

## CHAPTER 10. SEISMIC VELOCITIES AND ELASTIC MODULI OF IGNEOUS AND METAMORPHIC ROCKS FROM THE INDIAN OCEAN

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### Introduction

Within the past decade, over 60 deep crustal refraction profiles have been completed in the Indian Ocean. The interpretation of data from these profiles requires detailed information on seismic velocities of Indian Ocean rocks at elevated pressures. This paper is intended to summarize experimental studies of seismic velocities in rocks from the Indian Ocean and compare the laboratory measurements with seismic refraction velocities. Emphasis is placed on the nature of layer 2. Several new measurements of velocities at elevated pressures are given for Indian Ocean rocks obtained from the Deep Sea Drilling Project and by dredging.

In addition to compressional ( $V_p$ ) and shear ( $V_s$ ) velocities, several parameters useful in describing elastic properties and interpreting composition from seismic refraction studies are presented for Indian Ocean rocks. These include the shear modulus or rigidity ( $\mu$ ), Lame's constant ( $\lambda$ ), the bulk modulus ( $K$ ), Young's modulus ( $E$ ), compressibility ( $\beta$ ), Poisson's ratio ( $\sigma$ ) and the seismic parameter ( $\phi$ ) defined as  $K/\rho$  where  $\rho$  is density. Although there are several techniques for obtaining these constants, they all can be conveniently calculated at various pressures from  $V_p$ ,  $V_s$  and  $\rho$ . A detailed tabulation of the relationships between the various elastic moduli and velocities and density is given by Birch (1961).

### Velocity and Density Data

Variations of  $V_p$  and  $V_s$  with pressure for a basalt are shown in Figure 1. The rapid increase in velocity at low pressures is a consequence of the closure of grain boundary cracks and the accompanying reduction of porosity. Above a few kilobars the pore spaces are reduced in volume and the changes in velocity at higher pressures are often primarily related to the effect of pressure on the individual mineral components.

The importance of using velocities from water saturated samples in the interpretation of relatively shallow seismic data has been discussed in several studies (e.g., Dortman and Magid, 1968; Nur and Simmons, 1969; Christensen and Salisbury, 1972) and the influence of water saturation on velocities is illustrated in Figure 1. Here "air dry" refers to a sample with a moisture content related to the humidity of the laboratory prior to the measurements. During the runs pore pressures were kept minimal; water from the saturated samples was allowed to drain

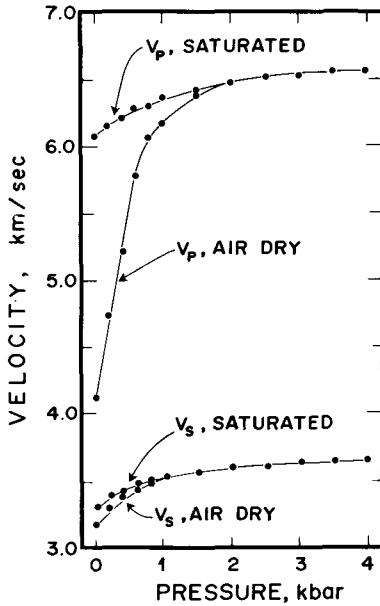


Fig. 1. The effect of water saturation on velocities for a typical oceanic basalt.

from the rock pore spaces into 100 mesh screens placed between the rock cores and copper jackets.

Of the 53 sites drilled in Legs 22 through 27, basalt was recovered at 30 sites. Compressional wave velocities have been reported at elevated pressures for basalts from 17 of these sites and shear wave velocities have been measured for samples from 7 sites. These measurements and bulk densities of the basalts are summarized in Table 1.

Sixty new measurements of velocities in Indian Ocean DSDP rocks to 6 kbar are presented in Table 2. Included are measurements of  $V_p$  and  $V_s$  for basalt from 8 sites for which no velocities have been previously reported for igneous rocks and additional measurements of  $V_s$  for 10 sites for which only  $V_p$  have been previously reported. Additional data are also given for holes in which only air dry samples were studied. All samples were water saturated prior to the measurements. Because of earlier findings that DSDP basalts are nearly isotropic (e.g., Christensen and Salisbury, 1972) velocities were measured in only one direction for each interval sampled.

With the exceptions of andesites from Site 214, a limestone from Site 213 and a volcanic sediment from Site 253, the rocks of Table 2 are basalts. Bulk densities of the samples are included in Table 2. Petrographic descriptions can be found in the initial reports and chemical analyses have been reported for several rocks at intervals close to where the samples for velocity measurements were selected.

The velocities were obtained by measuring the transit times of compressional and shear waves through cylindrical rock cores using a similar technique to that described by Birch (1960). Barium titanate and AC-cut quartz transducers with natural resonance frequencies of 1 to 2 MHz were used to generate the compressional and shear waves, respectively. Temperatures of all runs were between 20° and 30°C.

The elastic constants ( $K$ ,  $E$ ,  $\mu$ ,  $\lambda$ ,  $\beta$  and  $\sigma$ ),  $V_p/V_s$ , and  $\phi$  calculated from the velocities and densities at selected pressures are given in Table 3. The velocities and densities used in the calculations were corrected for length changes at elevated pressures using an iterative routine and the dynamically determined compressibilities.

TABLE 1. Summary of Indian Ocean Basalt  
Velocity Measurements at 0.5 kbar

Sample	Density (g/cm <sup>3</sup> )	V <sub>p</sub> (km/sec)	V <sub>s</sub> (km/sec)	Reference
24-231-64-1	2.74	4.74*	-	Schreiber et al. (1974) <sup>1</sup>
24-231-64-3	2.75	5.11	-	"
24-233-9-1	2.67	4.42	-	"
24-233-13-1	2.73	4.96*	-	"
24-235-20-2	2.71	5.26*	-	"
24-235-20-4	2.75	5.40*	-	"
24-235-20-5	2.67	5.31*	-	"
24-236-33-3	2.35	3.68	-	"
24-236-34-2	2.68	4.80*	-	"
24-236-36-1	2.73	4.93*	-	"
24-236-37-1	2.76	5.53	-	"
24-238-55-2	2.81	5.32	-	"
24-238-57-3	2.82	5.33*	-	"
24-238-59-2	2.90	5.96	-	"
24-238-61-4	2.82	5.54	-	"
24-238-64-1	2.71	5.57	-	"
25-239-20-1 (125-128)	2.72	5.43	2.97	Christensen et al. (1974a) <sup>2</sup>
25-239-21-1 (46-49)	2.76	5.47	2.99	"
25-240-7-1 (120-123)	2.80	5.87	3.26	"
25-245-19-1 (37-40)	2.89	6.11	3.30	"
25-248-15-1 (35-38)	2.68	5.39	2.91	"
25-248-17-2 (122-125)	2.76	5.88	3.23	"
25-249-33-2 (27-30)	2.32	2.61	2.15	"
25-249-33-2 (126-129)	2.19	3.84	1.97	"
25-249-33-3 (128-131)	2.39	4.23	2.23	"
26-250A-26-2 (140)	2.85	6.22	-	Hyndman (1974) <sup>2</sup>
26-250A-26-6 (58)	2.82	6.17	-	"
26-251A-31-2 (84)	2.82	5.61	-	"
26-251A-31-3 (50)	2.86	6.49	-	"
26-251A-31-4 (48)	2.93	6.13	-	"
26-251A-31-5 (105)	2.94	6.06	-	"
26-254-31-1 (111)	2.74	5.52	-	"
26-254-35-1 (107)	2.75	4.97	-	"
26-254-36-3 (105)	2.82	5.36	-	"
26-256-10-2 (68)	2.96	5.88	-	"
26-256-10-3 (85)	2.96	6.47	-	"
26-257-11-2 (74)	2.74	5.21	-	"
26-257-12-1 (130)	2.73	6.11	-	"
26-257-12-3 (35)	2.73	6.13	-	Hyndman (1974) <sup>2</sup>
26-257-13-3 (15)	2.82	5.60	-	"
26-257-14-2 (95)	2.75	5.27	-	"
26-257-15-1 (133)	2.89	6.13	-	"
27-259-35-1 (128-131)	2.26	3.78	1.92	Christensen et al. (1974b) <sup>2</sup>
27-259-36-2 (66-70)	2.08	3.47	1.78	"

TABLE 1 (continued)

Sample	Density (g/cm <sup>3</sup> )	$V_p$ (km/secP)	$V_s$ (km/sec)	Reference
27-259-37-2 (105-109)	2.43	4.27	2.27	"
27-259-39-1 (135-138)	2.55	4.66	2.51	"
27-259-41-3 (53-56)	2.66	4.95	2.78	"
27-261-33-1 (55-59)	2.59	4.97	2.63	"
27-261-33-1 (131-134)	2.79	5.55	2.86	"
27-261-34-3 (69-71)	3.00	6.50	3.60	"
27-261-35-3 (84-87)	2.60	4.47	2.30	"
27-261-37-2 (92-95)	2.72	5.35	2.93	"
27-261-38-2 (23-26)	2.75	5.50	2.81	"
27-261-38-5 (94-97)	2.80	5.77	3.18	"

\* Mean of measurements in more than one direction.

