area do not show a well-defined layer 2a and give normal layer 2 velocities. A low velocity upper layer, however, does appear to be present under the median valley (Fowler and Matthews, 1974; Whitmarsh, 1973; Poehls, 1974). The highest layer 2 velocities in the Mid-Atlantic Ridge crestal mountains region are about 5.7 km/sec (Le

Pichon et al., 1965). As discussed below, it is very significant that much more low velocity broken basalt and sediment was encountered in the upper basement at Sites 332 and 333 than at the other sites.

Our drilling, particularly at Site 332, appears to have resolved the discrepancy between laboratory velocities of basalts and layer 2 seismic refraction velocities. The upper part of Hole 332B penetrated interlayered solid basalt and broken and fractured basalt with some sediment. The broken and shattered basalt and sediment undoubtedly are responsible for the low refraction velocities. Unfortunately, only small amounts of the broken basalt and sediment were recovered in the core. The presence of the low refraction velocity surface layer under the median valley and a comparison of the layer thickness with the observed sedimentation rates and available deposition time require that the low velocity material be primarily shattered, porous basalt rather than sediment. The smooth variation with depth of the paleomagnetic inclinations of samples, although with very shallow inclinations (see Ade-Hall et al., this volume) imply that, at least the recovered material is not talus but rather flow breccia, drained pillows and lava tubes, and generally fractured and shattered rocks with large voids, open fissures, or cracks such as frequently have been observed in the submersible studies in the FAMOUS area of the median valley at 37°N (e.g., Heirtzler and Le Pichon, 1974). Lort and Matthews (1972) have shown that the fractured and shattered basalts of the Troodos ophiolite complex have similarly low refraction velocities of about 3.0 km/sec.

The high drilling water pressure required to clear the bit while drilling basalt tends to wash out any fractured or unconsolidated material. However, the drilling rate is much higher and bit pressure much lower when shattered basalt and sediment are being drilled. Both drilling rate and bit pressure are continuously recorded so the fraction of solid basalt and of shattered material or sediment in a drilled section can be computed approximately. We have assumed that the fraction of solid basalt in each section is proportional to a parameter we call the "relative drilling effort" (RDE).

$$\mathrm{RDE} = C \times \frac{L}{R}$$

where L is the bit load, R the drilling or penetration rate, and C is a constant chosen so that the maximum RDE that commonly is observed equals 1. The relative drilling effort and the computed fraction of solid basalt as a function of depth in Holes 332B and 333 are shown in Figure 4. Also the percent recovery is seen generally to follow the drilling effort. To estimate the velocity of the composite material, we have used our mean laboratory basalt velocity at 0.5-kbar pressure of 5.94 km/sec and an estimate of mean rubble and sediment velocity of 2.2 km/sec, i.e., about 50% voids or low velocity sediment. This velocity, of course, is poorly determined. Wyllie et al. (1958) have shown that if the velocities of two media are not too different, e.g., water and rock, the velocity V through the composite

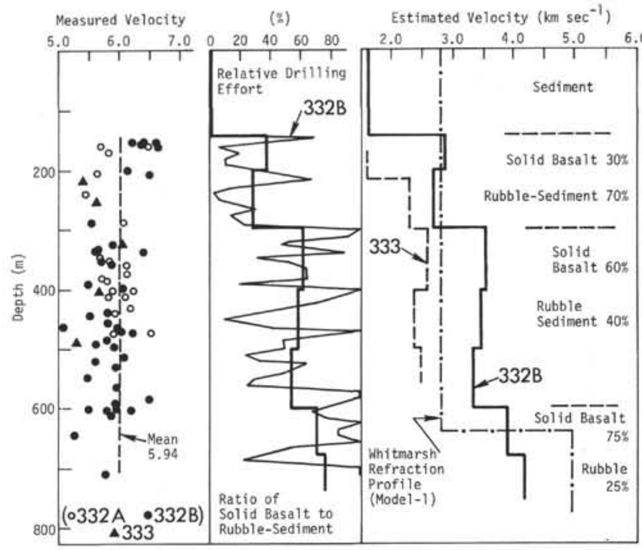

Figure 4. *Compressional velocities with depth of basalts at 0.5-kbar at Sites 332 and 333, the variation in relative drilling effort, the computed ratio of solid basalt to broken volcanic rubble and sediment, and the inferred velocity-depth profiles. The refraction model for the sites by R. B. Whitmarsh is given for comparison.*

material can be represented closely by the time average equation:

$$\frac{1}{V} = \frac{A}{V_1} + \frac{1-A}{V_2}$$

where V_1 and V_2 are the velocities in the two materials and A is the fraction of material with velocity V, and 1-A the fraction of material of velocity V_2.

