16. VELOCITIES OF COMPRESSIONAL AND SHEAR WAVES IN DSDP LEG 27 BASALTS

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INTRODUCTION

Two holes drilled during Leg 27 into basalt achieved significant penetrations of 38.5 meters at Site 259 and 47.5 meters at Site 261. Compressional and shear wave velocities have been measured to hydrostatic pressures of 6.0 kb for five basalt samples from Site 259 and seven basalt samples and one interlayered limestone from Site 261. The experimental technique used to obtain the velocities is similar to that described by Birch (1960), with the important exception that samples were water saturated prior to the measurements.

The purposes of this study were to: (a) investigate variations in velocities and related elastic properties of basement rocks from each site, (b) determine, if possible, if velocity gradients exist in the uppermost portion of Layer 2, (c) compare velocity-density relations of Leg 27 basalts with similar Atlantic and Pacific data, and (d) compare the laboratory-measured velocities with seismic-refraction velocities.

Samples 259-35-1, 128-131 cm and 259-36-2, 66-70 cm are altered, pale green, fractured basalts with intergranular to intersertal textures. The fractures are healed with dark green to reddish-brown vein fillings and white carbonate. Samples 259-37-2, 105-109 cm and 259-39-1, 135-138 cm (basalts) are both highly weathered, fine grained, and dark grayish-green in color. Sample 259-41-3, 53-56 cm is similar in texture to the overlying basalts, but is slightly coarser grained and highly vesicular.

Sample 261-33-1, 55-59 cm, the uppermost basalt of Site 261, contains highly altered plagioclase and pyroxene with a variolitic texture. Samples 261-33-1, 131-134 cm and 261-34-3, 69-73 cm were obtained beneath a half-meter-thick layer of recrystallized limestone (Sample 261-33-1, 67-71 cm), from a 10-meter-thick sill of relatively fresh coarse-grained basalt with a variolitic-textured groundmass containing clots of larger plagioclase and pyroxene crystals. Sample 261-35-3, 84-87 cm (basalt) is a medium-grained, highly altered rock with a variolitic texture. This sample may represent the lower portion of the sill, or, perhaps it is part of an underlying flow which has been altered by the intrusion. The lowest three samples studied (261-37-2, 92-95 cm; 261-38-2, 23-26 cm; and 261-38-5, 94-97 cm) are all extremely fine-grained basalts with felty-textured groundmasses. Alteration appears to decrease with depth in these three samples.

DATA

Bulk densities, obtained from the weights and dimensions of cylindrical samples, and compressional and shear-wave velocities are given in Table 1. Velocities were measured in only one core from each sample, since previous velocity studies (Christensen and Salisbury, 1972; 1973) have demonstrated low anisotrophy in other basalts from the DSDP samples, and petrographic examination of thin sections cut from the Leg 27 samples showed no evidence of strong preferred mineral orientation. For all samples included in the present study, wave propagation directions were parallel to the hole axes.

The samples were water saturated and 100-mesh screens were placed between the samples and copper jackets to obtain minimal pore pressures during the runs. Several studies (e.g., Dortman and Magid, 1968; Nur and Simmons, 1969; and Christensen, 1970; 1973) have shown significant increases in compressional wave velocities at pressures below approximately 2 kb after water saturation. This is illustrated in Figure 1 where compressional wave velocities were obtained from the same core of basalt under saturated conditions and again after the sample had been air dried at room temperature for several days.

Ratios of compressional to shear velocities (V_p/V_s), Poisson's ratios (σ), seismic parameters (ϕ), bulk moduli (K), compressibilities (β), shear moduli (μ), Young's moduli (E), and Lame's constants (λ) calculated from the densities and velocities are given in Table 2 at selected pressures.