1 Air dry.

2 Water saturated.

Some samples included in the present study were obtained from intervals close to those in which measurements have been reported from other laboratories. Comparisons of these data are presented in Table 4. Considering that different cores were studied, as is illustrated by density comparisons, the agreement of the velocity data of Table 1 with that of Hyndman (1974) is excellent. This agreement is probably a consequence of similarities in the initial preparation of the samples (i.e., water saturation) prior to the measurements. The compressional wave velocities of Schreiber *et al.* (1974) for air dry samples, on the other hand, are significantly lower than the velocities measured for saturated specimens.

In addition, velocities and densities have been measured in basalt, serpentinite and metagabbro dredged from the Central Indian Ridge. Velocities as a function of pressure, densities and calculated elastic constants are given in Tables 5 and 6. For each sample velocities were measured to 10 kbar in three cores cut in mutually perpendicular directions.

The basalt, recovered at depths of 3540 to 3880 meters at 12°25'S and 65°56'E, is very fresh and contains subradiating laths of plagioclase with minor pyroxene and olivine in a glassy matrix. The serpentinite and metagabbro were dredged at depths of 4240 to 4880 meters at 17°04'S and 66°50'E. The serpentinite contains lizardite with minor chrysotile and opaques. Relic olivine and enstatite constitute less than 10% of the rock. The metagabbro shows abundant evidence of recrystallization. Hornblende and clusters of fibrous actinolite after clinopyroxene and enstatite form approximately 60% of the rock. Plagioclase is variable in composition ranging from An<sub>30</sub> to An<sub>50</sub>. Less than 5% relic enstatite is also present. Preferred mineral orientation is lacking though evidence of deformation is indicated by bent plagioclase lamellae. Brief descriptions of the dredge hauls from which the samples of Tables 5 and 6 were obtained are given by Engel and Fisher (1969).

TABLE 2. Compressional (P) and Shear (S) Wave Velocities

Sample	Bulk Density g/cc	Mode	Velocity (km/sec) at Varying Pressures							
			0.2 kb	0.4 kb	0.6 kb	0.8 kb	1.0 kb	2.0 kb	4.0 kb	6.0 kb
211-12-1, 70-73 cm	2.670	P	5.18	5.21	5.24	5.25	5.27	5.33	5.41	5.48
		S	2.57	2.58	2.59	2.60	2.62	2.66	2.72	2.75
211-15-2, 69-71 cm	2.430	P	4.52	4.55	4.58	4.61	4.63	4.70	4.84	4.98
		S	2.19	2.22	2.25	2.28	2.31	2.44	2.54	2.58
211-15-4, 67-70 cm	2.480	P	4.91	4.93	4.95	4.96	4.97	5.01	5.08	5.15
		S	2.30	2.34	2.37	2.40	2.43	2.53	2.63	2.67
212-39-1, 58-61 cm	2.290	P	3.99	4.02	4.04	4.06	4.08	4.15	4.29	4.43
		S	1.96	2.00	2.02	2.04	2.06	2.09	2.14	2.19
213-17-2, 43-49 cm (limestone)	2.642	P	6.34	6.35	6.36	6.37	6.37	6.39	6.43	6.47
		S	3.24	3.25	3.26	3.27	3.27	3.29	3.30	3.31
214-48-1, 87-90 cm (andesite)	2.329	P	4.43	4.44	4.46	4.48	4.50	4.57	4.71	4.84
		S	1.80	1.86	1.93	1.98	2.03	2.25	2.51	2.59
214-48-2, 7-10 cm (andesite)	2.677	P	5.74	5.75	5.76	5.76	5.77	5.79	5.84	5.88
		S	3.09	3.11	3.12	3.13	3.14	3.17	3.19	3.22
214-49-1, 143-146 cm (andesite)	2.673	P	5.95	5.97	5.98	5.99	6.00	6.05	6.09	6.12
		S	2.62	2.65	2.67	2.69	2.71	2.75	2.79	2.89
214-53-1, 50-53 cm	2.738	P	5.00	5.02	5.04	5.06	5.06	5.13	5.23	5.34
		S	2.62	2.65	2.67	2.69	2.71	2.75	2.79	2.89
216-37-2 77-80 cm	2.602	P	4.66	4.69	4.72	4.74	4.76	4.82	4.90	4.98
		S	2.37	2.41	2.43	2.46	2.48	2.54	2.63	2.69

TABLE 2 (continued)

Sample	Bulk Density g/cc	Mode	Velocity (km/sec) at Varying Pressures							
			0.2 kb	0.4 kb	0.6 kb	0.8 kb	1.0 kb	2.0 kb	4.0 kb	6.0 kb
220-18-4, 75-79 cm	2.605	P	4.48	4.55	4.60	4.64	4.67	4.79	4.89	4.98
221-19-2, 18-21 cm	2.765	P	5.50	5.53	5.56	5.58	5.61	5.69	5.80	5.92
223-40-2, 46-50 cm	2.084	P	2.89	3.02	3.11	3.17	3.24	3.51	3.88	4.21
231-64-1, 60-64 cm	2.781	P	5.54	5.57	5.59	5.61	5.62	5.65	5.70	5.76
233A-8-2, 63-68 cm	2.756	P	5.21	5.24	5.26	5.28	5.30	5.37	5.46	5.55
235-19-1, 124-128 cm	2.681	P	5.30	5.33	5.35	5.36	5.37	5.42	5.49	5.57
236-34-1, 147-150 cm	2.672	P	5.06	5.10	5.14	5.17	5.19	5.25	5.36	5.47
238-55-2, 10-13 cm	2.860	P	5.90	5.93	5.95	5.96	5.98	6.05	6.16	6.29
238-59-2, 26-29 cm	2.920	P	6.22	6.24	6.25	6.26	6.27	6.29	6.34	6.38
238-62-2, 75-79 cm	2.859	P	5.93	5.95	5.97	5.98	6.00	6.04	6.10	6.15

TABLE 2 (continued)

