V_p/V_s and Poisson's ratios in marine sediments and rocks

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The ratio of compressional wave velocity V_p to shear wave velocity V_s, and Poisson's ratio in marine sediments and rocks are important in modeling the sea floor for underwater acoustics, geophysics, and foundation engineering. V_p and V_s versus depth information was linked at common depths in terrigenous sediments (to 1000 m) and in sands (to 20 m) to yield data on V_p vs V_s, and V_p/V_s and Poisson's ratios versus depth. Soft, terrigenous sediments usually grade with depth into mudstones and shales; V_p/V_s ratios vary from about 13 or more at the sea floor to about 2.6 at 1000 m. Poisson's ratios vary from above 0.49 at the sea floor to about 0.41 at 1000 m. In sands, V_p, V_s, and V_p/V_s have very high gradients in the first few meters; below about 5 m, V_p/V_s ratios decrease from about 9 to about 6 at 20 m; Poisson's ratios vary from above 0.49 at the surface to above 0.48 at 20 m. The mean value of V_p/V_s in 30 laboratory samples of chalk and limestone is 1.90 (standard error: 0.03); mean Poisson's ratio is 0.31. Literature data on basalts from the sea floor are reviewed. Equations relating V_p to V_s are given for terrigenous sediments, sands, and basalts.

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INTRODUCTION

The ratio of compressional wave velocity V_p to shear wave velocity V_s in sediments and rocks is of interest and importance in several scientific and engineering fields. In earthquake prediction the ratio V_p/V_s in the fault zone may decline prior to an earthquake, but may recover to near its previous value before the earthquake. The causes of this phenomenon were discussed by Nur[1] and reviewed and discussed by several other investigators (e.g., Anderson and Whitcomb[2]). The reduction in the value of V_p/V_s appears to be caused by a large reduction in V_p due to the dilation of the rocks to form open, dry, or undersaturated cracks. V_p then increases as these cracks fill with water, and the V_p/V_s ratio returns to near its previous value. V_p/V_s ratios may be useful in indicating the presence of gas in sediments and rocks during oil-exploration reflection measurements (e.g., Tatham and Stoffa,[3] Gregory,[4] Domenico[5,6]). The presence of gas in the pore spaces of a rock layer causes a marked drop in the V_p/V_s ratio. Gregory[4] (p. 912) estimates that V_p/V_s in most water-saturated rocks varies from about 1.42 to 1.98, but when pore spaces are filled with gas, the V_p/V_s ratio is apt to be lowered to about 1.30 to 1.69. Values for the V_p/V_s ratio can also be useful in estimating reasonable values for V_s, given a measured value of V_p in sediments or rocks (as from reflection or refraction surveys). Such values of V_s are important in modeling the sea floor for geophysical and underwater acoustics studies, and in foundation engineering.

Poisson's ratio σ is the ratio of transverse to longitudinal strain under an applied stress; it can be determined from the V_p/V_s ratio (see equation under Table I). When rigidity is zero (as in a suspension of mineral particles in water), no shear wave can be transmitted and Poisson's ratio is 0.50. As discussed by Hamilton,[7] most natural sediments and rocks possess sufficient rigidity to transmit shear waves. Consequently, most sediments and rocks have Poisson's ratios less than 0.50. Poisson's ratio is of importance in studies of elasticity in earth materials, in geotechnical (soils) engineering, and in some aspects of seismic exploration for gas and oil (e.g., Gregory[4]).

The principal objectives of this report are to establish generalized relationships between V_p and V_s and to determine V_p/V_s ratios in some major marine sediment and rock types in order to more realistically predict values of V_s at depth in the sea floor, given a measured value of V_p from seismic reflection or refraction measurements. Values of Poisson's ratio are also listed and discussed. All values of V_p, V_s, and Poisson's ratio are for the small strains (less than about 10^{-5} or 10^{-6}) caused by passage of elastic waves through fully saturated sediments and rocks; except for a few values of V_s in sands above the water table (see Hamilton[8] for discussion).

V_p/V_s and Poisson's ratios in basalts are reviewed herein because they are important in geophysical and acoustic modeling of the ocean basins.

I. METHODS AND RESULTS

A. Silt clays, turbidites, and mudstones

The methods used to derive the V_p/V_s ratios in silt clays, turbidites, and mudstones were to first establish values of *in situ* V_p versus depth, secondly to establish *in situ* V_s versus depth, and then to link V_p to V_s at common depths.

In a recent report (Hamilton[9]) V_p versus one-way travel time of sound for 20 areas of mostly turbidites and silt clays in the Indian Ocean, the Japan and Bering Seas, the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico were statistically examined and averaged values for the compressional velocity gradient were published. Data from the same 20 areas were used to establish averaged values of V_p versus depth in the sea floor (Table I, Fig. 1). The regression equation for these data is in the caption to Fig. 1.

Hamilton[8] reviewed literature values of V_s in silt

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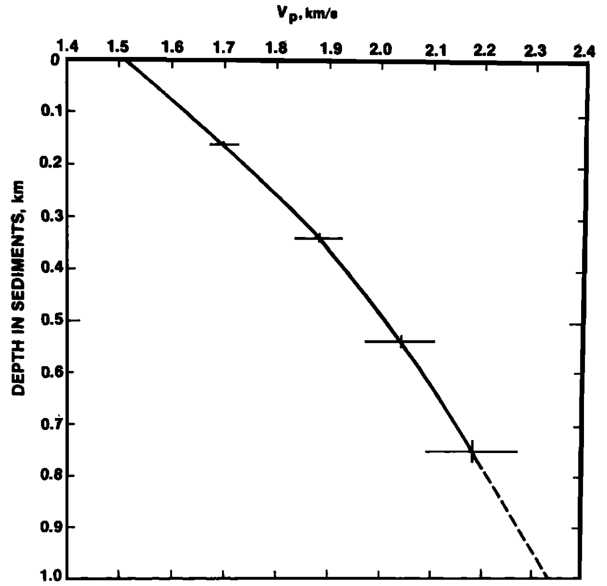

FIG. 1. Compressional wave velocity V_p versus depth in the sea floor in 20 areas of terrigenous sediments (mostly silt-clays, turbidites, mudstones shales); from Hamilton.[9] The error bars represent the 95% confidence limits. The regression equation is: $V_p = 1.511 + 1.304D - 0.741D^2 + 0.257D^3$; where V_p is in km/s, and depth, D, is in km.