VELOCITY-DENSITY RELATIONSHIPS

Christensen and Salisbury (1972; 1973) have shown that compressional- and shear-wave velocities of basalts in DSDP samples show excellent correlation with bulk density. The Leg 27 basalts show a range of densities from 2.081 g/cc to 2.997 g/cc, with corresponding compressional-wave velocities of 3.47 km/sec and 6.50 km/sec, respectively. The range of shear wave velocities is from 1.78 km/sec to 3.61 km/sec. The extremely wide range of densities for these rocks results primarily from the variation in stages of weathering apparent in the samples.

In Figures 2 and 3 compressional and shear wave velocities measured at 0.5 kb are plotted against density for 12 Leg 27 basalt samples together with 45 points from the Atlantic and Pacific oceans compiled by Christensen and Salisbury (1973). While the distribution of points for Leg 27 compressional-wave data is in excellent agreement with the Atlantic and Pacific point distributions, the Leg 27 shear-wave velocities appear to be slightly higher for given densities.

Also included in Figures 2 and 3 are least-squares regression lines computed by Christensen and Salisbury (1973) on the basis of 32 Pacific data points:

$$V_p = 3.22\rho - 3.55 \text{ km/sec}$$
$$V_s = 2.15\rho - 3.04 \text{ km/sec}$$

TABLE 1
Compressional (P) and Shear (S) Wave Velocities

Sample (Interval in cm)	Bulk Density	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
259-35-1,	2.255	P	3.58	3.74	3.81	3.85	3.89	4.03	4.24	4.45
128-131	2.255	S	1.86	1.90	1.94	1.98	2.01	2.15	2.29	2.35
259-36-2,	2.081	P	3.38	3.44	3.49	3.53	3.56	3.70	3.93	4.14
66-70	2.081	S	1.68	1.76	1.80	1.84	1.88	1.97	2.06	2.10
259-37-2,	2.430	P	4.22	4.26	4.28	4.30	4.32	4.38	4.49	4.61
105-109	2.430	S	2.26	2.26	2.27	2.28	2.28	2.30	2.33	2.34
259-39-1,	2.551	P	4.60	4.64	4.67	4.70	4.72	4.81	4.96	5.11
135-138	2.551	S	2.48	2.50	2.51	2.52	2.53	2.56	2.61	2.66
259-41-3,	2.662	P	4.90	4.93	4.96	4.98	4.99	5.06	5.17	5.27
53-56	2.662	S	2.75	2.77	2.78	2.79	2.80	2.83	2.86	2.89
261-33-1,	2.587	P	4.92	4.96	4.98	5.01	5.03	5.10	5.21	5.32
55-59	2.587	S	2.61	2.62	2.63	2.63	2.64	2.66	2.69	2.72
261-33-1,	2.676	P	5.50	5.58	5.64	5.69	5.73	5.87	6.00	6.07
67-71 (Sedimentary)	2.676	S	2.85	2.89	2.92	2.94	2.96	3.02	3.07	3.10
261-33-1,	2.790	P	5.52	5.54	5.56	5.57	5.58	5.63	5.71	5.80
131-134	2.790	S	2.83	2.85	2.86	2.87	2.88	2.90	2.91	2.93
261-34-3,	2.997	P	6.48	6.49	6.51	6.52	6.55	6.59	6.65	6.68
69-73	2.997	S	3.59	3.60	3.61	3.61	3.62	3.64	3.65	3.66
261-35-3,	2.599	P	4.43	4.46	4.48	4.50	4.52	4.59	4.73	4.87
84-87	2.599	S	2.26	2.29	2.31	2.33	2.34	2.38	2.43	2.46
261-37-2,	2.722	P	5.32	5.34	5.35	5.37	5.38	5.42	5.49	5.56
92-95	2.722	S	2.91	2.92	2.93	2.93	2.93	2.95	2.96	2.97
261-38-2,	2.745	P	5.48	5.49	5.51	5.52	5.53	5.56	5.62	5.68
23-26	2.745	S	2.80	2.81	2.82	2.83	2.84	2.85	2.86	2.87
261-38-5,	2.800	P	5.75	5.76	5.78	5.79	5.80	5.83	5.89	5.96
94-97	2.800	S	3.17	3.18	3.18	3.19	3.19	3.20	3.21	3.22

While it appears from the distribution of points in either figure that a nonlinear solution may provide a better fit, it is apparent that the linear solutions will predict velocities accurate to within approximately 0.2 km/sec for densities greater that 2.3 g/cc.