Sample	Bulk Density g/cc	Velocity (km/sec) at Varying Pressures								
		Mode	0.2 kb	0.4 kb	0.6 kb	0.8 kb	1.0 kb	2.0 kb	4.0 kb	6.0 kb
238-64-1, 29-131 cm	2.864	P S	5.99 3.25	6.02 3.27	6.04 3.29	6.06 3.30	6.08 3.31	6.14 3.33	6.18 3.34	6.23 3.35
250-A-25-3, 97-101 cm	2.821	P S	5.83 2.10	5.86 3.00	5.88 3.01	5.89 3.01	5.90 3.02	5.94 3.13	6.01 3.15	6.09 3.17
251A-31-2, 82-87 cm	2.792	P S	5.40 2.81	5.47 2.83	5.54 2.86	5.56 2.88	5.59 2.90	5.69 2.98	5.79 3.04	5.90 3.10
253-24-1, (volcanic 133-136cm arenite)	2.221	P S	4.30 1.87	4.36 2.01	4.40 2.10	4.43 2.17	4.45 2.22	4.51 2.33	4.62 2.43	4.72 2.46
254-35-2 47-52 cm	2.741	P S	4.87 2.47	4.97 2.49	5.03 2.51	5.08 2.53	5.12 2.54	5.30 2.62	5.35 2.70	5.46 2.76
254-36-3, 110-114 cm	2.785	P S	5.36 2.69	5.39 2.71	5.42 2.73	5.44 2.74	5.46 2.76	5.52 2.81	5.60 2.89	5.68 2.93
256-9-2, 50-53 cm	2.652	P S	4.68 2.32	4.75 2.34	4.80 2.37	4.83 2.39	4.86 2.42	4.95 2.51	5.12 2.61	5.25 2.68
257-11-2, 57-61 cm	2.665	P S	4.96 2.73	5.03 2.77	5.08 2.79	5.13 2.81	5.16 2.83	5.27 2.86	5.38 2.91	5.50 2.95
257-15-2, 1-4 cm	2.811	P S	5.94 2.95	5.97 2.97	5.98 2.99	6.00 3.00	6.01 3.02	6.05 3.06	6.13 3.11	6.21 3.14
257-17-5, 126-129 cm	2.933	P S	6.29 3.49	6.30 3.49	6.32 3.50	6.33 3.51	6.34 3.51	6.39 3.53	6.45 3.56	6.51 3.60
260-18 cc	2.307	P S	3.48 1.91	3.54 1.94	3.59 1.96	3.64 1.97	3.69 1.99	3.83 2.02	4.04 2.08	4.24 2.15

TABLE 3. Elastic Constants

Sample	Pressure (kb)	$v_p/v_s$	$\sigma$	$\phi$ (km/sec) <sup>2</sup>	K (Mb)	$\beta$ (Mb <sup>-1</sup> )	$u$ (Mb)	E (Mb)	$\lambda$ (Mb)
211-12-1, 70-73 cm	0.4	2.02	0.34	18.3	0.49	2.05	0.18	0.48	0.37
	1.0	2.02	0.34	18.6	0.50	2.01	0.18	0.49	0.38
	2.0	2.00	0.33	18.9	0.51	1.97	0.19	0.51	0.38
	6.0	1.99	0.33	19.8	0.54	1.87	0.20	0.54	0.40
211-15-2, 69-71 cm	0.4	2.06	0.35	14.2	0.35	2.90	0.12	0.32	0.27
	1.0	2.00	0.33	14.3	0.35	2.88	0.13	0.35	0.26
	2.0	1.93	0.32	14.1	0.35	2.91	0.14	0.38	0.25
	6.0	1.93	0.32	15.7	0.39	2.57	0.16	0.43	0.28
211-15-4, 67-70 cm	0.4	2.10	0.35	17.0	0.42	2.37	0.14	0.37	0.33
	1.0	2.05	0.34	16.8	0.42	2.39	0.15	0.39	0.32
	2.0	1.98	0.33	16.5	0.41	2.44	0.16	0.42	0.30
	6.0	1.93	0.32	16.9	0.42	2.36	0.18	0.47	0.31
212-39-1, 58-61 cm	0.4	2.01	0.34	10.8	0.25	4.03	0.09	0.24	0.19
	1.0	1.98	0.33	10.9	0.25	3.98	0.10	0.26	0.19
	2.0	1.98	0.33	11.3	0.26	3.83	0.10	0.27	0.19
	6.0	2.02	0.34	13.1	0.31	3.28	0.11	0.30	0.23
213-17-2, 43-49 cm	0.4	1.95	0.32	26.3	0.69	1.44	0.28	0.74	0.51
	1.0	1.95	0.32	26.3	0.70	1.44	0.28	0.75	0.51
	2.0	1.94	0.32	26.4	0.70	1.43	0.29	0.76	0.51
	6.0	1.96	0.32	27.1	0.72	1.39	0.29	0.77	0.53
214-48-1,	0.4	2.39	0.39	15.1	0.35	2.84	0.08	0.23	0.30
	1.0	2.21	0.37	14.7	0.34	2.92	0.10	0.26	0.28
	2.0	2.03	0.34	14.1	0.33	3.03	0.11	0.32	0.25
	6.0	1.87	0.30	14.3	0.34	2.95	0.16	0.41	0.23
214-48-2, 7-10 cm	0.4	1.85	0.29	20.2	0.54	1.86	0.26	0.67	0.37
	1.0	1.84	0.29	20.1	0.54	1.85	0.26	0.68	0.36
	2.0	1.83	0.29	20.1	0.54	1.85	0.27	0.69	0.36
	6.0	1.83	0.29	20.7	0.56	1.79	0.28	0.72	0.37
214-53-1, 50-53 cm	0.4	1.89	0.31	15.8	0.43	2.31	0.19	0.50	0.31
	1.0	1.87	0.30	15.8	0.43	2.30	0.20	0.52	0.30
	2.0	1.86	0.30	16.1	0.44	2.25	0.21	0.54	0.31
	6.0	1.85	0.29	17.2	0.48	2.09	0.23	0.59	0.32
216-37-2, 77-80 cm	0.4	1.95	0.32	14.3	0.37	2.69	0.15	0.40	0.27
	1.0	1.92	0.31	14.4	0.38	2.66	0.16	0.42	0.27
	2.0	1.90	0.31	14.6	0.38	2.63	0.17	0.44	0.27
	6.0	1.85	0.29	15.0	0.40	2.53	0.19	0.49	0.27
221-19-2, 18-21 cm	0.4	1.82	0.28	18.3	0.51	1.97	0.25	0.65	0.34
	1.0	1.81	0.28	18.7	0.52	1.93	0.26	0.68	0.34
	2.0	1.80	0.28	19.1	0.53	1.89	0.28	0.70	0.35
	6.0	1.82	0.28	20.8	0.58	1.72	0.29	0.75	0.39
223-40-2 46-50 cm	0.4	2.06	0.35	6.2	0.13	7.68	0.04	0.12	0.10
	1.0	2.10	0.35	7.3	0.15	6.56	0.05	0.13	0.12
	2.0	2.11	0.36	8.6	0.18	5.52	0.06	0.16	0.14

TABLE 3. (continued)