TABLE I. Compressional wave velocity, V_p, shear wave velocity, V_s, V_p/V_s, and Poisson's ratio, σ, in *in situ*, water-saturated silt clays, turbidites, and mudstones.

Depth (m)	V_p (m/s) [a]	V_s (m/s) [b]	V_p/V_s	σ [c]
0	1511	116	13.03	0.497
1	1512	121	12.50	0.497
5	1518	139	10.92	0.496
10	1524	163	9.35	0.494
20	1537	209	7.35	0.491
30	1549	256	6.05	0.486
40	1562	288	5.42	0.482
50	1574	301	5.23	0.481
100	1634	365	4.48	0.474
200	1744	438	3.98	0.466
300	1842	496	3.71	0.461
400	1930	554	3.48	0.455
500	2010	612	3.28	0.449
600	2082	670	3.11	0.442
700	2149	728	2.95	0.435
800	2212	786	2.81	0.428
900	2272	844	2.69	0.420
1000	2331	902	2.58	0.412

[a] Equation (V_p versus depth) in caption, Fig. 1.
[b] Equations (V_s versus depth) in caption, Fig. 2.
[c] Poisson's ratio, $\sigma = [(V_p/V_s)^2 - 2]/2[(V_p/V_s)^2 - 1]$.

clays and turbidites to depths of 650 m. Three linear equations were used to characterize the data (47 measurements). These curves, regression equations, and data are reproduced in Fig. 2, and the data listed in Table I.

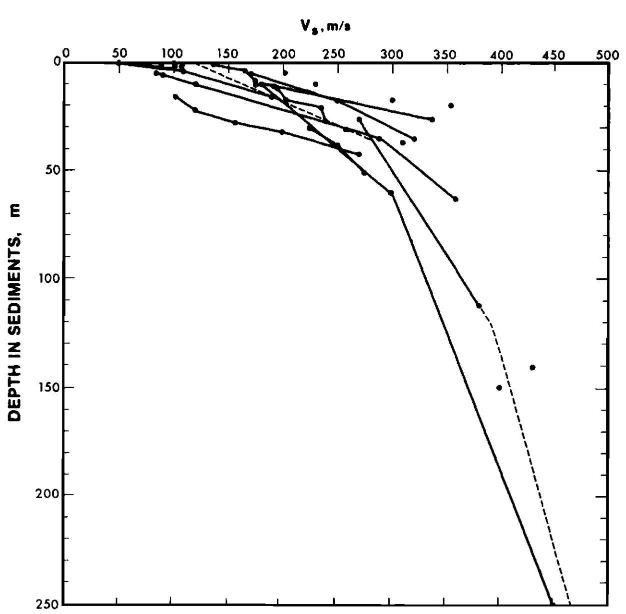

FIG. 2. Shear wave velocity V_s versus depth in selected water-saturated silt clays and turbidites; from Hamilton.[8] Multiple measurements at the same site are connected by solid lines. One measurement ($V_s = 700$ m/s at 650 m) is not shown. The dashed lines are three regression equations (V_s is in m/s, and depth D is in m): 0 to 36 m, $V_s = 116 + 4.65D$; 36 to 120 m, $V_s = 237 + 1.28D$; 120 to 650 m, $V_s = 322 + 0.58D$.

Also listed in Table I are the V_p/V_s ratios computed from the listed values of V_p and V_s, and Poisson's ratios computed from the V_p/V_s ratios. The data in Table I are also illustrated in Fig. 3 (V_p/V_s versus depth), Fig. 4 (V_p vs V_s), and Fig. 5 (Poisson's ratio versus depth).

B. Sands

The regression equation which was computed for 29 selected *in situ* measurements of V_s in natural sands

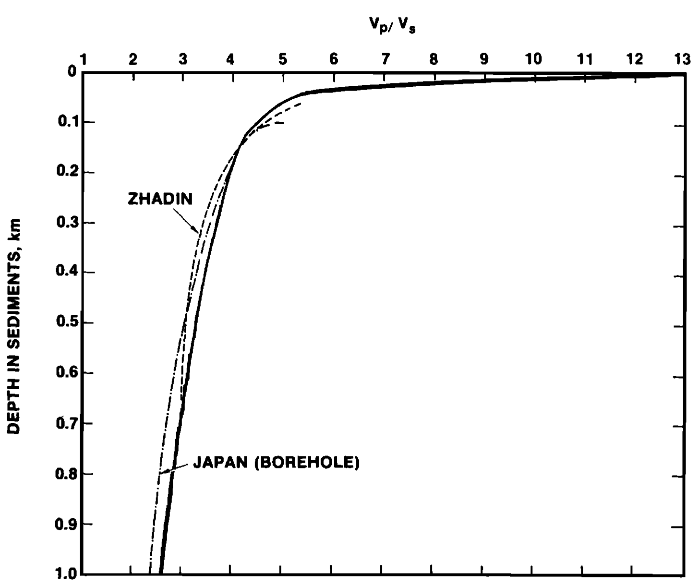

FIG. 3. V_p/V_s ratio versus depth in terrigenous sediments (mostly silt clays, turbidites, mudstones shales); data in Table I. Data from deep boreholes in Japan[19] and Russia[20] are included for comparisons.

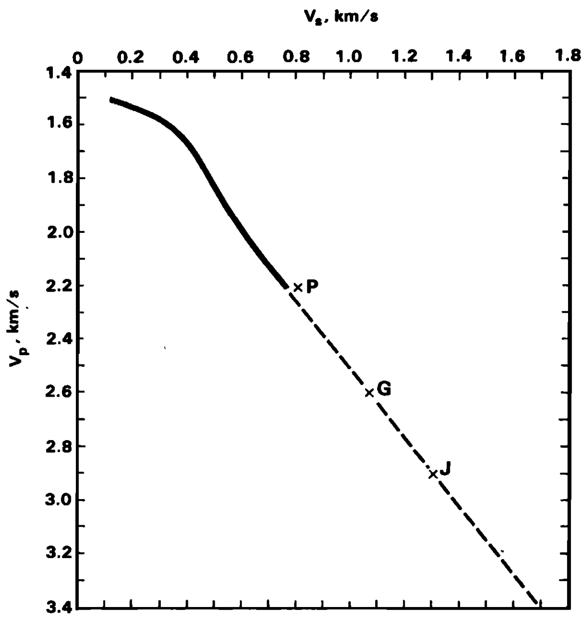

FIG. 4. Compressional wave velocity V_p versus shear wave velocity V_s in terrigenous marine sediments (mostly silt clays, turbidites, mudstones shales); data in Table I. The solid curve represents three regression equations (V_p and V_s in km/s): V_p from 1.512 to 1.555, $V_s = 3.884 V_p - 5.757$; V_p from 1.555 to 1.650, $V_s = 1.137 V_p - 1.485$; V_p from 1.650 to 2.150, $V_s = 0.991 - 1.136 V_p + 0.47 V_p^2$; dashed line ($V_p$ greater than 2.150): $V_s = 0.78 V_p - 0.962$. The letters "P", "G", and "J" represent Pierre shale,[16] Grayson shale,[18] and data from a deep borehole in Japan.[19]