The computed velocity-depth profiles for Holes 332B and 333A are compared with Whitmarsh's refraction model 1 for the site in Figure 4. Although our computed profiles show much more detail than the broad average layering obtained from the refraction measurements, there is general agreement in the thickness and velocity of the low velocity surface layer 2a and in the velocity of the underlying layer 2b. A gradual increase in refraction velocity with depth in the oceanic basement, such as inferred from our drill holes has been found wherever they have provided sufficient detail. For example, Sutton et al. (1971) found that velocities of about 3.6, 4.5, and 5.8 km/sec occur frequently in layer 2. The computed profile implies up to 35% voids or low velocity sediment near the top of the drilled section decreasing to about 10% at a depth of 700 meters.

MAFIC AND ULTRAMAFIC ROCKS AS POSSIBLE CONSTITUENTS OF LAYER 3

Oceanic crustal layer 3 lies at an average depth of 1.7 km beneath oceanic basement. It has a thickness of 4 to 7 km and an average seismic refraction velocity of 6.7 km/sec (Raitt, 1963; Ludwig et al., 1971; Christensen and Salisbury, 1975). The lower 3 km of layer 3, i.e., 3b, is frequently delineated as a separate "basal layer" with refraction velocity of 6.7 km/sec where the seismic data are sufficiently detailed (Sutton et al., 1971). The average velocity of the upper part of layer 3, i.e., 3a, corresponds to the laboratory velocity of a number of mafic and some ultramafic rocks. Since some low velocity material or fractures must be present (see Lort and Matthews, 1972) although much less than in layer 2, laboratory velocities should be somewhat higher than 6.7 km/sec. The smaller range of refraction velocities for upper layer 3 compared to layer 2 undoubtedly reflects a smaller fraction of low velocity material. The most likely constituents of upper layer 3 are gabbro, metagabbro, and metabasalt (Cann, 1968; Barrett and Aumento, 1970; Christensen, 1970; Fox et al., 1973; Christensen and Salisbury, 1975). Amphibolites can have the required velocity, but they are not frequently dredged, and the high temperature conditions for their formation probably do not occur frequently in the oceanic crust. Serpentinites also can have the required velocity, but are discounted except as a minor constituent because their range of velocity, depending on the degree of serpentinization, is much greater than the observed range of refraction velocities and because the Poisson's ratio, and ratio of compressional to shear velocity measured in the laboratory, are much higher than that obtained from seismic data (Christensen, 1966; Christensen, 1972; Christensen and Salisbury, 1975). Gabbros and low-grade metamorphic mafic rocks have the required velocities and Poisson's ratios and are frequently dredged.

The lower part of layer 3, the basal layer or 3b, has seismic refraction velocities intermediate between the laboratory velocities of gabbros and peridotite. Few rocks have this velocity. A mix of gabbro and peridotite is a possibility. Serpentinite is discounted except as a minor constituent as discussed above. Ophiolite complexes suggest a gabbroic upper layer 3 and a basal layer of mixed mafic and ultramafic rocks that frequently are layered cumulates. Serpentinites also are observed, but much of the serpentinization probably has taken place after surface exposure of the ophiolites (Magaritz and Taylor, 1974).

Hole 334 penetrated first a 50-meter thick surface layer of basalts, then a complex sequence of gabbro, olivine gabbro, serpentinized peridotites, and breccias consisting of the latter three rock types with some sedimentary matrix. The hole was sited at the base of a faulted slope in an attempt to penetrate to deep crustal material. The presence of the sedimentary breccias suggests surface exposure of a plutonic melange prior to burial by subsequent basaltic eruptions. About 45% of the plutonic sequence is gabbro and olivine gabbro, 25% serpentinized peridotite, and 30% breccia. There is no direct evidence that the drilled sequence represents lower crustal material, but it is important to compare the measured velocities of the rock types recovered with seismic refraction results. Olivine gabbros very frequently occur in the lower part of ophiolite complexes and may be characteristic of the lower crust, and the high density of the plutonic rocks (mean of gabbros, 2.96 g/cm^3, mean of serpentinized peridotites, 2.70 g/cm^3) argues against a diapiric intrusion and for an upward displacement by faulting. The more completely serpentinized rocks commonly dredged have lower densities, about 2.5 g/cm^3, and could rise diapirically along fault zones.

