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OCEANIC CRUSTAL BASEMENT: A COMPARISON OF SEISMIC PROPERTIES OF D.S.D.P. BASALTS AND CONSOLIDATED SEDIMENTS

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ABSTRACT

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Compressional (V_P) and shear (V_s) wave velocities have been measured to 1.0 kbar for 14 cores of well-consolidated sedimentary rock from Atlantic and Pacific sites of the Deep Sea Drilling Project. The range of V_P (2.05–5.38 km/sec at 0.5 kbar) shows significant overlap with the range of oceanic layer-2 seismic velocities determined by marine refraction surveys, suggesting that sedimentary rocks may, in some regions, constitute the upper portion of layer 2. Differing linear relationships between V_P and V_s for basalts and sedimentary rocks, however, may provide a method of resolving layer-2 composition. This is illustrated for a refraction survey site on the flank of the Mid-Atlantic Ridge where layer-2 velocities agree with basalt, and two sites on the Saya de Malha Bank in the Indian Ocean where layer-2 velocities appear to represent sedimentary rock.

INTRODUCTION

The structure of the oceanic crust has been defined in terms of layers of varying thickness with fairly well-defined seismic velocities. The uppermost layer (layer 1) has been shown by dredging, piston coring, and more recently by deep-sea drilling to consist primarily of sedimentary material often unconsolidated or semiconsolidated. The boundary between layer 1 and the underlying layer 2 or oceanic basement is usually assumed to represent an abrupt transition from sediment to oceanic basalt. Deep-sea drilling has, in fact, established this to be the case in several regions.

Early papers speculating on the nature of the oceanic crust (e.g., Hamilton, 1959) suggested the layer-1 and -2 boundary may represent a transition from semi-consolidated sediments to consolidated sedimentary rocks. Since the boundary between layer 1 and 2 is defined in terms of seismic velocities, it is possible that in some localities the uppermost portions of layer 2 consist of sedimentary rocks which possess velocities high enough to be interpreted by refraction data to represent layer 2. Houtz et al. (1970) have recognized this problem and have discussed possible sonobuoy techniques to identify non-basaltic basement. Some sedimentary rocks from continental areas, especially limestones (Wyllie et al., 1958) have been long known to have velocities in the range of those reported for layer 2. Many sediments on the other hand have velocities much lower than that of layer 2 (Laughton, 1957; Schreiber, 1968; Hamilton, 1970). These latter measurements have been made at atmospheric pressure and frequently the degree of water saturation was not reported.

To investigate the possibility that in some oceanic regions seismic velocities of layer 2 or basement may actually represent sedimentary rock rather than basalt, we have measured compressional and shear velocities at elevated pressure in several well-consolidated sedimentary rocks obtained from deep-sea drilling in the Atlantic and Pacific Oceans. Seismic data for layer 2 are compared with the laboratory data at appropriate pressures.

DESCRIPTION OF SAMPLES

Samples were selected which could be readily cut without breaking and also withstand hydrostatic pressures to 1 kbar. In the following description the sample numbers give the leg, site, barrel, section and interval from which the samples were selected. Additional information on locations and physical properties can be found in the Initial Reports Volume for the respective D.S.D.P. Leg. A brief site summary for each sample is presented in Table I.

The 10 rocks studied in this report include 6 limestones, 2 mudstones, 1 calcite-cemented sandstone, and 1 chert. The limestone from the distal end of Delgada Fan in the Northeast Pacific (5-34-13-2/80–90 cm) contains 5–10% radiolarian and foraminiferal tests, all of which are filled with chalcedony. In addition, many of the radiolaria are either replaced or coated with pyrite. The sample from the flank of Iwo Jima Ridge (6-53-6-1/140–150 cm) is lithified foram-bearing biomicrite, containing 1–3% phosphate and hematite and traces of feldspar. All foraminifera are recrystallized and filled with sparry calcite, and sparry calcite veins cut the rock.

The limestones from the Aleutian Abyssal Plain (19-183-35-1/60–73 cm) and the highest sample from Umnak Plateau (19-184-16-1/41–43 cm) are both calcite-cemented diatom oozes, in which all diatom tests have been replaced by calcite. In addition, the sample from Umnak Plateau contains rare (< 1%) quartz, feldspar, and phosphate grains. The second sample from Umnak Plateau (19-184-20-5/70–75 cm) is a burrowed, lithified biomicrite with up to 15% clay and silt-sized quartz and feldspar grains. The sample from Meiji Guyot in the Northwest Pacific (19-192-35-1/88–90 cm) is a lithified foram-bearing nannofossil ooze containing many calcite platelets, probably originating from dissolution and disaggregation of original nannofossil tests.