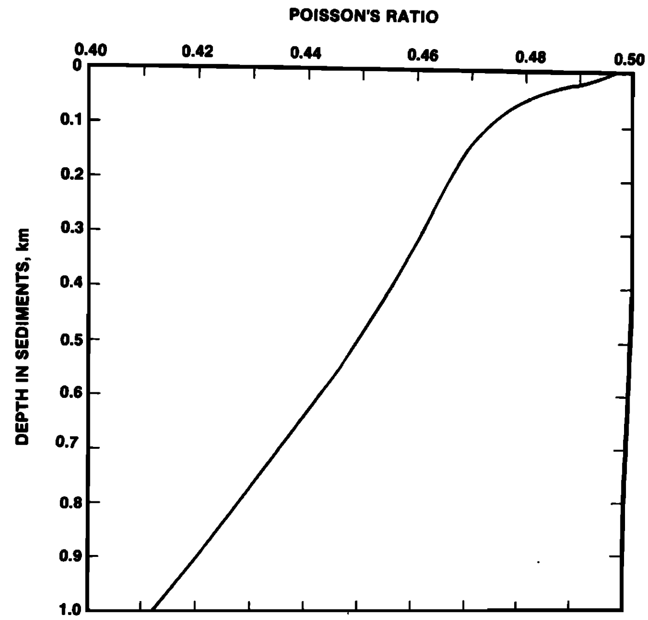

FIG. 5. Poisson's ratio versus depth in terrigenous marine sediments (mostly silt clays, turbidites, mudstones shales); data in Table I.

(Hamilton[8]) was used to generalize shear wave velocity versus depth ($V_s = 128D^{0.28}$; where D is depth in *m*, and V_s is shear wave velocity in m/s). The data were extrapolated to 20 m, and the results are illustrated in Fig. 6 and listed in Table II.

An equation for V_p versus depth in sand was computed following Hamilton.[8] In that report it was noted, on the basis of some laboratory measurements at lower pressures at the Shell Development Company, that compressional velocity increased with depth in the upper tens of meters in fully water-saturated sands to about the 0.015 power (i.e., $V_p = KD^{0.015}$; where V_p is in m/s, depth D is in m, and K is a constant). An average value for V_p in fine sand (1753 m/s) in the laboratory (Hamilton,[10] p. 297) was corrected (following Hamilton[11]) to an *in situ* value of 1727 m/s at 20 m water depth off San Diego. The laboratory measurements, at atmospheric pressures, were in samples about 10 cm high. It was therefore assumed that the measurements were at a "depth" of 0.05 m. The above equation was solved for the constant K with the velocity (1727 m/s) and depth (0.05) given. The resulting equation was then: $V_p = 1806D^{0.015}$. This equation was used to compute V_p to

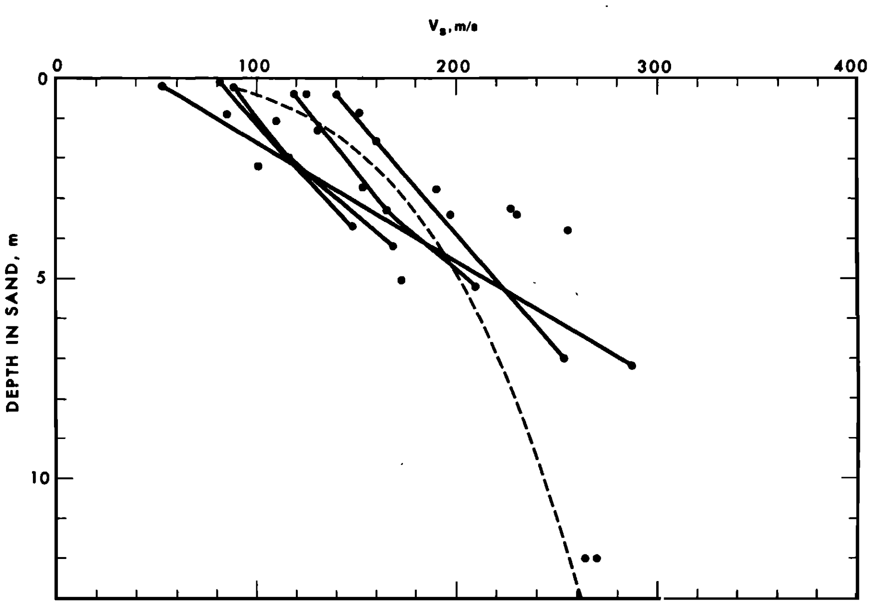

FIG. 6. Shear wave velocity V_s versus depth D in selected water-saturated sands. Multiple measurements at the same site are connected by solid lines; from Hamilton.[8] The dashed line is the regression equation: $V_s = 128D^{0.28}$; where V_s is in m/s, and D is in m.

TABLE II. Compressional wave velocity, V_p, shear wave velocity, V_s, V_p/V_s, and Poisson's ratio, σ, in *in situ*, water-saturated sands.

Depth (m)	V_p (m/s) [a]	V_s (m/s) [b]	V_p/V_s	σ [c]
0.05	1727	55	31.40	0.4995
1	1806	128	14.11	0.4975
2	1825	155	11.77	0.4964
3	1836	174	10.55	0.4955
4	1844	189	9.76	0.4947
5	1850	201	9.20	0.4940
6	1855	211	8.79	0.4934
8	1863	229	8.14	0.4923
10	1869	244	7.66	0.4913
12	1875	257	7.30	0.4904
14	1879	268	7.01	0.4896
16	1883	278	6.77	0.4888
18	1886	288	6.55	0.4880
20	1889	296	6.38	0.4874

[a] $V_p = 1806D^{0.015}$; V_p in m/s, D is depth in m.
[b] $V_s = 128D^{0.28}$; V_s in m/s, D is depth in m.
[c] Computed with equation under Table I.