Sample	Pressure (kb)	$v_p/v_s$	$\sigma$	$\phi$ (km/sec) <sup>2</sup>	K (Mb)	$\beta$ (Mb <sup>-1</sup> )	$\mu$ (Mb)	E (Mb)	$\lambda$ (Mb)
	6.0	2.13	0.36	12.3	0.26	3.81	0.08	0.22	0.21
231-64-1, 60-64 cm	0.4	1.89	0.30	19.4	0.54	1.85	0.24	0.63	0.38
	1.0	1.87	0.30	19.5	0.54	1.84	0.25	0.65	0.38
	2.0	1.88	0.30	19.8	0.55	1.81	0.25	0.66	0.38
	6.0	1.91	0.31	70.9	0.59	1.71	0.25	0.66	0.42
233A-8-2, 62-68 cm	0.4	1.92	0.31	17.5	0.48	2.07	0.21	0.54	0.35
	1.0	1.91	0.31	17.8	0.49	2.03	0.21	0.56	0.35
	2.0	1.92	0.31	18.4	0.51	1.97	0.22	0.57	0.36
	6.0	1.92	0.31	19.5	0.54	1.84	0.23	0.61	0.39
235-19-1, 124-128 cm	0.4	1.94	0.32	18.2	0.49	2.05	0.20	0.54	0.35
	1.0	1.92	0.31	18.4	0.49	2.03	0.21	0.55	0.35
	2.0	1.90	0.31	18.4	0.50	2.01	0.22	0.57	0.35
	6.0	1.90	0.31	19.4	0.53	1.90	0.23	0.61	0.37
236-34-1, 147-150 cm	0.4	1.89	0.31	16.3	0.44	2.30	0.19	0.51	0.31
	1.0	1.91	0.31	17.0	0.46	2.19	0.20	0.52	0.32
	2.0	1.91	0.31	17.5	0.47	2.13	0.20	0.53	0.33
	6.0	1.92	0.31	18.9	0.51	1.96	0.22	0.57	0.37
238-55-2, 10-13 cm	0.4	1.86	0.30	21.5	0.62	1.62	0.29	0.75	0.42
	1.0	1.86	0.30	21.8	0.62	1.60	0.30	0.77	0.43
	2.0	1.85	0.29	22.2	0.64	1.57	0.31	0.79	0.43
	6.0	1.88	0.30	24.4	0.70	1.42	0.32	0.84	0.49
238-59-2, 26-29 cm	0.4	1.84	0.29	23.6	0.69	1.45	0.34	0.87	0.46
	1.0	1.83	0.29	23.7	0.69	1.44	0.34	0.88	0.46
	2.0	1.83	0.29	23.9	0.70	1.43	0.34	0.89	0.47
	6.0	1.85	0.29	24.7	0.73	1.37	0.35	0.90	0.50
238-62-2, 75-79 cm	0.4	1.80	0.28	20.8	0.60	1.68	0.31	0.80	0.39
	1.0	1.81	0.28	21.3	0.61	1.64	0.31	0.80	0.40
	2.0	1.82	0.28	21.7	0.62	1.61	0.32	0.81	0.41
	6.0	1.83	0.29	22.6	0.65	1.53	0.32	0.83	0.44
238-64-1, 129-131 cm	0.4	1.84	0.29	21.9	0.63	1.59	0.31	0.79	0.42
	1.0	1.84	0.29	22.3	0.64	1.57	0.31	0.81	0.43
	2.0	1.85	0.29	22.9	0.66	1.52	0.32	0.82	0.45
	6.0	1.86	0.30	23.7	0.68	1.46	0.32	0.84	0.47
250A-25-3, 97-101 cm	0.4	1.95	0.32	22.3	0.63	1.59	0.25	0.67	0.46
	1.0	1.96	0.32	22.7	0.64	1.56	0.26	0.68	0.47
	2.0	1.90	0.31	22.2	0.63	1.59	0.29	0.72	0.44
	6.0	1.92	0.31	23.5	0.67	1.49	0.28	0.75	0.48
253-24-1, 133-136 cm	0.4	2.17	0.37	13.6	0.30	3.30	0.09	0.25	0.24
	1.0	2.00	0.33	13.2	0.29	3.41	0.11	0.29	0.22
	2.0	1.94	0.32	13.1	0.29	3.42	0.12	0.32	0.21
	6.0	1.92	0.31	14.0	0.32	3.15	0.14	0.36	0.23
254-35-2, 47-52 cm	0.4	2.00	0.33	16.4	0.45	2.22	0.17	0.45	0.34
	1.0	2.01	0.34	17.6	0.48	2.07	0.18	0.47	0.36

TABLE 3. (continued)

Sample	Pressure (kb)	$V_p/V_s$	$\sigma$	$\phi$ (km/sec) <sup>2</sup>	K (Mb)	$\beta$ (Mb <sup>-1</sup> )	$\mu$ (Mb)	E (Mb)	$\lambda$ (Mb)
	2.0	2.02	0.34	18.9	0.52	1.93	0.19	0.50	0.39
	6.0	1.98	0.33	19.5	0.54	1.85	0.21	0.56	0.40
254-36-3, 110-114 cm	0.4	1.99	0.33	19.3	0.54	1.86	0.20	0.54	0.40
	1.0	1.98	0.33	19.7	0.55	1.82	0.21	0.56	0.41
	2.0	1.96	0.32	19.9	0.56	1.80	0.22	0.58	0.41
	6.0	1.94	0.32	20.7	0.58	1.72	0.24	0.63	0.42
256-9-2, 50-53 cm	0.4	2.03	0.34	15.3	0.41	2.47	0.15	0.39	0.31
	1.0	2.01	0.34	15.8	0.42	2.38	0.15	0.41	0.32
	2.0	1.97	0.33	16.1	0.43	2.33	0.17	0.44	0.32
	6.0	1.96	0.32	17.9	0.48	2.09	0.19	0.41	0.35
257-11-2, 57-61 cm	0.4	1.82	0.28	15.1	0.40	2.48	0.20	0.52	0.27
	1.0	1.83	0.29	16.0	0.43	2.34	0.21	0.55	0.28
	2.0	1.84	0.29	16.7	0.45	2.23	0.22	0.56	0.30
	6.0	1.86	0.30	18.5	0.50	2.01	0.23	0.61	0.34
257-15-2, 1-4 cm	0.4	2.01	0.34	23.8	0.67	1.49	0.25	0.66	0.51
	1.0	1.99	0.33	24.0	0.67	1.48	0.26	0.68	0.50
	2.0	1.98	0.33	24.1	0.68	1.47	0.26	0.70	0.50
	6.0	1.98	0.33	25.3	0.72	1.39	0.28	0.74	0.53
257-17-5, 126-129 cm	0.4	1.80	0.28	23.4	0.69	1.46	0.36	0.92	0.45
	1.0	1.81	0.28	23.8	0.70	1.43	0.36	0.93	0.46
	2.0	1.81	0.28	24.2	0.71	1.41	0.37	0.94	0.47
	6.0	1.81	0.28	25.0	0.74	1.35	0.38	0.97	0.49
260-18 cc	0.4	1.82	0.29	7.5	0.17	5.77	0.09	0.22	0.12
	1.0	1.86	0.30	8.3	0.19	5.19	0.09	0.24	0.13
	2.0	1.90	0.31	9.2	0.21	4.67	0.09	0.25	0.15
	6.0	1.97	0.33	11.7	0.27	3.64	0.11	0.28	0.20

## Velocity-Density Relationships

Because of the limited time for sea floor weathering to effect rock properties, dredge basalts from or near ridge crests are relatively high in velocity and density (e.g., Christensen, 1972a; Barrett and Aumento, 1970). Older basalts obtained from deep sea drilling, however, show wide ranges in density and velocities which correlate with age (Christensen and Salisbury, 1972, 1973). Combined Pacific and Atlantic data give rates of decreasing velocity of 1.89 and 1:35 km/sec per 100 my for  $V_p$  and  $V_s$ , respectively.

The vertical extent of weathering in oceanic crust is still an important unknown, which is likely controlled by the depth and continuity of fractures and the downward diffusion of sea water through these fractures and grain boundary cracks. For Sites 259 and 261 of Leg 27 it appears that weathering extends downward from the sediment-basalt interface to at least 50 meters (Christensen *et al.*, 1974b). Data of Hyndman (1974) for Site 257 of Leg 26 suggest a similar depth. Older sites most likely are weathered to greater depths.

As expected from the wide range in age of basalt samples recovered

TABLE 4. Comparisons of Compressional Wave Velocities of Indian Ocean Basalts with Previously Reported Velocities

Sample	Density (g/cm <sup>3</sup> )	Velocities (km/sec) at Varying Pressure (kbar)			Reference
		0.5	1.0	2.0	
251-A-31-2 (85 cm)	2.79	5.51	5.59	5.69	Table 2
251-A-31-2 (84 cm)	2.84	5.61	5.68	5.76	Hyndman (1974)
254-36-3 (112 cm)	2.79	5.41	5.46	5.52	Table 2
254-36-3 (105 cm)	2.82	5.36	5.48	5.55	Hyndman (1974)
257-11-2 (59 cm)	2.67	5.06	5.16	5.27	Table 2
257-11-2 (74 cm)	2.74	5.21	5.31	5.38	Hyndman (1974)
257-15-2 (2 cm)	2.81	5.97	6.01	6.05	Table 2
257-15-1 (133 cm)	2.89	6.13	6.22	6.31	Hyndman (1974)
231-64-1 (62 cm)	2.78	5.58	5.62	5.65	Table 2
231-64-1A	2.76	4.76	5.04	5.17	Schreiber et al. (1974)
231-64-1B	2.72	4.53	4.66	4.84	Schreiber et al. (1974)
238-55-2 (12 cm)	2.86	5.94	5.98	6.05	Table 2
238-55-2A	2.81	5.32	5.41	5.54	Schreiber et al. (1974)
238-59-2 (28 cm)	2.92	6.24	6.27	6.29	Table 2
238-59-2A	2.90	5.76	6.00	6.04	Schreiber et al. (1974)

from the Indian Ocean, densities and velocities vary significantly (Figure 2). For comparisons with the Indian Ocean DSDP velocities, mean velocities of the dredge samples of Table 5 and Atlantic and Pacific Ocean DSDP data are included in Figure 2. Only velocities from water saturated samples have been included. The linear and nonlinear solutions are least-squares regression lines for 77 water saturated DSDP basalts with the following parameters (Christensen and Salisbury, 1975):

$$\begin{aligned} V_p &= 3.56\rho - 4.26 \\ V_p &= 2.33 + 0.081\rho^{3.63} \\ V_s &= 2.17\rho - 3.07 \\ V_s &= 1.33 + 0.011\rho^{4.85} \end{aligned}$$