The two mudstone samples (5-40-17-cc and 19-191-13-2/42–56 cm) both show strong preferred orientation of clay platelets parallel to bedding, presumably due to diagenesis and compaction. In addition, both contain remains of radiolarian tests, now recrystallized and filled with chalcedony. Sample 5-40-17-cc also contains about 5% sponge

TABLE I
Site summary

Sample	Location	Age	Water depth (m)	Subbottom depth (m)	Lithology	Reference
2-8A-3-1/51–63 cm	N. Atlantic 35°23.0′ N 67°33.2′ W	Eocene	5169	296	radiolarian chert	Peterson et al., 1970
5-34-13-2/80–90 cm	E. Pacific 39°28.21′ N 127°16.54′ W	M. Miocene	4322	300	limestone	McManus et al., 1970
5-40-17-cc	Pacific 19°47.57′ N 139°54.08′ W	L. Eocene	5176	150	mudstone	McManus et al., 1970
6-53-6-1/140–150 cm	W. Pacific 18°02.0′ N 141°11.5′ E	E. Oligocene– E. Miocene	4629	200	limestone	Fischer et al., 1971
19-183-35-1/60–73 cm	N. Pacific 52°34.30′ N 161°12.33′ W	M.–U. Eocene	4688	388	limestone	Creager et al., 1973
19-183-35-1/130–133 cm	N. Pacific 52°34.30′ N 161°12.33′ W	M.–U. Eocene	4688	389	calcite-cemented sandstone	Creager et al., 1973
19-184-16-1/41–43 cm	Bering Sea 53°42.64′ N 170°55.39′ W	U. Miocene	1896	427	limestone	Creager et al., 1973
19-184-20-5/70–75 cm	Bering Sea 53°42.64′ N 170°55.39′W	U. Miocene	1896	544	limestone	Creager et al., 1973
19-191-13-2/42–56 cm	Kamchatka Basin 56°56.70′ N 168°10.72′ E	Pliocene?	3854	622	mudstone	Creager et al., 1973
19-192-35-1/88–90 cm	Meiji Guyot 53°00.57′ N 164°42.81′ E	Eocene	3014	933	limestone	Creager et al., 1973

TABLE II

Compressional (V_P) and shear (V_S) wave velocities in km/sec

Identification no.		Bulk density (g/cm³)	Mode	Pressure (kbar) 0.0	0.2	0.4	0.6	0.8	1.0
2-8A-3-1/51–63 cm	A	2.083	P	3.610	3.642	3.660	3.674	3.686	3.700
	B	1.946	P	3.712	3.737	3.752	3.762	3.771	3.782
	Mean	2.015	P	3.661	3.689	3.706	3.718	3.728	3.741
	A	2.083	S	2.160	2.200	2.230	2.249	2.264	2.278
	B	1.946	S	1.956	2.000	2.025	2.041	2.056	2.070
	Mean	2.015	S	2.058	2.100	2.127	2.145	2.160	2.174
5-34-13-2/80–90 cm		2.262	P	4.355	4.390	4.398	4.405	4.412	4.417
		2.262	S	2.550	2.570	2.582	2.586	2.589	2.591
50-40-17-cc		2.150	P	3.730	3.746	3.759	3.769	3.778	3.788
		2.150	S	2.184	2.188	2.192	2.195	2.198	2.200
6-53-6-1/140–150 cm		2.197	P	3.680	3.730	3.782	3.825	3.870	3.915
		2.197	S	2.200	2.226	2.248	2.270	2.287	2.305
19-183-35-1/130–133 cm	A	2.637	P	5.056	5.270	5.347	5.395	5.426	5.444
	B	2.637	P	5.010	5.159	5.220	5.253	5.272	5.285
	Mean	2.637	P	5.033	5.214	5.283	5.324	5.349	5.364
	A	2.637	S	2.735	2.777	2.810	2.850	2.869	2.890
	B	2.637	S	2.704	2.759	2.798	2.840	2.856	2.875
	Mean	2.637	S	2.719	2.768	2.804	2.845	2.862	2.882
19-183-35-1/60–73 cm		2.185	P	4.225	4.280	4.318	4.350	4.378	4.404
		2.185	S	2.128	2.145	2.164	2.187	2.206	2.220
19-184-16-1/41–43 cm	A	2.380	P	5.010	5.051	5.069	5.082	5.092	5.100
	B	2.402	P	4.875	4.940	4.978	5.000	5.010	5.018
	Mean	2.391	P	4.942	4.995	5.023	5.041	5.051	5.059
	A	2.380	S	2.739	2.750	2.757	2.762	2.765	2.767
	B	2.402	S	2.685	2.702	2.713	2.718	2.720	2.722
	Mean	2.391	S	2.712	2.726	2.735	2.740	2.742	2.744
19-184-20-5/70–75 cm	A	2.355	P	5.016	5.035	5.041	5.048	5.055	5.062
	B	2.359	P	4.960	4.975	4.986	4.995	4.998	4.999
	Mean	2.357	P	4.988	5.005	5.013	5.021	5.026	5.030
	A	2.355	S	2.708	2.743	2.752	2.757	2.760	2.762
	B	2.359	S	2.863	2.882	2.890	2.894	2.898	2.899
	Mean	2.357	S	2.785	2.812	2.821	2.825	2.829	2.830
19-191-13-2/42–56 cm		1.695	P	1.938	1.984	2.026	2.070	2.110	2.145
19-192-35-1/88–90 cm		2.130	P	2.760	2.813	2.862	2.912	2.960	2.998
		2.130	S	1.293	1.362	1.404	1.425	1.439	1.446