VELOCITY-DEPTH RELATIONSHIPS

The relatively deep drill penetrations into Layer 2 at Sites 259 and 261 provide a unique opportunity to examine variations in seismic velocity as a function of depth and thus to measure seismic-velocity gradients in the upper levels of Layer 2 directly.

In Figure 4 the compressional- (V_p) and shear-(V_s) wave velocities of representative samples from Sites 259 and 261 are presented as a function of recovery depth in Layer 2. Neglecting the effects of a sill in the upper 10 meters in Site 261, both sites display marked velocity gradients in both V_p and V_s (Table 3). From both hand-sample and thin-section analyses, this effect can be clearly attributed to differential submarine weathering. The uppermost extrusives at either site are profoundly weathered, in keeping with their ages (120 and 150 m.y., respectively). Their low velocities are consistent with both the velocity-density relations presented in this paper and our earlier findings of a marked decrease in density and seismic velocity of basalts from DSDP samples with age and weathering (Christensen and Salisbury, 1972; 1973). With increasing depth at both sites, weathering effects become less pronounced (feldspars and interstitial pyroxenes become less altered, for example) and seismic velocities increase. Projecting the observed velocity gradients downward, it is apparent that weathering extends to at least 70 and 55 meters at Sites 259 and 261, respectively. (Beyond these depths, if possible effects of changing lithology or metamorphic grade are ignored, seismic velocities would presumably be that of fresh basalt, Vp = 6.5 km/sec and Vs = 3.5 km/sec.)

COMPARISONS WITH REFRACTION DATA

The proximity of seismic refraction surveys (Francis and Raitt, 1967) to Sites 259 and 261 afford an excellent opportunity to compare laboratory-measured compressional wave velocities of Leg 27 basalts to velocities determined for Layer 2 from refraction work in the eastern Indian Ocean. The locations of profiles run by Francis and Raitt (1967) and the locations of Sites 259 and 261 are shown in Figure 5. A Layer-2 velocity of 4.98 km/sec was reported for Profile 49. The closest agreement with the refraction data is obtained for the basalt recovered from the 37-meter basalt penetration depth (Figure 4). Two profiles were determined by Francis and Raitt (1967) near Site 261, but a refracted Layer-2 arrival was not reported for the closest profile