Figure 2 illustrates several important differences in velocities for the various rock types. In particular, andesite, serpentinite and metagabbro have higher compressional wave velocities than ocean floor basalts having similar densities. Serpentinite and andesite have lower mean atomic weights and thus the observed higher velocities are in agreement with predictions based on chemistry (Birch, 1961). The metagabbro, on the other hand, is probably similar in chemistry to the fresh basalts and its relatively high velocity is related to its coarser grain size and lower porosity. The differences in shear velocities for the DSDP basalts and the andesites, serpentinite and metagabbro are less pronounced than those observed for compressional wave velocities.

TABLE 5. Compressional (P) and Shear (S) Wave Velocities in Dredged Rocks

Sample	Bulk Density (g/cm <sup>3</sup> )	Mode	Velocity (km/sec) at Varying Pressures (kbar)							
			0.2	0.4	0.6	0.8	1.0	2.0	4.0	6.0
Basalt	2.781	P	5.77	5.95	6.09	6.20	6.22	6.37	6.51	6.56
	2.818	P	5.86	6.04	6.16	6.24	6.29	6.45	6.57	6.62
	2.813	P	5.86	6.04	6.15	6.22	6.27	6.42	6.55	6.60
	2.804	P	5.83	6.01	6.13	6.22	6.26	6.41	6.54	6.59
Basalt	2.781	S	2.96	3.09	3.21	3.28	3.32	3.45	3.52	3.61
	2.818	S	2.97	3.10	3.26	3.32	3.37	3.51	3.62	3.65
	2.813	S	2.97	3.10	3.26	3.32	3.36	3.50	3.59	3.63
	2.804	S	2.97	3.10	3.24	3.31	3.35	3.49	3.58	3.63
Serpentinite	2.686	P	5.64	5.68	5.69	5.71	5.72	5.78	5.89	5.95
	2.698	P	5.81	5.86	5.87	5.89	5.90	5.95	6.05	6.12
	2.715	P	6.03	6.07	6.09	6.11	6.13	6.19	6.28	6.35
	2.700	P	5.83	5.87	5.88	5.90	5.91	5.97	6.07	6.15
Serpentinite	2.686	S	2.57	2.58	2.59	2.60	2.60	2.64	2.68	2.69
	2.698	S	2.64	2.65	2.66	2.67	2.67	2.71	2.75	2.78
	2.715	S	2.81	2.83	2.84	2.85	2.86	2.90	2.94	2.95
	2.700	S	2.67	2.69	2.70	2.71	2.71	2.75	2.79	2.81
Metagabbro	2.926	P	6.77	6.80	6.81	6.82	6.83	6.87	6.91	6.95
	2.921	P	6.74	6.76	6.78	6.80	6.82	6.86	6.92	6.98
	2.882	P	6.54	6.59	6.62	6.64	6.66	6.73	6.82	6.90
	2.910	P	6.68	6.72	6.74	6.75	6.77	6.82	6.88	6.94
Metagabbro	2.926	S	3.59	3.61	3.62	3.64	3.64	3.69	3.75	3.78
	2.921	S	3.64	3.66	3.67	3.69	3.69	3.74	3.79	3.81
	2.882	S	3.57	3.60	3.63	3.65	3.67	3.73	3.78	3.80
	2.910	S	3.60	3.62	3.64	3.66	3.67	3.72	3.77	3.80

TABLE 6. Elastic Constants

Sample	Pressure (kb)	$V_p/V_s$	$\sigma$	$\phi$ (km/sec) <sup>2</sup>	K (Mb)	$\beta$ (Mb)	$\mu$ (Mb)	E (Mb)	$\lambda$ (Mb)
Basalt	0.4	1.94	0.32	23.3	0.65	1.52	0.27	0.71	0.47
	1.0	1.87	0.30	24.2	0.68	1.47	0.32	0.82	0.47
	2.0	1.84	0.29	24.9	0.70	1.43	0.34	0.88	0.47
	6.0	1.82	0.28	25.7	0.73	1.37	0.37	0.95	0.48
	10.0	1.82	0.28	25.9	0.74	1.36	0.37	0.96	0.49
Serpentinite	0.4	2.18	0.37	24.8	0.67	1.48	0.20	0.54	0.54
	1.0	2.18	0.37	25.1	0.68	1.46	0.20	0.55	0.55
	2.0	2.17	0.37	25.6	0.70	1.44	0.21	0.56	0.56
	6.0	2.19	0.37	27.2	0.74	1.35	0.21	0.59	0.60
	10.0	2.22	0.37	28.6	0.79	1.27	0.22	0.60	0.64
Metagabbro	0.4	1.86	0.30	27.7	0.81	1.24	0.38	0.99	0.55
	1.0	1.84	0.29	27.8	0.81	1.23	0.39	1.01	0.55
	2.0	1.83	0.29	28.0	0.81	1.22	0.40	1.04	0.55
	6.0	1.83	0.29	28.8	0.84	1.18	0.42	1.08	0.56
	10.0	1.83	0.29	29.3	0.86	1.16	0.43	1.10	0.58

Since  $V_s$  is inherently more difficult to measure than  $V_p$ , any relationship between the two velocities is useful in estimating  $V_s$  once  $V_p$  has been measured. In Figure 3,  $V_p$  is plotted against  $V_s$  for the Indian Ocean Rocks at 0.4 kbar. A linear relationship between  $V_p$  and  $V_s$  for the basalts is apparent; the least squares solution being  $V_s = 0.59 V_p - 0.32$ . For this solution the correlation coefficient is 0.98 and the standard error of estimate of  $V_s$  from  $V_p$  is 0.10 km/sec. Also of importance is the anomalous nature of serpentinite, whereas the andesites and metagabbro velocities fall close to the least squares solution. The high ratios of  $V_p$  to  $V_s$  for serpentinite also have been observed for serpentinites dredged from the Mid-Atlantic Ridge and have been used as an argument against models with abundant serpentinite in the lower oceanic crust (Christensen, 1972b).

Since the velocities are related to density, many elastic constants should also vary systematically with density, the trends being related to the degree of sea floor weathering. This is shown in Figure 4 where elastic constants at 0.4 kbar decrease markedly with decreasing density. The elastic constants of the dredged rocks and andesites are also shown in Figure 4 for comparison with the DSDP basalts. Of significance are the observations that (1)  $\mu$  and E of the andesites and dredged rocks agree well with DSDP basalts of similar density and (2)  $\lambda$  and K of andesite and serpentinite are much higher than basalts of equivalent density.

