42. INFLUENCE OF POROSITY AND WATER SATURATION ON THE COMPRESSIONAL-WAVE VELOCITIES OF BASALTS FROM THE NORTH PHILIPPINE SEA

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INTRODUCTION

The effects of water saturation and open pore space on the seismic velocities of crystalline rocks are extremely important when comparing laboratory data to *in situ* geophysical observations (e.g., Dortman and Magid, 1969; Nur and Simmons, 1969; Christensen and Salisbury, 1975). The existence of fractured rocks, flow breccias and drained pillows in oceanic crustal layer 2a, for instance, may appreciably reduce seismic velocities in that layer (Hyndman, 1976). Laboratory data assessing the influence of porosity and water saturation on seismic velocities of oceanic crustal rocks would certainly aid interpretation of marine geophysical data.

Igneous rocks recovered during Leg 58 of the Deep Sea Drilling Project, in the Shikoku Basin and Daito Basin in the North Philippine Sea, are extremely vesicular, as evidenced by shipboard measurements of porosities, which range from 0 to 30 per cent (see reports on Sites 442, 443, 444, and 446, this volume). Samples with this range of porosities afford an excellent opportunity to examine the influence of porosity and water saturation on seismic velocities of oceanic basalts. This paper presents compressional-wave velocities to confining pressures of 1.5 kbars for water-saturated and air-dried basalt samples from the North Philippine Sea. Samples used in this study are from sites 442, 443 and 444 in the Shikoku Basin and Site 446 in the Daito Basin.

Excellent negative correlation between porosity and compressional-wave velocity demonstrates that water-filled pore space can significantly reduce compressional-wave velocities in porous basalts. Velocities measured in air-dried samples indicate that the velocity difference between dry samples and saturated samples is small for porosities exceeding 10 per cent, and very large for lower porosities.

EXPERIMENTAL TECHNIQUES AND DATA

Basalt samples used in this study were placed in sea water aboard ship upon recovery and kept saturated until arrival in the laboratory. Cylinders 1.25 or 2 cm in diameter and 3 to 5 cm in length were cut and weighed to determine wet-bulk densities. The water-saturated cylinders were wrapped with 100-mesh copper screen and then jacketed with copper foil. The copper screen allowed maintenance of pore pressures at values lower than external pressures. Barium-titanate transducers (1 MHz frequency) were attached to the core ends. The entire sample assembly was placed in a pressure vessel, where hydrostatic confining pressures as high as 1.5 kbars were applied. Compressional-wave velocities were then measured at 0.2-kbar increments to 1.0 kbar, and at 1.5 kbar. Table 1 presents compressional-wave velocities for the water-saturated samples and also lists wet-bulk densities and the mean atomic weights for the samples. Calculations of mean atomic weight were based on geochemical analyses of Leg 58 igneous rocks (site reports, this volume).

Samples with least apparent alteration were selected, air-dried for periods greater than 48 hours, and reweighed. Effective porosities and grain densities were calculated (Table 2). Values for effective porosities and grain densities are minimum values, because all pore water was probably not evacuated. The air-dried samples were subjected to pressures as high as 1.5 kbars, and measurements of compressional-wave velocity were repeated. Table 2 presents compressional wave velocities for air-dried samples.

RESULTS

Figure 1 shows the relationship between compressional wave velocity at 0.5 kbar and wet bulk density for water saturated Leg 58 basalts. Only samples from Sites 442, 443, and 444 were included in the least-squares fit, because of the obvious deviation of Site 446 data from the trend. This distinctive deviation results from the higher mean atomic weights of the Site 446 samples (Table 1). Shikoku Basin samples have mean atomic weights around 22, typical of oceanic basalts. Site 446 samples, because of higher iron and titanium contents (Site 446 report, this volume), have mean atomic weights close to 23; therefore, they should not plot on the velocity-density relationship for lower mean atomic weights (Birch, 1960). A better correlation between velocity and wet-bulk density is obtained for selected samples from Sites 442, 443, and 444 which have no filled vesicles and minimal apparent alteration (Figure 2).

The range of wet-bulk densities in Figure 2 is primarily related to the porosity of the samples. Figure 3 shows a strong negative correlation between porosity and wet-bulk density for the selected Shikoku Basin samples. Also plotted on Figure 3 are theoretical lines relating porosity to wet-bulk density for given grain densities. Most samples plot near the theoretical lines for grain densities of 2.8 and 2.9 g/cm^3, in agreement with the measured grain densities (Table 2). The influence of grain density on wet-bulk density, therefore, is small in comparison to the influence of porosity.