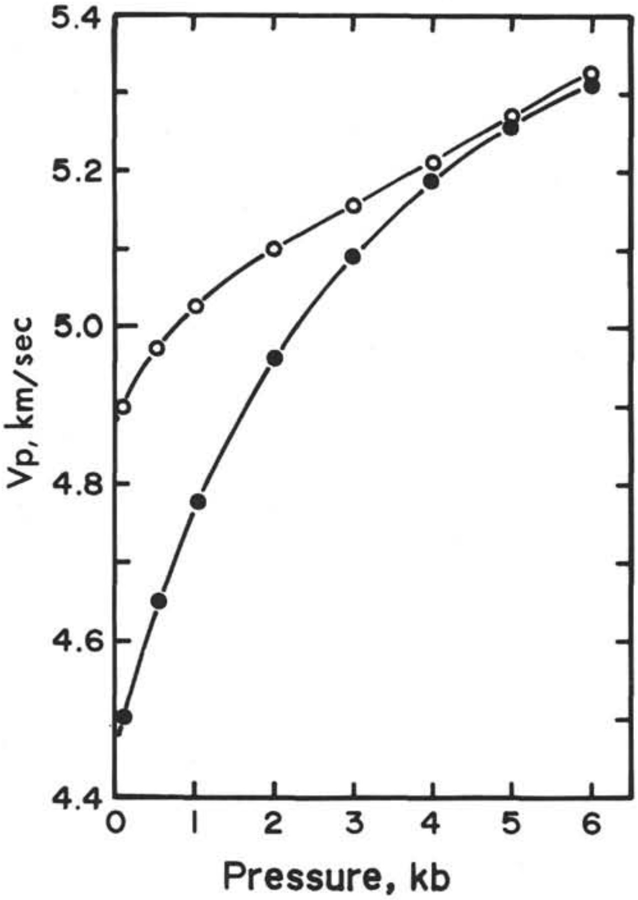

Figure 1. *Velocities for Sample 261-33-1, 55-59 cm (basalt), water saturated (open circles) and air dry (solid circles).*

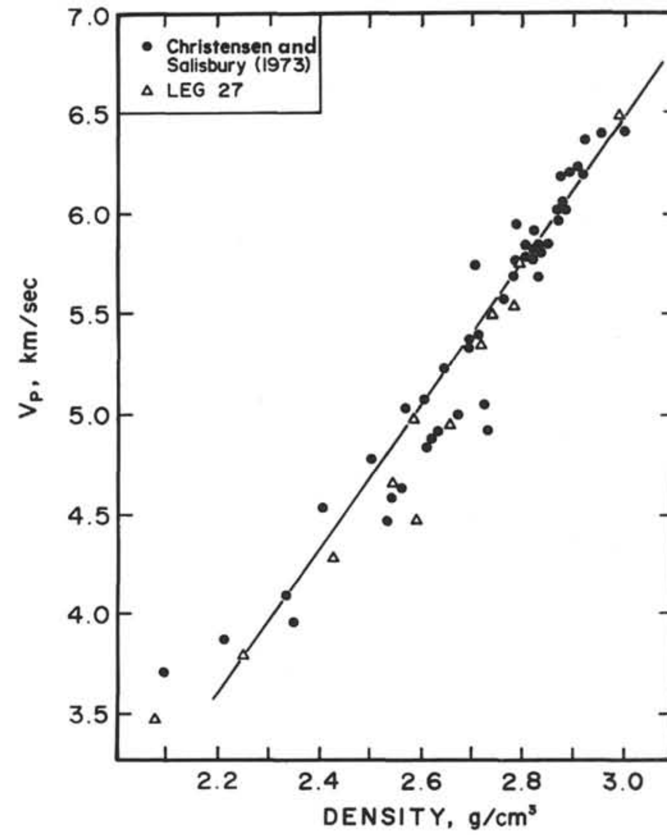

Figure 2. *Compressional wave velocities versus densities at 0.5 kb.*

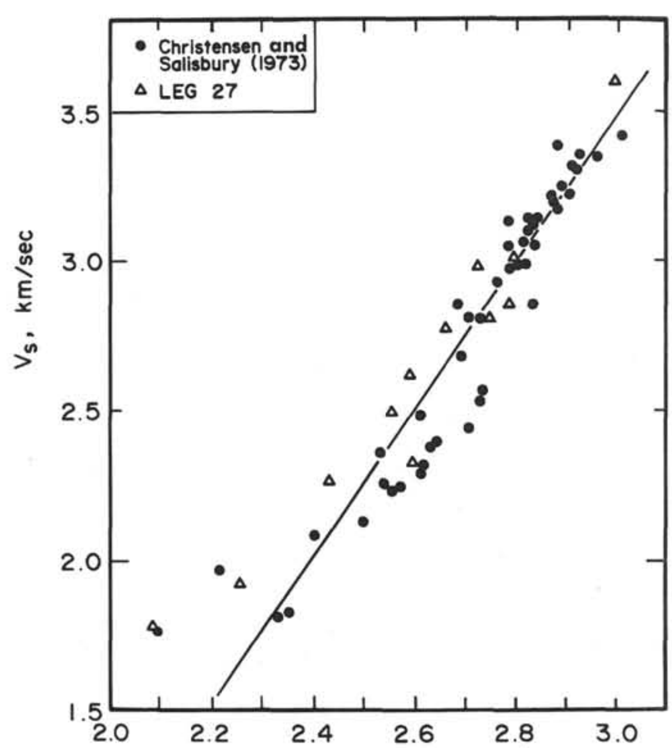

Figure 3. *Shear wave velocities versus densities at 0.5 kb.*

and the assumed velocity is not presented here. The compressional wave velocity reported for Refraction Station 58 is 5.18 km/sec, which compares most favorably with the basalt from a penetration depth of about 32 meters (Figure 4).