#### Layer 2 Seismic Refraction Velocities

Locations of Indian Ocean refraction survey sites and DSDP sites are shown in Figure 5. Drilling sites for which basalt velocities have been measured (Tables 1 and 2) are indicated by solid circles. Seismic refraction locations are labeled S-1 through S-64. Water depths, sediment thicknesses, basement velocities, and basement thicknesses are summarized in Table 7. Lower crustal velocities and thicknesses and

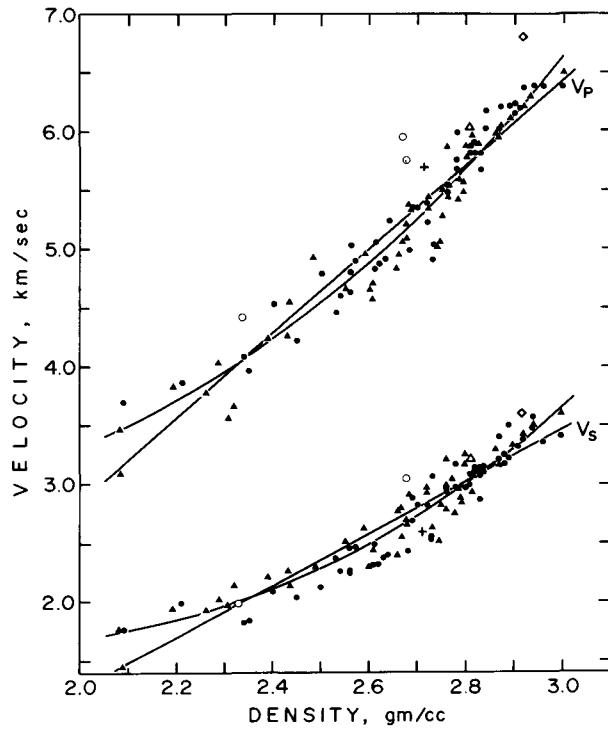


Fig. 2. Velocity-density relations at 0.5 kbar for Indian Ocean DSDP basalts (solid triangles), other DSDP basalts (dots), Indian Ocean andesite (circles), serpentinite (plus), dredge basalt (open triangle) and metagabbro (diamond).

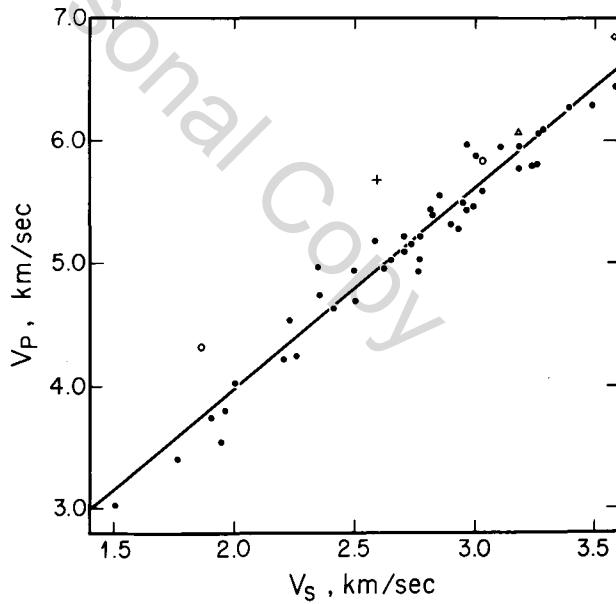


Fig. 3. The relationship between  $V_p$  and  $V_s$  for Indian Ocean DSDP basalts (dots), andesites (circles), serpentinite (plus), dredge basalt (triangle) and metagabbro (diamond).

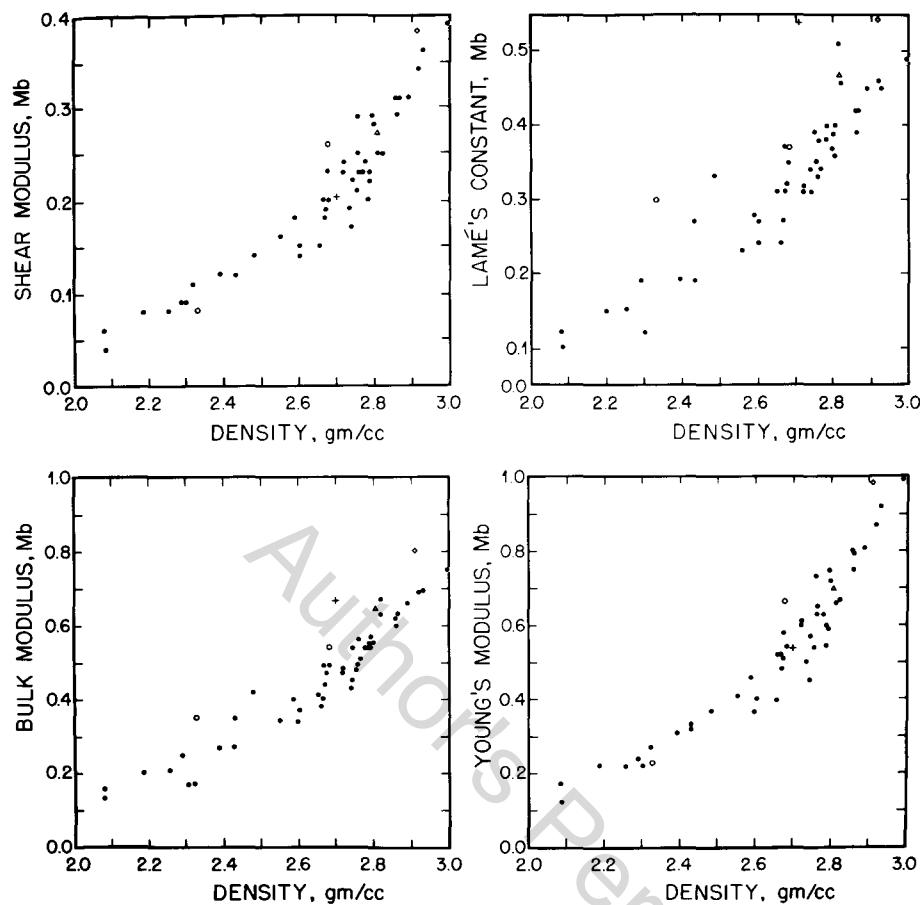


Fig. 4. Elastic constants at 0.5 kbar versus density for Indian Ocean DSDP basalts (dots), andesites (circles), serpentinite (plus), dredge basalt (triangle) and metagabbro (diamond).

upper mantle velocities, when reported, can be found in the references of Table 7.

The proximities of several seismic refraction surveys to sites in which velocities have been measured for basement rocks allow comparisons of laboratory velocities with refraction velocities (e.g., Schreiber *et al.*, 1974; Christensen *et al.*, 1972b). Such comparisons, however, are complicated by many factors. Of critical importance is the influence of fractures which, if abundant in the upper oceanic crust, are expected to reduce velocities. Laboratory measurements are usually from specimens which have been selected to be as free of fractures as possible. Also significant is the depth of weathering, as has been illustrated by the studies of velocities from Site 257 (Hyndman, 1974) and Sites 259 and 261 (Christensen *et al.*, 1974b). For these sites weathering decreases with depth producing velocity gradients within the upper portion of basalt.

Weathering has been found to lower velocities and densities of layer 2 basalts. Of particular significance, it has been demonstrated that weathering increases with age such that compressional wave velocities of basalts from the uppermost portion of layer 2 decrease approximately

TABLE 7. Indian Ocean Seismic Refraction Measurements

Station Number	Water Depth (km)	Sediment Thickness (km)	Basement Velocity (km/sec)	Basement Thickness (km)	Reference
S-1*	1.18*	0.22*	4.28*	--	Tramontini & Davies (1969)
S-2	0.71	0.47	3.98	2.03	Laughton & Tramontini (1969)
S-3	1.39	1.16	4.33	2.88	"
S-4	1.10	0.42	3.99	1.71	"
S-5	1.98	0.53	3.94	1.83	"
S-6	1.4	1.23	4.25	1.71	"
S-7	2.17	0.41	5.22	2.81	"
S-8	2.4	0.34	4.07	2.00	"
S-9	2.24	1.14	4.60	1.59	"
S-10	1.61	1.52	5.30	1.51	"
S-11	2.22	0.65	4.81	1.82	"
S-12	2.33	0.39	4.11	1.11	"
S-13	1.98	1.87	5.0	2.9	Francis & Shor (1966)
S-14	2.84	1.04	6.13	4.4	"
S-15	0.06	1.13	6.22	?	Francis & Pollard (1963)
S-16	3.23	0.67	4.48	1.4	Francis & Shor (1966)
S-17	3.97	0.45	5.41	1.9	"
S-18	4.04	0.66	5.79	2.2	"
S-19	4.27	0.15	5.02	2.4	"
S-20	4.31	0.78	5.0(?)	?	"
S-21	3.86	0.65	6.31	3.6	"
S-22	0.91	1.42	4.76	4.2	"
S-23	4.84	0.23	5.0	0.11	"
S-24	3.95	0.60	5.37	2.10	"
S-25	3.15	0.35	5.48	2.8	"
S-26	2.66	0.51	5.5	2.5	"
S-27	0.12	1.31	4.55	?	Shor & Pollard (1963)
S-28	0.12	1.25	4.36	?	"
S-29	2.71	0.71	4.67	2.2	Francis & Raitt (1967)
S-30	5.73	0.15	4.80	0.6	"
S-31	5.00	0.21	5.38	1.4	Francis & Raitt (1967)
S-32	5.22	0.08	5.09	1.2	"
S-33	5.95	0.13	5.37	1.7	"