spicules, up to 10% radiolaria, at least one chalcedony veinlet, and iron and manganese micronodules which resemble iron- and manganese-enriched sediments recovered from other D.S.D.P. sites in the Pacific (Bostrom and Peterson, 1966; Cronan et al., 1972; Natland, 1973).

The only sandstone studied in this report is a calcite-cemented arkose from the turbidite sequence on the Aleutian Abyssal Plain (19-183-35-1/130–133 cm). Average grain size is 0.1 mm, and a visual estimate of mineral composition is 40% quartz, 30% calcite, 20% feldspar and 10% miscellaneous grains, mostly hornblende, biotite and opaque grains.

The one chert studied (2-8A-3-1/51–63 cm) is a sample from Horizon A recovered on Leg 2 from the rise between the Hatteras and Sohm Abyssal Plains. The rock consists of well-rounded, very fine sand and coarse silt-sized grains of quartz (15–25%), feldspar (5%; includes potassium feldspar), and glauconite (5%), all of which are dispersed in a framework of radiolarian tests. The rock is cemented with chalcedony and all of the radiolarian tests are filled with chalcedony. In addition, 5–10% of the rock is dispersed clay minerals, along with traces of phosphate, opaque grains and detrital micas.

DATA

Samples in the form of right circular cylinders, 1.28 cm in diameter and 2–3 cm in length, were cut for the velocity measurements. Velocities were measured by the pulse transmission technique described by Birch (1960). Barium titanate and A.C.-cut quartz transducers of 2-MHz frequencies were used to produce and receive the elastic waves. The samples were jacketed with copper foil and enclosed in rubber tubing to exclude the pressure fluid from pore spaces in the rocks. The samples were water-saturated, and during the runs pore pressures were maintained at values much less than external pressures.

To investigate possible anisotropy, velocities were measured in perpendicular directions for several samples. The results are given in Table II. Velocities measured for propagation directions perpendicular and parallel to the core axes are designated A and B, respectively. The densities in Table II are bulk densities obtained from the dimensions and weights of the samples. Elastic constants of the samples calculated from mean velocities and densities are given in Table III.

Discussion

Early investigations of elastic wave velocities in sedimentary rocks (e.g., Wyllie et al., 1958) have shown the importance of water saturation on elastic wave velocities. In general it has been found that water-saturated sedimentary rocks possess significantly higher compressional wave velocities than unsaturated rocks. Similar results were obtained by Nur and Simmons (1969) for rocks of low porosity and they caution that the degree of saturation of rocks must be considered in analyzing shallow-seismic data. Thus, to properly compare laboratory-measured velocities of oceanic sedimentary rocks