The refraction velocities noted above are higher than the velocities measured in the uppermost extrusive samples recovered from Layer 2 at each site (the effects of a thin sill at Site 261 may be neglected). The measured refraction velocities are lower, however, than those predicted from the velocity gradients of Figure 4 for greater depths. It is thus apparent that the refraction arrivals reported for these sites sampled intermediate levels producing an effective velocity similar to that measured directly in samples recovered 30 to 40 meters below the surface of Layer 2.

ACKNOWLEDGEMENTS

We wish to thank Robert McConaghy for his help in operating and maintaining the high-pressure system. This investigation was supported by National Science Foundation grant GA-36138 and the Office of Naval Research Contract N-00014-67-A-0103-0014.

TABLE 2
Elastic Constants, Leg 27

Sample (Interval in cm)	Pressure (kb)	Vp/Vs	σ	ϕ $(km/sec)^2$	K (Mb)	β (Mb^{-1})	μ (Mb)	E (Mb)	λ (Mb)
259-35-1, 128-131	0.4	1.97	0.33	9.15	0.21	4.84	0.08	0.22	0.15
	1.0	1.93	0.32	9.73	0.22	4.54	0.09	0.24	0.16
	2.0	1.87	0.30	10.01	0.23	4.39	0.10	0.27	0.16
	6.0	1.90	0.31	12.32	0.28	3.52	0.12	0.33	0.20
259-36-2, 66-70	0.4	1.96	0.32	7.72	0.16	6.21	0.06	0.17	0.12
	1.0	1.90	0.31	7.96	0.17	6.00	0.07	0.19	0.12
	2.0	1.87	0.30	8.39	0.18	5.66	0.08	0.21	0.12
	6.0	1.97	0.33	11.09	0.24	4.22	0.09	0.25	0.18
259-37-2, 105-109	0.4	1.88	0.30	11.27	0.27	3.64	0.12	0.32	0.19
	1.0	1.89	0.31	11.69	0.29	3.51	0.13	0.33	0.20
	2.0	1.90	0.31	12.03	0.29	3.40	0.13	0.34	0.21
	6.0	1.97	0.33	13.80	0.34	2.93	0.13	0.35	0.25
259-39-1, 135-138	0.4	1.86	0.30	13.19	0.34	2.97	0.16	0.41	0.23
	1.0	1.86	0.30	13.71	0.35	2.85	0.16	0.42	0.24
	2.0	1.88	0.30	14.32	0.37	2.72	0.17	0.44	0.26
	6.0	1.92	0.32	16.59	0.43	2.33	0.18	0.48	0.31