20 m (Table II, Fig. 7).

Also listed in Table II are the V_p/V_s values computed from the listed V_p and V_s values, and Poisson's ratios computed from the V_p/V_s ratios. The data in Table II are also illustrated in Fig. 8 (V_p/V_s versus depth), Fig. 9 (V_p vs V_s), and Fig. 10 (Poisson's ratio versus depth).

C. Calcareous sediments and rocks

Data on shear wave velocity in soft, unlithified calcareous sediments are insufficient to examine V_p/V_s ratios. Consequently, the study of calcareous materials was confined to chalks and limestones. Calcite is included to indicate values at zero porosity.

Thirty samples of chalk and limestone were selected to establish statistical values of V_p/V_s for these rocks. In selecting the 30 samples of chalk and limestone to characterize V_p/V_s ratios (Table III), laboratory values were favored because of careful control of water saturation, pressures, and measurements of velocity. Al-

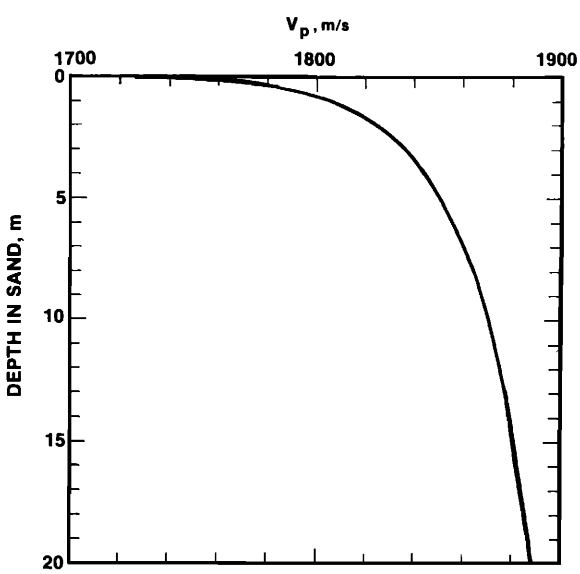

FIG. 7. Compressional wave velocity V_p versus depth D in sand; from Hamilton.[9] Data are in Table II; see text for discussion. Regression equation is: $V_p = 1806D^{0.015}$; where V_p is in m/s, and D is in m.

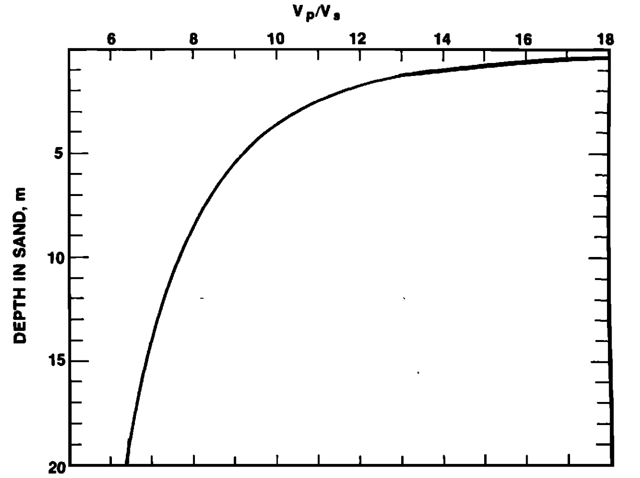

FIG. 8. V_p/V_s ratio versus depth in sand; data is in Table II.

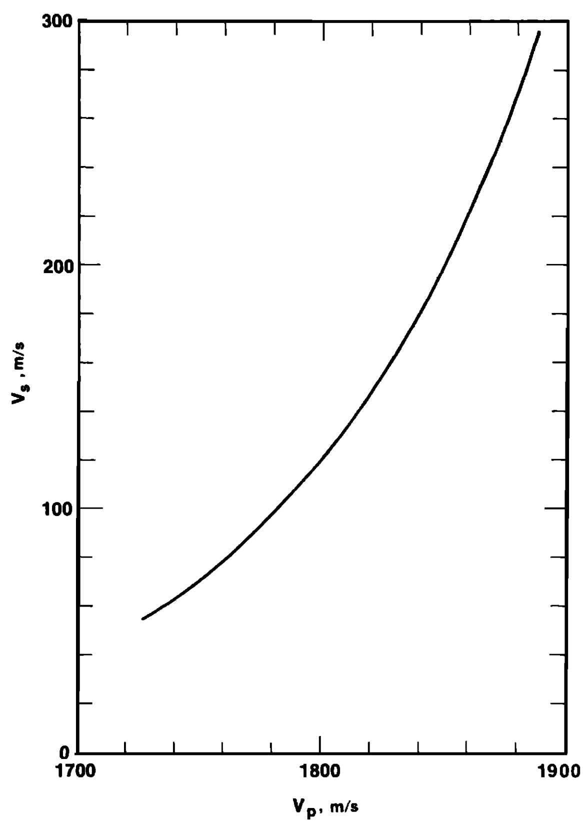

FIG. 9. Compressional wave velocity V_p versus shear wave velocity V_s in sand; data are in Table II. The regression equation is: $V_s = 21.05 - 24.617V_p + 7.215V_p^2$; where V_p and V_s are in km/s.

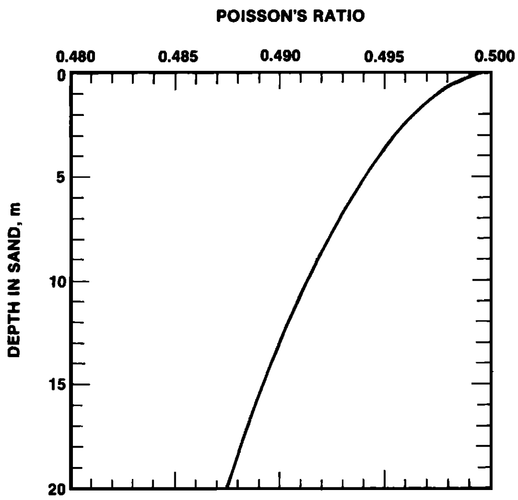

FIG. 10. Poisson's ratio versus depth in sand; data are in Table II.

though porosity in these materials ranged from 0% to 41%, the V_p/V_s ratios varied so little that all 30 samples were averaged. Velocity values for chalks and limestones were selected for pressures corresponding to probable pressures in the sea floor at which most chalks and limestones might occur. These pressures usually varied between 0.1 and 0.4 kbar, but some values for Solenhofen limestone at zero axial pressure, and a suite of samples from Timur[12] at 0.9 kbar were used. As evidenced by Christensen *et al.*,[13] Gregory,[4] and others, there is usually little difference in V_p/V_s values because of differential pressures to one kilobar in chalks and limestones.