The compressional velocity of one serpentinized peridotite at 2.0-kbar pressure corresponding to the lower crust, is 6.96 km/sec. The velocity is somewhat higher than that computed from the relation between velocity and degree of serpentinization as determined from the density. The density of 2.84 g/cm^3 is appropriate for a velocity of about 6.0 km/sec according to the data of Christensen (1972). The sample must have about 50% serpentine by volume. The shear velocity is 3.21 km/sec, the ratio of compressional to shear velocity is 2.17, and Poisson's ratio is 0.36. The Poisson's ratio is much higher than for basalts and gabbros and much higher than found for layer 3 from refraction measurements (Christensen and Salisbury, 1975). It agrees with the average serpentinite value of 0.37 given by Christensen (1972).

The gabbros measured are very fresh with a mean density of 2.96 g/cm^3 and a water content from low temperature drying of only 0.4% by weight. They are coarse grained with primary igneous textures. The pyroxenes contain well-developed exsolution lamellae of coexisting orthopyroxene and clinopyroxene. The mean compressional velocity and standard deviation of six individual values is 7.13 $\pm$0.19 km/sec at 0.5 kbar increasing to 7.21 $\pm$0.19 km/sec at the lower crustal pressure of 2.0 kbar. The mean shear velocity at 0.5 kbar is 3.76 $\pm$0.07 km/sec and 3.79 $\pm$0.10 km/sec at 2.0 kbar. The ratio of compressional to shear velocity is 1.89 and Poisson's ratio is 0.31, very slightly higher than for the Leg 37 basalts.

The compressional velocity of 7.21 km/sec of the gabbros is close to 7.1 which is about the maximum commonly recorded layer 3 (or 3a) velocity from seismic refraction measurements. To obtain the average layer 3 velocity of 6.7 km/sec only 2% of cracks or other voids filled with water or other very low velocity material is required if the travel time average equation of Wyllie et al. (1958) is correct. Alternatively about 10% of material with velocity 4.5 km/sec is required. Faulting and fracturing of the crust certainly is sufficient for there to be enough voids and perhaps veins of low velocity carbonates to produce this velocity reduction. The measured Poisson's ratio is slightly higher than the average but within the range from refraction, and as shown above, Poisson's ratio is reduced by the presence of voids and fractures.

The lower crustal layer 3b could consist of a mix of gabbro and high velocity peridotite, e.g., our peridotite before serpentinization following surface exposure, as inferred from ophiolite sections (e.g., Moores and Jackson, 1974; Peterson et al., 1974). About 25% peridotite with a velocity of 8.2 km/sec and 75% of our gabbro would give the observed velocity of 7.4 km/sec. Less gabbro and more peridotite is required if fractures and low velocity veins are important. Thus, the fractions we observe in our drilled section would give the observed basal layer seismic refraction velocity.

CONCLUSIONS

Deep drilling near the crest of the Mid-Atlantic Ridge by *Glomar Challenger* has explained the low velocity (less than 4.0 km/sec) upper crustal layer 2a outlined by seismic refraction measurements in some areas. In these areas, there is an upper layer of highly fractured low density volcanic material, flow breccia, drained pillows, and lava tubes with extensive voids and some intercalated sediments. The results also explain why refraction velocities for layer 2 are in general so much lower and more variable than the velocities of sea-floor basalts measured in the laboratory. The refraction velocity profile depends on the amount of fracturing, voids, and sediment and not on a downward change in general rock composition or metamorphic grade. The velocities measured in the laboratory on solid basalt should be related to the maximum commonly and accurately recorded refraction velocities.

Poisson's ratio for unweathered basalts is found to decrease with decreasing velocity. The relation predicts a Poisson's ratio of 0.28 for a layer 2 refraction compressional velocity of 5 km/sec and 0.24 for a layer 2a velocity of 2.8 km/sec in good agreement with the values observed.

Gabbros recovered from one hole on Leg 37 have velocities appropriate to the upper part of crustal layer 3. If the ultramafic rocks in Hole 334 had undergone little serpentinization, such a complex at the base of the crust would explain the basal layer that has been observed by refraction measurements, with velocities between those of the oceanic layer 3 and the mantle. Similar mixed mafic-ultramafic complexes are common at the base of the inferred crustal parts of ophiolites.

Much better recovery of the basement rocks is needed to determine the exact nature of the low velocity broken material that makes up layer 2a. In-hole velocity logging also now is required so that the velocity of material not recovered may be determined. Many more crustal holes are needed to outline the extent and distribution laterally of layer 2a. Deeper drilling, in excess of 2 km into the deep oceanic basement that is essential for the understanding of layer 3 now is clearly possible with the *Glomar Challenger* technology. We believe that a major effort should be made as soon as possible for deep drilling into the oceanic basement.

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