259-41-3, 53-56	0.4	1.78	0.27	14.11	0.38	2.66	0.20	0.52	0.24
	1.0	1.78	0.27	14.44	0.39	2.59	0.21	0.53	0.25
	2.0	1.79	0.27	14.83	0.40	2.52	0.21	0.54	0.25
	6.0	1.82	0.29	16.49	0.44	2.25	0.22	0.57	0.30
261-33-1, 55-59	0.4	1.89	0.31	15.42	0.40	2.50	0.18	0.46	0.28
	1.0	1.91	0.31	15.96	0.41	2.42	0.18	0.47	0.29
	2.0	1.92	0.31	16.52	0.43	2.33	0.18	0.48	0.31
	6.0	1.96	0.32	18.33	0.48	2.08	0.19	0.51	0.35
261-33-1, 67-71 (Sedimentary)	0.4	1.93	0.32	19.93	0.53	1.87	0.22	0.59	0.38
	1.0	1.94	0.32	21.16	0.57	1.76	0.23	0.62	0.41
	2.0	1.94	0.32	22.27	0.60	1.67	0.24	0.65	0.44
	6.0	1.96	0.32	23.94	0.65	1.55	0.26	0.68	0.48
261-33-1, 131-134	0.4	1.94	0.32	19.87	0.55	1.80	0.23	0.60	0.40
	1.0	1.94	0.32	20.14	0.56	1.78	0.23	0.61	0.41
	2.0	1.94	0.32	20.47	0.57	1.74	0.23	0.62	0.42
	6.0	1.98	0.33	22.00	0.62	1.61	0.24	0.64	0.46
261-34-3, 69-73	0.4	1.81	0.28	24.91	0.75	1.34	0.39	0.99	0.49
	1.0	1.81	0.28	25.34	0.76	1.32	0.39	1.01	0.50
	2.0	1.81	0.28	25.73	0.77	1.29	0.40	1.02	0.51
	6.0	1.82	0.28	26.52	0.80	1.25	0.40	1.04	0.53
261-35-3, 84-87	0.4	1.95	0.32	12.88	0.34	2.98	0.14	0.36	0.24
	1.0	1.93	0.32	13.07	0.34	2.93	0.14	0.37	0.25
	2.0	1.93	0.32	13.42	0.35	2.85	0.15	0.39	0.25
	6.0	1.98	0.33	15.53	0.41	2.44	0.16	0.42	0.30
261-37-2, 92-95	0.4	1.83	0.29	17.17	0.47	2.14	0.23	0.60	0.31
	1.0	1.83	0.29	17.44	0.48	2.11	0.23	0.60	0.32
	2.0	1.84	0.29	17.71	0.48	2.07	0.24	0.61	0.33
	6.0	1.87	0.30	19.04	0.52	1.91	0.24	0.63	0.36
261-38-2, 23-26	0.4	1.95	0.32	19.64	0.54	1.85	0.22	0.57	0.39
	1.0	1.95	0.32	19.82	0.55	1.83	0.22	0.58	0.40
	2.0	1.95	0.32	20.08	0.55	1.81	0.22	0.59	0.40
	6.0	1.98	0.33	21.18	0.59	1.70	0.23	0.60	0.44
261-38-5, 94-97	0.4	1.81	0.28	19.73	0.55	1.81	0.28	0.72	0.36
	1.0	1.82	0.28	19.99	0.56	1.78	0.29	0.73	0.37
	2.0	1.82	0.28	20.24	0.57	1.76	0.29	0.74	0.38
	6.0	1.85	0.29	21.53	0.61	1.64	0.29	0.75	0.41