The full range in values of V_p/V_s in Table III is from 1.68 to 2.66. The mean value of V_p/V_s in the 30 samples is 1.90, the standard error of the mean is 0.03. Within 95% confidence limits the values of V_p/V_s are 1.90 ± 0.06. These values of V_p/V_s define Poisson's ratios of 0.31 (mean), and 0.32, and 0.29.

D. Basalts

The laboratory measurements of V_p and V_s in water-saturated basalts at 0.5 kbar (Christensen and Salisbury,[14] Table 9, Fig. 16) were selected to represent oceanic basalts because of the precision of the measurements and identification of the rock types from the Deep Sea Drilling Project boreholes.

Christensen and Salisbury[14] related both V_p and V_s to density, ρ. At a pressure of 0.5 kbar (considered appropriate for the basalts of the oceanic crust) the equations were: $V_p = 2.33 + 0.081\rho^{3.63}$, and $V_s = 1.33 + 0.011\rho^{4.85}$ (where V_p and V_s are in km/s and ρ is in g/cm^3). Their data ranged from densities of about 2.1 to 3.0 g/cm^3.

The equations noted above were solved for V_p and V_s at various densities. The results are noted in Table IV, and V_p versus V_s is illustrated in Fig. 11. The regression equation is in the caption to the figure. Poisson's ratios in Table IV range from 0.30 to 0.34, and V_p/V_s ratios from 1.86 to 2.04.

TABLE III. Compressional wave velocity, V_p, shear wave velocity, V_s, V_p/V_s, and Poisson's ratio, σ, at pressure, P, in laboratory samples of water-saturated chalk and limestone.

Material	V_p (m/s)	V_s (m/s)	V_p/V_s	σ [a]	P (kbar)	Reference
Calcite	6566	3414	1.92	0.31	0.1	b
Solenhofen ls	5560	2900	1.92	0.31	0	c
	6100	3200	1.91	0.31	0	
	6300	3200	1.97	0.33	0	
Solenhofen ls	5640	3000	1.88	0.30	0.1	38
Solenhofen ls	5370	2880	1.87	0.30	0	d
	5820	3070	1.90	0.31	0	
	6100	3180	1.92	0.31	0	
Bedford ls	4680	1760	2.66	0.42	0.1	38
Spergen ls	4700	2490	1.89	0.30	0	e
Carbonate-1	5961	3301	1.81	0.28	0.92	12
-2	5840	3414	1.71	0.24	0.92	
-3	6261	3237	1.93	0.32	0.92	
-4	5936	3128	1.90	0.31	0.92	
-5	5609	2925	1.92	0.31	0.92	
-6	5589	2963	1.89	0.30	0.95	
-7	5491	2918	1.88	0.30	0.95	
Limestone	4390	2570	1.71	0.24	0.2	13
	3730	2226	1.68	0.22	0.2	
	4280	2145	1.99	0.33	0.2	
	4995	2726	1.83	0.29	0.2	
	5005	2812	1.78	0.27	0.2	
	2813	1362	2.06	0.35	0.2	
Leuders ls	4119	2260	1.82	0.28	0.1	4
Indiana ls	···	···	1.75	0.26	0.1	
Chalk E-1b	···	···	1.93	0.32	0.1	
Chalk E-2b	···	···	1.84	0.29	0.1	
Chalk E35, 36	···	···	1.97	0.33	0.1	
Chalk E30, 31	···	···	1.92	0.31	0.1	
Chalk E38, 39	···	···	1.83	0.29	0.1	

[a] Computed with equation under Table I.
[b] G. Simmons and H. Wang, *Single Crystal Elastic Constants and Calculated Aggregate Properties: A Handbook* (MIT Press, Cambridge, MA, 1971), p. 329.
[c] L. Peselnick and I. Zietz, "Internal Friction of Fine-Grained Limestones at Ultrasonic Frequencies," Geophysics **24**, 285–296 (1959).
[d] L. Peselnick, "Elastic Constants of Solenhofen Limestone and Their Dependence upon Density and Saturation," J. Geophys. Res. **67**, 4441–4448 (1962).
[e] M. N. Toksöz, C. H. Cheng, and A. Timur, "Velocities of Seismic Waves in Porous Rocks," Geophysics **41**, 621–645 (1976).

II. DISCUSSION AND CONCLUSIONS

A. Silt clays, turbidites, and mudstones

The curves for V_p and V_s versus depth in the sea floor (Figs. 1 and 2) represent a large amount of *in situ* data. In the case of V_p versus depth (Fig. 1) 20 different areas are averaged to about 750 m, and the curve then extrapolated to 1000 m. The curve for V_s versus depth (Fig. 2), representing 47 measurements, was extrapolated from 650 to 1000 m. As discussed by Hamilton[10] below about 500- to 600-m depth in the sea floor, terrigenous silt-clay sediments are apt to be hard enough to be called a mudstone, or in some cases, a shale. Consequently, the data in Table I and associated figures (Figs. 1 to 5) should indicate general values from soft, high-porosity sediments at the sea floor to

TABLE IV. Density, compressional wave velocity, V_p, shear wave velocity, V_s, V_p/V_s, and Poisson's ratio, σ, in laboratory samples of water-saturated basalts from the Deep Sea Drilling Project at a pressure of 0.5 kb (from Christensen and Salisbury, Ref. 14).

Density (g/cm^3)	V_p (m/s) [a]	V_s (m/s) [b]	V_p/V_s	σ [c]
2.1	3527	1732	2.04	0.34
2.2	3747	1834	2.04	0.34
2.3	3996	1955	2.04	0.34
2.4	4274	2098	2.04	0.34
2.5	4584	2266	2.02	0.34
2.6	4929	2462	2.00	0.33
2.7	5311	2690	1.97	0.33
2.8	5731	2952	1.94	0.32
2.9	6194	3253	1.90	0.31
3.0	6700	3597	1.86	0.30

[a] $V_p = 2.33 + 0.081\rho^{3.63}$; V_p in km/s; density, ρ, in g/cm^3.
[b] $V_s = 1.33 + 0.011\rho^{4.85}$; V_s in km/s; density, ρ, in g/cm^3.
[c] Computed with equation under Table I.

mudstone and shale at deeper depths.