TABLE III

Elastic constants calculated from V_P, V_S, and ρ

Identification no.	Pressure (kbar)	V_P/V_S	σ	ϕ (km/sec)^2	K (Mbar)	β (Mbar^{-1})	μ (Mbar)	E (Mbar)	λ (Mbar)
2-8A-3-1/51–63 cm	0.2	1.78	0.27	7.78	0.16	6.37	0.08	0.21	0.10
	0.4	1.75	0.26	7.78	0.16	6.32	0.09	0.23	0.10
	0.6	1.74	0.25	7.79	0.16	6.35	0.09	0.23	0.10
	0.8	1.73	0.25	7.74	0.16	6.38	0.09	0.23	0.09
	1.0	1.72	0.25	7.73	0.16	6.38	0.09	0.24	0.09
5-34-13-2/80–90 cm	0.2	1.71	0.24	10.46	0.24	4.22	0.15	0.37	0.14
	0.4	1.70	0.24	10.44	0.24	4.23	0.15	0.37	0.14
	0.6	1.70	0.24	10.47	0.24	4.21	0.15	0.37	0.14
	0.8	1.70	0.24	10.50	0.24	4.19	0.15	0.37	0.14
	1.0	1.70	0.24	10.53	0.24	4.18	0.15	0.38	0.14
5-40-17-cc	0.2	1.71	0.24	7.64	0.16	6.08	0.10	0.26	0.10
	0.4	1.71	0.24	7.71	0.17	6.02	0.10	0.26	0.10
	0.6	1.72	0.24	7.76	0.17	5.97	0.10	0.26	0.10
	0.8	1.72	0.24	7.81	0.17	5.93	0.10	0.26	0.10
	1.0	1.72	0.25	7.86	0.17	5.88	0.10	0.26	0.10
6-53-6-1/140–150 cm	0.2	1.68	0.22	7.30	0.16	6.23	0.11	0.27	0.09
	0.4	1.68	0.23	7.55	0.17	6.01	0.11	0.27	0.09
	0.6	1.68	0.23	7.74	0.17	5.86	0.11	0.28	0.10
	0.8	1.69	0.23	7.98	0.18	5.68	0.11	0.28	0.10
	1.0	1.70	0.23	8.21	0.18	5.51	0.12	0.29	0.10
19-183-35-1/60–73 cm	0.2	1.99	0.33	12.18	0.27	3.75	0.10	0.27	0.20
	0.4	1.99	0.33	12.39	0.27	3.69	0.10	0.27	0.20
	0.6	1.99	0.33	12.53	0.27	3.64	0.10	0.28	0.20
	0.8	1.98	0.33	12.65	0.28	3.61	0.11	0.28	0.21
	1.0	1.98	0.33	12.79	0.28	3.56	0.11	0.29	0.21

TABLE III (*continued*)

Identification no.	Pressure (kbar)	V_P/V_S	σ	ϕ (km/sec)^2	K (Mbar)	β (Mbar^{-1})	μ (Mbar)	E (Mbar)	λ (Mbar)
19-183-35-1/130–133 cm	0.2	1.88	0.30	16.96	0.45	2.23	0.20	0.53	0.31
	0.4	1.88	0.30	17.42	0.46	2.17	0.21	0.54	0.32
	0.6	1.87	0.30	17.54	0.46	2.16	0.21	0.56	0.32
	0.8	1.87	0.30	17.67	0.47	2.14	0.22	0.56	0.32
	1.0	1.86	0.30	17.67	0.47	2.14	0.22	0.57	0.32
19-184-16-1/41–43 cm	0.2	1.83	0.29	15.04	0.36	2.78	0.18	0.46	0.24
	0.4	1.84	0.29	15.24	0.36	2.74	0.18	0.46	0.25
	0.6	1.84	0.29	15.38	0.37	2.71	0.18	0.46	0.25
	0.8	1.84	0.29	15.46	0.37	2.70	0.18	0.46	0.25
	1.0	1.84	0.29	15.53	0.37	2.69	0.18	0.46	0.25
19-184-20-5/70–75 cm	0.2	1.78	0.27	14.50	0.34	2.92	0.19	0.47	0.22
	0.4	1.78	0.27	14.51	0.34	2.92	0.19	0.48	0.22
	0.6	1.78	0.27	14.55	0.34	2.91	0.19	0.48	0.22
	0.8	1.78	0.27	14.57	0.34	2.91	0.19	0.48	0.22
	1.0	1.78	0.27	14.59	0.34	2.90	0.19	0.48	0.22
19-192-35-1/88–90 cm	0.2	2.06	0.35	5.43	0.12	8.63	0.04	0.11	0.09
	0.4	2.04	0.34	5.55	0.12	8.43	0.04	0.11	0.09
	0.6	2.04	0.34	5.75	0.12	8.12	0.04	0.12	0.09
	0.8	2.06	0.34	5.97	0.13	7.81	0.04	0.12	0.10
	1.0	2.07	0.35	6.17	0.13	7.55	0.04	0.12	0.10