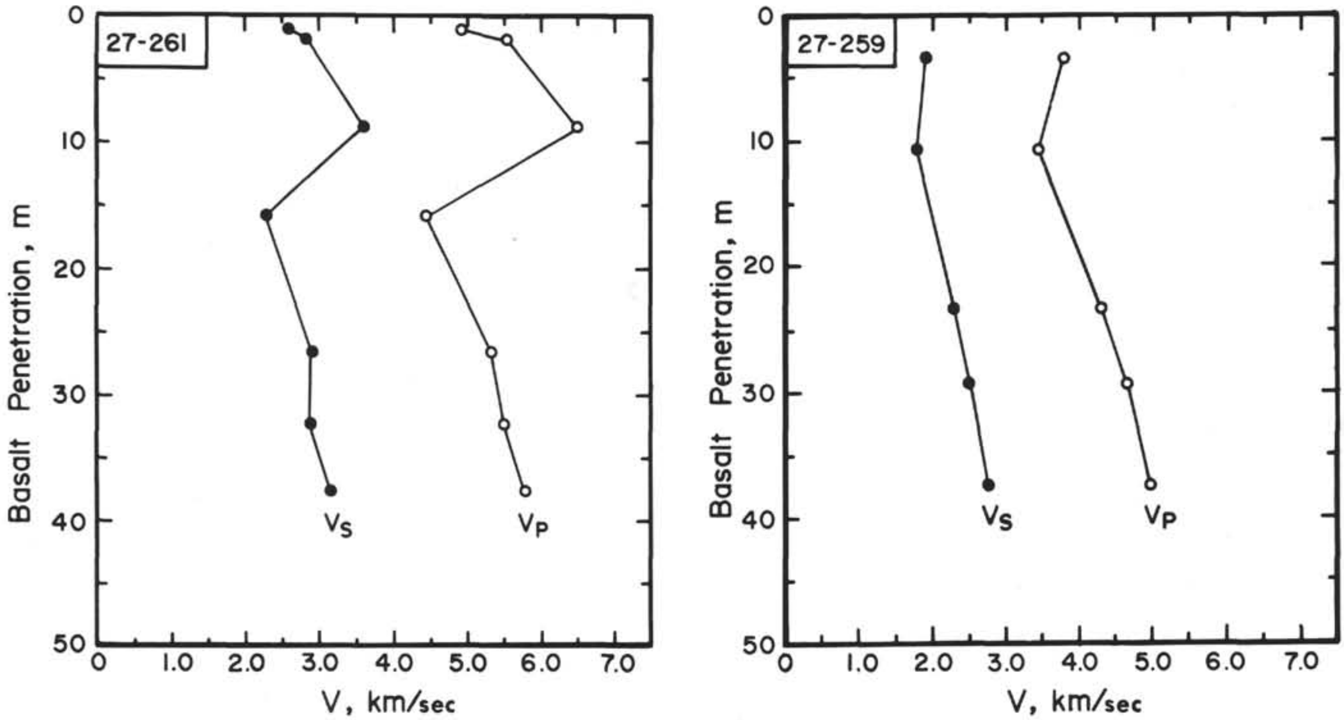

Figure 4. *Compressional and shear wave velocities at 0.5 kb versus recovery depth in Layer 2.*

TABLE 3
Compressional and Shear Wave Velocity Gradients

	$\partial V_p/\partial_z$ $\frac{(km/sec)}{m}$	$\partial V_s/\partial_z$ $\frac{(km/sec)}{m}$
Site 259	0.041	0.028
Site 261[a]	0.038	0.022

[a]Compiled from deepest three samples below sill.

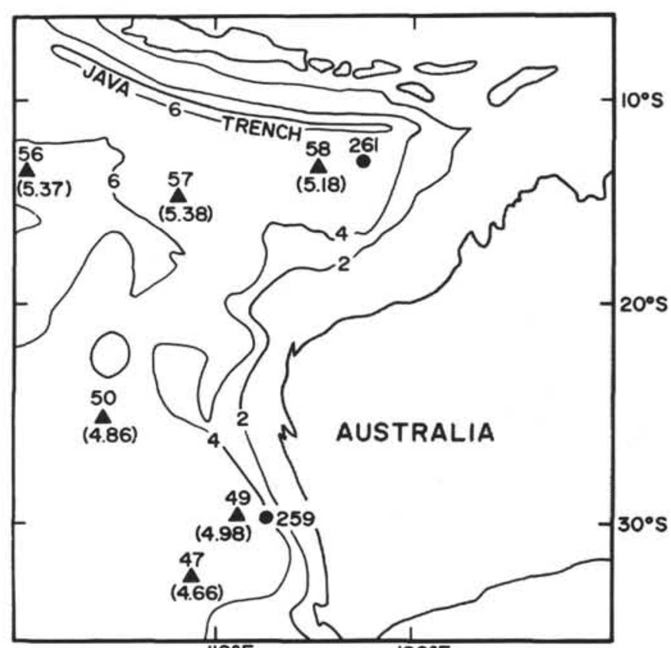

Figure 5. *Layer 2 seismic refraction velocities (km/sec) in the vicinity of DSDP Leg 27 Sites 259 and 261.*

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