The use of *in situ* V_p and V_s data versus depth in the sea floor has the advantage of "built-in" temperature and pressure corrections, and in allowing for the reduction of sediment porosity with increasing overburden pressures.

In this data set, values of V_p/V_s in silt clays, turbidites, and mudstones (Fig. 3) range from about 13 at the sea floor to about 2.6 at 1000 m. Values of V_p/V_s in natural silt clays (muds) can be very large, especially in the nearshore or bay environments. For example, Lasswell[15] recorded values of 1506 m/s for V_p and 33 m/s for V_s in Elkhorn Slough near Monterey, California, for a V_p/V_s ratio of about 46. Even higher values can be expected when V_s approaches zero in some sediments which are virtual suspensions.

The V_p/V_s ratio is less than 3.0 below about 600-m depth (Fig. 3, Table I). Such values are consistent with some good measurements in Pierre shale: 2.7 by McDonal *et al.*,[16] and 2.8 by White and Sengbush[17]; and in Grayson shale (2.43) by Geyer and Martner.[18] The computed data are also consistent (Fig. 3) with information from a deep borehole in mud, silt, sand, and gravel in Japan (Yamamizu *et al.*[19]), and from a deep borehole in clay, mudstone, and sandstone in Russia (Zhadin, in Vassil'ev and Gurevich[20]).

To facilitate estimation of V_s, given V_p (as from a seismic reflection or refraction measurement), V_p is plotted versus V_s in Fig. 4. The two linear segments of the curve (between $V_p = 1500$ and 1650 m/s) are artifacts (as far as linearity is concerned) of the statistical examination of V_s versus depth by Hamilton,[8] wherein the V_s data were characterized by three linear equations (Fig. 2).

Poisson's ratio versus depth (Fig. 5) illustrates the high values in the upper unlithified section. Values greater than 0.49 are typical in the first 25 m below the sea floor. All of the section between 0 and 500 m has Poisson's ratios greater than 0.45. The nearly linear segments above 125 m are, as noted above, due to statistical examination of the V_s data. Between 500 and 1000 m Poisson's ratio varies between about 0.41 and 0.45, which are typical values in some shales (e.g., Pierre shale: 0.42, 0.43).[16,17]

It should be noted that Poisson's ratio decreases with depth as a consequence of linking V_p with V_s at common depths. Data from the two deep boreholes in Fig. 3 confirm the reality of this decrease. In the Soviet borehole[20] Poisson's ratio decreased from 0.494 at 10 m to 0.438 at 650 m. In the Japanese borehole[19] Poisson's ratio decreased from 0.479 at 25 m to 0.425 at 650 m. This is especially noted because Eaton[21] illustrated Poisson's ratio versus depth and concluded that Poisson's ratio increases with depth in terrigenous sediments in the Gulf Coast area.

B. Sands

The velocity gradients of both V_p and V_s in sands are very high in the first few meters (Figs. 6 and 7). This results in a very high gradient of V_p/V_s with depth to

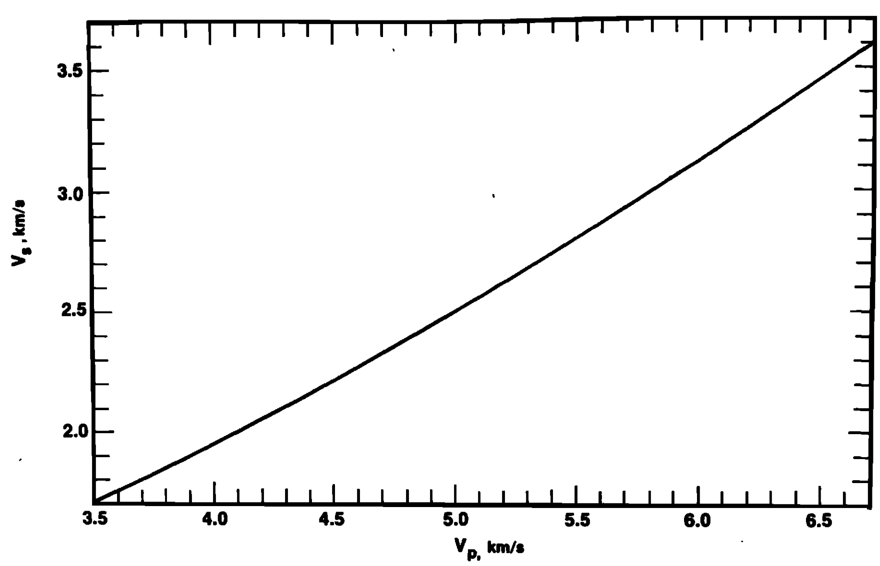

FIG. 11. Compressional wave velocity V_p versus shear wave velocity V_s in laboratory samples of water-saturated basalts from the Deep Sea Drilling Project at a pressure of 0.5 kb (from Christensen and Salisbury[14]); data are in Table IV. The regression equation is: $V_s = 0.531 + 0.2077 V_p + 0.0374 V_p^2$; where V_p and V_s are in km/s.

about 5 m, followed by much smaller gradients (Fig. 8). Although these gradients are probably typical for all sands, the actual illustrated and listed V_p and V_s data are more apt to be for fine sands (the most common type).

The small increases of V_p with increasing pressure or depth in water-saturated sands, at depths below a few meters, were illustrated by Brandt[22] at low pressures, and has been recently affirmed at higher pressures by Elliot and Wiley,[23] and by Domenico.[5,6] Schirmer (personal communication, 1977) recently measured, *in situ*, a V_p of 1800 m/s, and a Stoneley wave velocity which yielded a V_s of 123 m/s in the sandy floor of the North Sea at a water depth of 132 m. These measurements compare favorably with those computed and listed in Table II at 1-m depth ($V_p = 1806$ m/s, $V_s = 128$ m/s).

Shear wave velocity is frequently measured in geotechnical (soil mechanics) investigations in which no compressional velocity is measured. On the other hand, in acoustic modeling of the sea floor, V_p is known or can be closely estimated, and V_s is required. To facilitate estimation of V_p or V_s, given either property, V_p is plotted versus V_s in Fig. 9.