TABLE 7. (continued)

Station Number	Water Depth (km)	Sediment Thickness (km)	Basement Velocity (km/sec)	Basement Thickness (km)	Reference
S-34	5.59	0.27	5.38	1.3	"
S-35	5.68	0.49	5.18	2.4	"
S-36	5.67	0.56	4.89	0.8	"
S-37	5.74	0.14	4.78	1.4	"
S-38	5.10	0.07	4.86	2.4	"
S-39	5.35	0.35	4.98	1.3	"
S-40	5.35	0.60	4.66	1.1	"
S-41	5.57	0.47	5.98	1.2	"
S-42	5.00	0.40	5.0	0.9	"
S-43	2.21	0.60	4.70	2.0	"
S-44	1.97	0.68	4.80	2.1	Francis & Rairr (1967)
S-45	4.83	0.55	6.57	1.6	"
S-46	3.75	0.32	4.57	0.5	"
S-47	1.90	0.37	4.52	1.5	"
S-48	3.20	0.33	4.43	1.2	"
S-49	4.04	0.26	5.03	0.9	"
S-50	4.99	0.12	5.46	1.7	"
S-51	4.82	0.18	5.62	1.4	"
S-52	4.79	0.22	5.78	1.2	"
S-53	4.33	0.31	6.24	1.8	"
S-54	5.49	0.21	5.48	1.2	"
S-55	4.91	0.11	5.00	0.7	"
S-56	5.03	0.48	5.02	2.11	Ludwig et al. (1968)
S-57	3.60	3.5	5.28	3.1	Francis et al. (1966)
S-58	4.17	3.7	6.56	4.6	"
S-59	4.81	1.7	5.28	2.5	"
S-60	5.04	0.7	4.20	3.0	"
S-61	5.06	0.3	6.24	3.1	"
S-62	4.38	0.3	4.86	1.8	"
S-63	0.05	0.3	5.72	3.3	"
S-64	3.91	0.81	5.4	0.65	Francis & Shor (1966)

\* Average of 10 closely spaced stations.

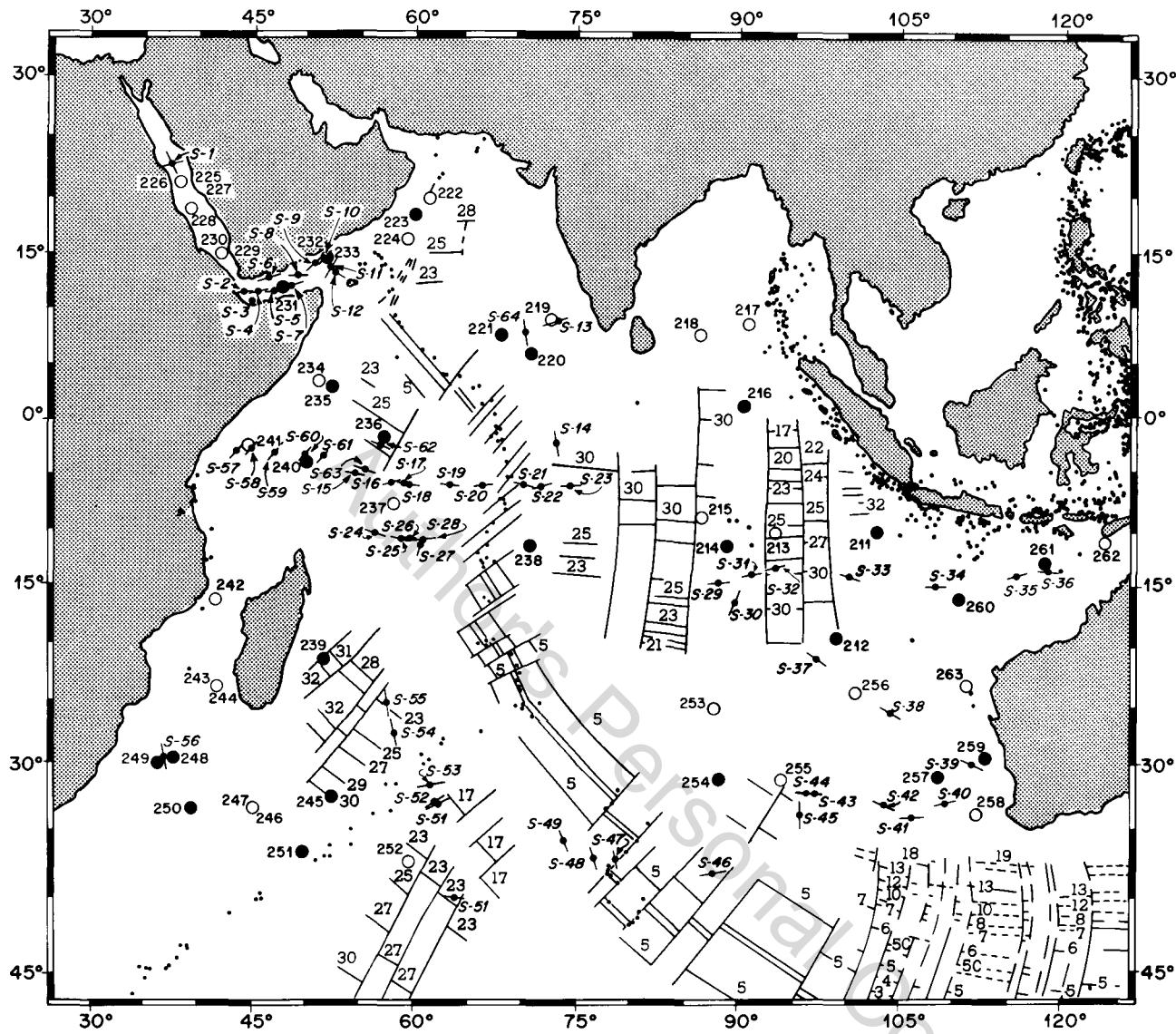


Fig. 5. Locations of seismic refraction surveys (S-1 through S-64) and DSDP sites. Lines through the refraction sites indicate azimuth of profile. Magnetic anomalies are after the tabulation of Pitman et al. (1974).

1.9 km/sec per 100 my (Christensen and Salisbury, 1972, 1973). Fractures, on the other hand, are likely to be abundant in relatively young crust. Examination of DSDP cores shows that fractures in older basalts are often filled with secondary minerals such as carbonates. At greater depths within layer 2 metamorphism is likely to play an important role in healing fractures created at ridge crests. Thus the influence of fractures on layer 2 velocities will also be age dependent, but velocities will increase with age because of fracture closure.

A difficulty encountered in comparing refraction and laboratory velocities of layer 2 is related to the techniques commonly used in refraction

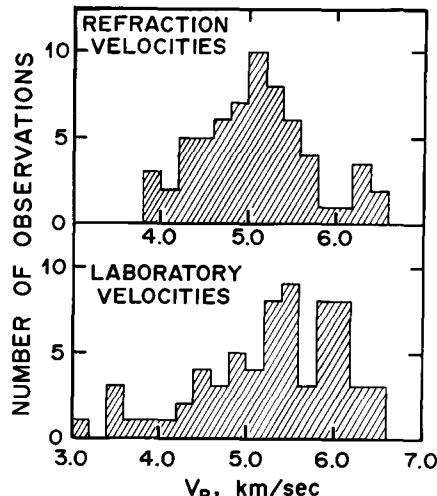


Fig. 6. Histograms of measured seismic velocities at 0.4 kbar for Indian Ocean basalts and Indian Ocean layer 2 seismic refraction velocities.

profiling. Since most seismic experiments within the Indian Ocean have been designed to investigate lower crustal and upper mantle structure as well as layer 2 velocities and thicknesses, a limited number of arrivals are usually recorded from layer 2. Thus the reported seismic velocities are low in accuracy (Raitt, 1963) and fine structure such as subdivisions of layer 2 which have been found in the Atlantic Ocean from sonobuoy studies (Talwani *et al.*, 1971), often can be missed.