with seismic refraction velocities, it is essential to saturate the rocks prior to measurement. The differences in "wet" and "dry" velocities vary considerably from rock to rock depending upon the porosity and pore geometry of the samples. A typical example showing the differences in velocities for a sample included in the present study is illustrated in Fig. 1. Velocities in the "dry" sample were obtained after the sample was air-dried at room temperature for several days. Measured elastic wave velocities for some samples, however, showed little difference between the saturated and unsaturated conditions.

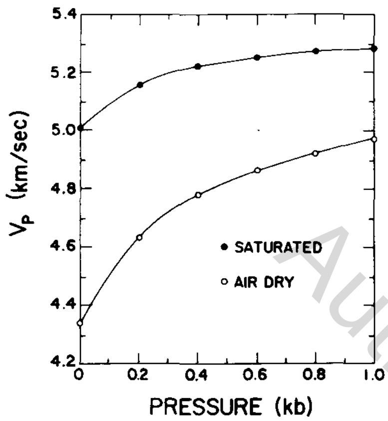

Fig.1. Compressional wave velocity (V_P) vs pressure for sample 19-183-35-1/130–133 cm A, saturated and air dry.

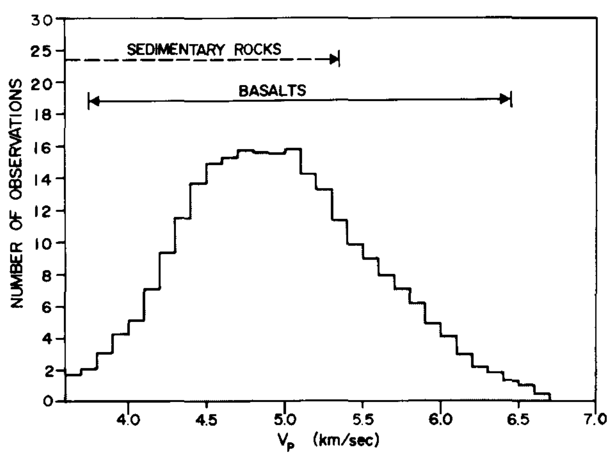

Fig.2. Compressional wave refraction histogram for layer 2 showing range of compressional wave velocities for D.S.D.P. basalts and sedimentary rocks. Data from Raitt (1956, 1963), Ewing and Ewing (1959), Le Pichon et al. (1965), Francis and Shor (1966), Francis and Raitt (1967), Murauchi et al. (1968), Shor et al. (1968, 1971), Den et al. (1969), Helmberger and Morris (1969), Ewing et al. (1971), Furumoto et al. (1971) and Keen and Barrett (1971).

In order to compare the compressional wave velocities reported here to marine refraction data, we have compiled a histogram of 252 observed velocities for layer 2 (Fig.2). For convenience of presentation this data has been statistically smoothed. Also shown in Fig.2 are the ranges of laboratory-measured compressional wave velocities, at the appropriate layer-2 pressure of 0.5 kbar, for oceanic sedimentary rocks as well as for basalts recovered by deep-sea drilling (Christensen and Salisbury, 1972, 1973). Significantly, the upper range of the sedimentary-rock velocities corresponds with velocities reported for layer 2. The large overlap of basalt and sedimentary-rock velocities is, in large part, due to low basalt velocities resulting from the progressive alteration of oceanic basalts with age observed by Christensen and Salisbury (1972). Thus, it is a distinct possibility that the uppermost portions of layer 2, in some regions, could be composed of sedimentary rocks. The potential of this occurring is perhaps greatest in regions characterized by old oceanic crust where lithified sediments and weathered basalts could have nearly equal compressional wave velocities and, thus, remain unresolved in marine refraction surveys. Results from surveys conducted in the same vicinity as Leg 19 of the Deep Sea Drilling Project (Den et al., 1969), for instance, show layer-2 velocities (4.36–5.56 km/sec) which can be interpreted as either basalts or sedimentary rocks. These results clearly indicate the ambiguities possible in determination of layer-2 composition from marine seismic refraction data. Furthermore, it may be possible that in some regions, high-velocity sedimentary rocks may overlie basalts of lower velocity, thus giving rise to a local low-velocity zone in the uppermost oceanic crust.