In soil mechanics literature, Poisson's ratios in fully water-saturated sands are frequently estimated at values which are too low, at least for the small strains caused by passage of elastic waves. The reasons for this were discussed by Hamilton.[7] In general, the low Poisson's ratios are caused by reporting low values of V_p in sands supposedly 100% saturated, but which are only partially saturated. Figure 10 (Poisson's ratio versus depth) illustrates the very high values of Poisson's ratio in the first 20 m of a water-saturated sand layer: the decrease is only from 0.4995 to 0.4874. The fourth decimal place is shown because rounding to two places would falsely indicate values of 0.50 near the surface (0.50 indicates zero rigidity and no shear wave). These high values are supported by recent *in situ* measurements where both V_p and V_s were measured. For examples: 0.494 was measured in medium sand off San Diego by Hamilton *et al.*,[24] 0.498 in sands in the North Sea by Schirmer (personal communication, 1977), an average of 0.492 in three medium sands, and 0.485 in a coral sand by Cunny and Fry.[25] Similar high values were noted by Hamilton[7] from other, referenced, measurements.

C. Calcareous sediments and rocks

A large number of V_p measurements in calcareous rock layers in the sea floor are accumulating as a result of expendable sonobuoy measurements (e.g., Houtz *et al*,[26,27] Johnson *et al.*[28]). The fact that these layers are chalk and limestone has been established by the Deep Sea Drilling Project. By using the average V_p/V_s ratio of 1.90, reasonable values of V_s can be computed from the sonobuoy reflection and refraction measurements.

A good example of the use of the ratio would have been in some studies by Ingenito and Wolf.[29] These investigators measured by refraction methods a compressional wave velocity of 1900 m/s in shallow-water, long-range experiments in the Yucatan Peninsula, in cemented reef limestones. They assumed a shear velocity of 1000 m/s to fit certain theoretical and experimental values. Their choice appears to be excellent because their V_p/V_s ratio of 1.90 is exactly that of the average ratio for 30 samples of Table III.

Pending further measurements, it is recommended that the figures and data for terrigenous silt clays (Table I, Figs. 1–5) be used to estimate generalized V_s, V_p/V_s, and Poisson's ratios in soft, uncemented calcareous oozes.

D. Basalts

It should be emphasized that the laboratory measurements of Christensen and Salisbury[15] in basalts were in hand samples, whereas the field measurements by seismic methods are in large volumes of rock. Hyndman and Drury[30] and Francis[31] have reported measurements of V_p and V_s in the Mid-Atlantic Ridge crestal area. They emphasize that low V_p's in such areas may reflect large scale fissures and cracks, as well as volcanic detrital material mixed with normal sediments. Away from such ridges (where new sea floor is being added) the cracks and fissures are thought to be filled with sedimentary material, and the consequent compressional velocities higher (e.g., Talwani *et al.*,[32] Houtz,[33] Hamilton[34]). The data of Christensen and Salisbury[14] should be more representative of *in situ* conditions in the top of the basaltic crust away from ridges.

E. V_p/V_s as an index to lithology

Attempts to determine sediment and rock types from their V_p/V_s ratios have met with indifferent success because of overlap in ratios. However, some generalizations can be made.

Gardner and Harris[35] and Gregory[4] have noted that unconsolidated (unlithified) sands have V_p/V_s ratios greater than 2.0. Measurements in field and laboratory have supported this general statement. As noted in Table II, V_p/V_s ratios in sands to 20 m are all greater than 6.0. Recent measurements in sands by Domenico[6] at pressures between 28 and 352 kg/cm^2 (equivalent to depths from about 280 to 3520 m) indicated V_p/V_s ratios from 3.3 to 2.2.

Gardner and Harris[35] and others have noted that V_p/V_s ratios in cemented sandstones are usually less than 2.0; they indicated a "usual value" of 1.75 ± 0.2. This average value was generally supported by King[36] who measured an average value of 1.77 in five water-saturated sandstones under a pressure of 35 kg/cm^2, and by Gregory[4] who measured an average ratio of 1.72 in 12 sandstones at atmospheric pressures, and 1.67 at 0.3 kbar.

Pickett[37] in 1963 indicated an average value of 1.9 for V_p/V_s in limestones. This is the average value for the 30 samples of chalks and limestones of this report (Table III) which includes much additional (later) data.

Summarizing the discussions in a previous section:

soft, terrigenous sediments grading with depth into mudstones and shales should have V_p/V_s ratios from about 13 or more at the sea floor to values on the order of 2.6 at 1000 m (Table I, Fig. 3). The lower values are supported by measurements in Pierre shale[16,17]: 2.8 and 2.7; in Grayson shale[18]: 2.43; and by measurements in boreholes in Japan[19] and Russia[20] (Fig. 3).

It is a mistake to assume that all cemented rocks have V_p/V_s ratios less than 2.0. As noted above, almost all mudstones and shales have ratios greater than 2.0. Additionally (Table IV), basalts with V_p less than about 5.00 km/s are apt to have ratios greater than 2.00. And there are numerous examples from laboratory and field of other rocks with higher ratios. For examples: a ratio of 2.66 at 0.1 kbar was measured in Bedford limestone in the laboratory by Nur and Simmons,[38] and Geyer and Martner[18] measured (*in situ*) a ratio of 2.75 in Edwards limestone. There are many other examples in the Soviet literature (e.g., Molotova and Vassil'ev[39] and Vassil'ev and Gurevich[20]).

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[1]A. Nur, "Dilatancy, Pore Fluids, and Premonitory Variations of t_s/t_p Travel Times," Bull. Seismol. Soc. Am. 62, 1217–1222 (1972).

[2]D. L. Anderson and J. H. Whitcomb, "Time-Dependent Seismology," J. Geophys. Res. 80, 1497–1503 (1975).

[3]R. H. Tatham and P. L. Stoffa, "V_p/V_s—A Potential Hydrocarbon Indicator," Geophysics 41, 837–849 (1976).

[4]A. R. Gregory, "Fluid Saturation Effects on Dynamic Elastic Properties of Sedimentary Rocks," Geophysics 41, 895–921 (1976).

[5]S. N. Domenico, "Effect of Brine-Gas Mixture on Velocity in an Unconsolidated Sand Reservoir," Geophysics 41, 882–894 (1976).

[6]S. N. Domenico, "Elastic Properties of Unconsolidated Porous Sand Reservoirs," Geophysics 42, 1339–1368 (1977).

[7]E. L. Hamilton, "Elastic Properties of Marine Sediments," J. Geophys. Res. 76, 579–604 (1971).