The new data in Table 2 allow several additional comparisons of refraction and laboratory velocities. However, as discussed above, these comparisons must be viewed with caution. The velocities of basalts from Sites 231, 236, 240 and 248 are higher than basement velocities reported in the vicinities of these sites (see Figure 5 and Table 7). It is concluded that cracks and/or sediments interlayered within the basalts significantly lower basement velocities in these regions. The laboratory velocities for Site 260, on the other hand, are much slower than the 5.38 km/sec basement refraction velocity reported at S-34. It appears that the velocity structure at this site is similar to Sites 259 and 261, in which thin layers of highly weathered basalt form the top of layer 2 (Christensen *et al.*, 1974b).

Good agreement exists between the basement refraction velocity at S-33 (5.37 km/sec) and the laboratory velocities for basalt from Site 211 (5.21 km/sec at 0.4 kbar). Also the basement velocity of 5.4 km/sec at S-64 is similar to the 5.53 km/sec velocity for the basalt from Site 221.

The variability in layer 2 has been emphasized in summaries of oceanic crustal refraction data (Raitt, 1963; Shor *et al.*, 1971; Christensen and Salisbury, 1975) and is illustrated for the Indian Ocean in Figure 6, where the 64 layer 2 seismic refraction velocities for sites located in Figure 5 and tabulated in Table 7 are shown in histogram form. Also illustrated in Figure 6 are 67 laboratory measured velocities of water saturated Indian Ocean basalt at 0.4 kbar. Note that the maximum basalt velocities agree well with maximum layer 2 velocities. Layer 2 seismic refraction velocities lower than those included in the histogram of Figure 6 may very well be present in the Indian Ocean. These could either be confused with sediment velocities or be masked by overlying higher velocity sediments (Christensen *et al.*, 1973). Thus the ranges of refraction and laboratory velocities could be in even closer agreement than that illustrated in Figure 6. The histogram of refraction velocities is fairly symmetric, whereas the laboratory velocities are

skewed toward the higher velocities. The latter may simply result from a biased selection of young relatively unweathered samples for the measurements, or it may be that the symmetrical shape of the refraction velocity histogram is influenced by fracturing in layer 2.

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#### References

- Barrett, D. L., and F. Aumento, The Mid-Atlantic Ridge near 45°N. XI. Seismic velocity, density and layering of the crust, Can. J. Earth Sci., 7, 1117-1124, 1970.
- Birch, F., The velocity of compressional waves in rocks to 10 kb, 1, J. Geophys. Res., 65, 1083-1102, 1960.
- Birch, F., The velocity of compressional waves in rocks to 10 kb, 2, J. Geophys. Res., 66, 2199-2224, 1961.
- Christensen, N. I., Compressional and shear wave velocities at pressures to 10 kilobars for basalts from the East Pacific Rise, Geophys. J. Roy. Astron. Soc., 28, 425-429, 1972a.
- Christensen, N. I., The abundance of serpentinites in the oceanic crust, J. Geol., 80, 709-719, 1972b.
- Christensen, N. I. and M. H. Salisbury, Sea floor spreading, progressive alteration of Layer 2 basalts, and associated changes in seismic velocities, Earth Planet. Sci. Lett., 15, 367-375, 1972.
- Christensen, N. I., Velocities, elastic moduli and weathering-age relations for Pacific Layer 2 basalts, Earth Planet. Sci. Lett., 19, 461-470, 1973.
- Christensen, N. I., Structure and constitution of the lower oceanic crust, Rev. Geophys. Space Phys., 13, 57-86, 1975.
- Christensen, N. I., D. M. Fountain, and R. J. Stewart, Oceanic crustal basement: a comparison of seismic properties of DSDP basalts and consolidated sediments, Mar. Geol., 15, 215-226, 1973.
- Christensen, N. I., D. M. Fountain, R. L. Carlson, and M. H. Salisbury, Velocities and elastic moduli of volcanic and sedimentary rocks recovered on DSDP Leg 25. in Simpson, E.S.W., Schlich, R., et al., Initial Reports of the Deep Sea Drilling Project, XXV, Washington (U. S. Government Printing Office), 357-360, 1974a.
- Christensen, N. I., M. H. Salisbury, D. M. Fountain, and R. L. Carlson, Velocities of compressional and shear waves in DSDP Leg 27 basalts. in Veevers, J. J., Heirtzler, J. R., et al., Initial Reports of the Deep Sea Drilling Project, XXVII, Washington (U. S. Govern. Printing Office), 445-449, 1974b.
- Dortman, N. B., and H. Sh., Magid, Velocity of elastic waves in crystalline rocks and its dependence on moisture content, Dokl. Akad. Nauk SSSR, Earth Sci. Sec., English Transl., 179, 1-8, 1968.
- Engel, C. G., and R. L. Fisher, Lherzolite, anorthosite, gabbro, and basalt dredged from the mid-Indian Ocean ridge, Science, 166, 1136-1141, 1969.
- Francis, T.J.G., R. W. Raith, Seismic refraction measurements in the southern Indian Ocean, J. Geophys. Res., 72, 3015-3041, 1967.
- Francis, T.J.G., and G. G. Short, Seismic refraction measurements in the northwest Indian Ocean, J. Geophys. Res., 71, 427-449, 1966.

- Francis, T.J.G., D. Davies, and M. N. Hill, Crustal structure between Kenya and the Seychelles, Roy. Soc. London Phil. Trans., Series A, 259, 240-261, 1966.
- Hyndman, R. D., Seismic velocities of basalts from DSDP Leg 26, in Luyendyk, B. P. and Davies, T.A., et al., Initial Reports of the Deep Sea Drilling Project, XXVI, Washington (U. S. Govern. Printing Office), 509-512, 1974.
- Laughton, A. S., C. Tramontini, Recent studies of the crustal structure in the Gulf of Aden, Tectonophysics, 8, 359-375, 1969.
- Ludwig, W. J., J. E. Nafe, E.S.W. Simpson, and S. Sacks, Seismic-refraction measurements on the southeast African continental margin, J. Geophys. Res., 73, 3707-3719, 1968.
- Nur, A., and G. Simmons, The effect of saturation on velocity in low porosity rocks, Earth Planet. Sci. Lett., 7, 183-193, 1969.
- Pitman, W. C., R. L. Larson, and E. M. Herron, Age of the ocean basins determined from magnetic anomaly lineations. Printed by the Geol. Soc. of Amer., Inc., Boulder, Colorado, 1974.
- Raitt, R. W., The crustal rocks, in Hill, M. N. (ed.), The Sea: v. 3, New York, (Interscience), 85-102, 1963.
- Schreiber, E., M. R. Perfit, and P. J. Cernock, Compressional wave velocities in samples of basalt recovered by DSDP Leg 24, in Fisher, R. L., Bunce, E.T., et al., Initial Reports of the Deep Sea Drilling Project, XXIV, Washington (U. S. Govern. Printing Office), 787-790, 1974.
- Shor, G. G., Jr., and D. D. Pollard, Seismic investigations of Seychelles and Saya de Malha Banks, Northwest Indian Ocean, Science, 48-49, 1963.
- Shor, G. G., Jr., H. W. Menard, and R. W. Raitt, Structure of the Pacific Basin, in Maxwell, A.E. (ed.) The Sea, 4, New York (Wiley and Sons), 3-27, 1971.
- Talwani, M., C. C. Windisch, and M. G. Langseth, Jr., Reykjanes ridge crest: a detailed geophysical study, J. Geophys. Res., 76, 473-517, 1971.
- Tramontini, C. and D. Davies, A seismic refraction survey in the Red Sea, Geophys. J. R. Astron. Soc., 17, 225-241, 1969.