A possible technique for resolution of the composition of layer 2 is suggested by Fig.3, in which we have plotted compressional wave velocity versus shear wave velocity at 0.4 kbar for D.S.D.P. sedimentary rocks and basalts (Christensen and Salisbury, 1972, 1973). For each rock type a different linear relationship exists between V_P and V_s. The least-squares solution for the sedimentary rock data is given by:

$$V_P = (1.71 \pm 0.39) V_s + 0.25 \text{ km/sec}$$

with a correlation coefficient of 0.95. The linear relationship for the basalt data, however, is:

$$V_P = (1.43 \pm 0.10) V_s + 1.45 \text{ km/sec}$$

with a correlation coefficient of 0.97. Although there is little difference between the slopes of the regression lines, determinations of the 95% confidence intervals for each line show no overlap except at high compressional wave velocities (greater than 6 km/sec). The least-squares solutions show that for a given compressional wave velocity the corresponding shear wave velocity is higher for oceanic sedimentary rocks than for oceanic basalt (i.e., the sedimentary rocks have lower Poisson's ratios). This is consistent with single crystal studies of many of the important mineral constituents of these rocks. Calculated aggregate Poisson's ratios of quartz and calcite are quite low, whereas Poisson's ratios for feldspars and many alteration products of basalts are relatively high (Simmons and Wang, 1971).

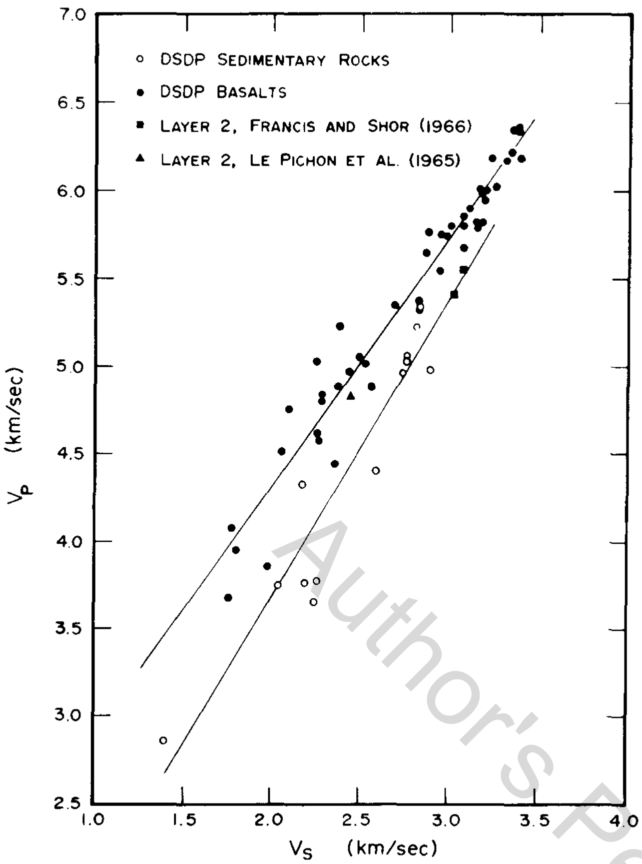

Fig.3. Compressional wave velocity (V_P) vs shear wave velocity (V_s) for D.S.D.P. basalts and sedimentary rocks at 0.4 kbar.

To illustrate the application of the compressional wave velocity/shear wave velocity relationships, data from three oceanic refraction sites which contain reliable shear velocity observations are included in Fig.3. The velocities (V_P = 4.83 km/sec, V_s = 2.43 km/sec) of Le Pichon et al. (1965) from a profile on the flank of the Mid-Atlantic Ridge fall quite close to the basalt least-squares solution, whereas refraction data (V_P = 5.41 km/sec, V_s = 3.01 km/sec, and V_P = 5.54 km/sec, V_s = 3.08 km/sec) of Francis and Shor (1966) west of the Saya de Malha Bank in the Indian Ocean fall on the sedimentary rock line implying that the upper portion of layer 2 in this area is sedimentary rock (Fig.3). Unfortunately additional layer-2 shear velocity information is rather limited. Thus, the utility of this relationship must await further oceanic refraction studies of layer-2 shear velocities as well as continued laboratory measurements of the elastic properties of deep-sea sedimentary rocks.

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