[8]E. L. Hamilton, "Shear-Wave Velocity versus Depth in Marine Sediments: a Review," Geophysics 41, 985–996 (1976).

[9]E. L. Hamilton, "Sound Velocity Gradients in Marine Sediments," J. Acoust. Soc. Am. 65, 909–922 (1979).

[10]E. L. Hamilton, "Variations of Density and Porosity with Depth in Deep-Sea Sediments," J. Sediment. Petrol. 46, 280–300 (1976).

[11]E. L. Hamilton, "Predictions of *In-Situ* Acoustic and Elastic Properties of Marine Sediments," Geophysics 36, 266–284 (1971).

[12]A. Timur, "Temperature Dependence of Compressional and Shear Wave Velocities in Rocks," Geophysics 42, 950–956 (1977).

[13]N. I. Christensen, D. M. Fountain, and R. J. Stewart, "Oceanic Crustal Basement: A Comparison of Seismic Properties of D.S.D.P. Basalts and Consolidated Sediments," Marine Geol. 15, 215–226 (1973).

[14]N. I. Christensen and M. H. Salisbury, "Structure and Constitution of the Lower Oceanic Crust," Rev. Geophys. Space Phys. 13, 57–86 (1975).

[15]J. B. Lasswell, "A Comparison of Two Methods for Measuring Rigidity of Saturated Marine Sediments," MS thesis, Naval Postgraduate School, Monterey, CA (1970), pp. 1–61.

[16]F. J. McDonal, F. A. Angona, R. L. Mills, R. L. Sengbush, R. G. Van Nostrand, and J. E. White, "Attenuation of Shear and Compressional Waves in Pierre Shale," Geophysics 23, 421–439 (1958).

[17]J. E. White and R. L. Sengbush, "Shear Waves from Explosive Sources," Geophysics 28, 1001–1019 (1963).

[18]R. L. Geyer and S. T. Martner, "SH Waves from Explosive Sources," Geophysics 34, 893–905 (1969).

[19]F. Yamamizu, H. Takahashi, N. Gotoh, Y. Ohta, and K. Shiono, "Vertical Distribution of the Seismic S-Wave Velocities at the Site of the Iwatsuki Deep Borehole Observatory of Crustal Activities," preprint of oral presentation (1976).

[20]Y. I. Vassil'ev and G. I. Gurevich, "On the Ratio Between Attenuation Decrements and Propagation Velocities of Longitudinal and Transverse Waves," English translation, Izv. Acad. Sci. USSR, Geophys. Ser. 12, 1061–1074 (1962).

[21]B. A. Eaton, "Fracture Gradient Prediction and its Application in Oilfield Operations," J. Petrol. Technol. 21, 1353–1360 (1969).

[22]H. Brandt, "Factors Affecting Compressional Wave Velocity in Unconsolidated Marine Sand Sediments," J. Acoust. Soc. Am. 32, 171–179 (1960).

[23]S. E. Elliott and B. F. Wiley, "Compressional Velocities of Partially Saturated, Unconsolidated Sands," Geophysics 40, 949–954 (1975).

[24]E. L. Hamilton, H. P. Bucker, D. L. Keir, and J. A. Whitney, "Velocities of Compressional and Shear Waves in Marine Sediments Determined from a Research Submersible," J. Geophys. Res. 75, 4039–4049 (1970).

[25]R. W. Cunny and Z. B. Fry, "Vibratory *In Situ* and Laboratory Soil Moduli Compared," J. Soil Mech. Foundation Div., Am. Soc. Civil Engin. 99 (SM 12), 1055–1076 (1973).

[26]R. Houtz, J. Ewing, and P. Buhl, "Seismic Data from Sonobuoy Stations in the Northern and Equatorial Pacific," J. Geophys. Res. 75, 5093–5111 (1970).

[27]R. E. Houtz, "Preliminary Study of Global Sediment Sound Velocities from Sonobuoy Data," in *Physics of Sound in Marine Sediments*, edited by L. Hampton (Plenum, New York, 1974), pp. 519–535.

[28]T. C. Johnson, E. L. Hamilton, R. T. Bachman, and W. H. Berger, "Sound Velocities in Calcareous Oozes and Chalks from Sonobuoy Data: Ontong-Java Plateau, Western Equatorial Pacific," J. Geophys. Res. 83, 283–288 (1978).

[29]F. Ingenito and S. N. Wolf, "Acoustic Propagation in Shallow Water Overlying a Consolidated Bottom," J. Acoust. Soc. Am. 60, 611–617 (1976).

[30]R. D. Hyndman and M. J. Drury, "The Physical Properties of Oceanic Basement Rocks from Deep Drilling on the Mid-Atlantic Ridge," J. Geophys. Res. 81, 4042–4052 (1976).

[31]T. J. G. Francis, "The Ratio of Compressional to Shear Velocity and Rock Porosity on the Axis of the Mid-Atlantic Ridge," J. Geophys. Res. 81, 4361–4364 (1976).

[32]M. Talwani, C. C. Windisch, and M. G. Langseth, Jr., "Reykjanes Ridge Crest: a Detailed Geophysical Study," J. Geophys. Res. 76, 473–517 (1971).

[33]R. E. Houtz, "Seismic Properties of Layer 2A in the Pacific," J. Geophys. Res. 81, 6321–6331 (1976).

[34]E. L. Hamilton, "Sound Velocity-Density Relations in Sea-Floor Sediments and Rocks," J. Acoust. Soc. Am. 63, 366–377 (1978).

[35]G. H. F. Gardner and M. H. Harris, "Velocity and Attenuation of Elastic Waves in Sands," in Trans. 9th Annual Logging Symposium, p. M1–M19 (1968).

[36]M. S. King, "Wave Velocities in Rocks as a Function of Changes in Overburden Pressure and Pore Fluid Saturants," Geophysics 31, 50–73 (1966).

[37]G. R. Pickett, "Acoustic Character Logs and Their Applications in Formation Evaluation," J. Petrol. Technol. 15, 659–667 (1963).
[38]A. Nur and G. Simmons, "The Effect of Saturation on Velocity in Low Porosity Rocks," Earth Planet. Sci. Lett. 7, 183–193 (1969).
[39]L. V. Molotova and Y. I. Vassil'ev, "Velocity Ratio of Longitudinal and Transverse Waves in Rocks, II," English translation, Izv. Acad. Sci. USSR, Geophys. Ser. 8, 731–743 (1960).