Figure 4 shows the relationship between compressional-wave velocity at 0.5 kbar and porosity for the selected Shikoku Basin samples. The strong negative correlation between porosity and velocity is close to the

TABLE 1
Wet-Bulk Densities, Mean Atomic Weights, and Compressional-Wave Velocities for Water-Saturated Basalts of DSDP Leg 58

Sample (Interval in cm)	Wet-Bulk Density (g/cm^3)	Mean Atomic Weight	Compressional-Wave Velocity (km/s) at Various Pressures (kbar)					
			0.2	0.4	0.6	0.8	1.0	1.5
442A-31-1, 83–93	2.531	22.07	5.055	5.108	5.144	5.179	5.206	5.248
442A-32-2, 54–57	2.461	21.74	4.690	4.753	4.795	4.826	4.850	4.876
442A-33-1, 97–100	2.600	21.95	5.250	5.325	5.387	5.428	5.452	5.474
442A-34-1, 82–85	2.395	21.91	4.062	4.089	4.117	4.144	4.166	4.224
442B-5-2, 106–109	2.440	21.85	4.595	4.694	4.755	4.786	4.805	4.730
442B-7-1, 49–52	2.529	21.96	4.745	4.797	4.840	4.871	4.886	4.902
442B-9-1, 110–114	2.479	21.90	4.424	4.502	4.552	4.582	4.599	4.630
442B-11-2, 123–126	2.471	22.31	4.377	4.430	4.457	4.485	4.513	4.566
442B-13-1, 38–42	2.350	22.53	4.158	4.230	4.297	4.352	4.390	4.446
442B-15-1, 78–82	2.312	22.19	4.415	4.467	4.498	4.519	4.540	4.590
442B-16-1, 121–124	2.657	21.91	5.080	5.098	5.150	5.182	5.206	5.255
443-49-3, 137–142	2.871	22.29	6.289	6.331	6.360	6.380	6.396	6.430
443-50-1, 117–120	2.873	22.33	6.330	6.390	6.433	6.463	6.486	6.517
443-53-1, 115–119	2.836	22.19	5.688	5.744	5.800	5.856	5.910	5.986
443-54-1, 90–92	2.872	22.27	6.032	6.101	6.140	6.165	6.185	6.245
443-54-3, 7–10	2.884	22.32	6.147	6.214	6.263	6.300	6.334	6.373
443-54-7, 64–67	2.907	22.36	6.148	6.198	6.240	6.277	6.304	6.357
443-55-1, 78–81	2.500	22.36	4.450	4.522	4.556	4.584	4.599	4.635
443-56-2, 50–52	2.484	22.22	4.275	4.321	4.350	4.376	4.400	4.457
443-57-1, 70–74	2.628	22.26	4.734	4.794	4.858	4.888	4.918	4.964
443-58-3, 137–141	2.492	21.71	4.141	4.231	4.288	4.319	4.337	4.371
443-59-3, 98–102	2.782	22.06	5.764	5.818	5.851	5.877	5.894	5.925
443-60-5, 113–116	2.821	22.03	5.870	5.930	5.970	6.030	6.047	6.140
443-61-4, 77–79	2.868	22.19	5.991	6.050	6.103	6.150	6.187	6.235
443-62-2, 43–45	2.690	21.88	5.180	5.270	5.337	5.384	5.412	5.445
443-63-3, 103–107	2.709	22.02	5.446	5.501	5.534	5.560	5.578	5.605
443-64-1, 24–27	2.771	21.85	5.640	5.730	5.794	5.836	5.878	5.910
444A-25-1, 8–12	2.829	22.32	5.820	5.898	5.967	6.024	6.062	6.098
446A-5-1, 12–16	2.934	22.52	6.084	6.110	6.139	6.164	6.185	6.220
446A-7-3, 80–83	2.760	22.73	5.010	5.088	5.150	5.192	5.217	5.247
446A-10-5, 113–117	2.585	22.69	4.980	5.008	5.035	5.060	5.082	5.127
446A-14-1, 85–88	2.661	22.92	4.250	4.310	4.345	4.367	4.383	4.417
446A-15-3, 64–70	2.717	22.88	4.768	4.837	4.876	4.902	4.912	4.950
446A-20-1, 96–99	2.786	22.88	4.948	4.993	5.020	5.042	5.057	5.077

theoretical values predicted for water-saturated basalts by the time-average equation (Wyllie et al., 1956). The first-order control of velocity by porosity is clearly demonstrated by Figure 4. The second-order influence of grain density is demonstrated by Figure 5. Although grain density and velocity correlate well, the high value for the slope of the regression line indicates that the influence of grain density is small when compared to the influence of porosity. The compressional-wave velocities of the selected samples are primarily dependent upon the influence of water-filled pore space. The strong negative correlation between porosity and velocity (Figure 4) was discovered using 1-MHz transducers. Similar strong negative correlations between porosity and velocity were observed for shipboard measurements using 0.4-MHz transducers. These results demonstrate that the compressional waves travel through vesicular basalts at an aggregate velocity which depends only upon the velocity through the solid rock, the velocity through the fluid, and the proportion of the porous rock saturated with fluid. The time-average equation presented by Wyllie et al. (1956) is the best description of the relationships presented here. This behavior is distinctly different than the data for the Lau Basin basalts discussed by Christensen and Salisbury (1975). In that case, compressional waves travelled through vesicular basalts at speeds too great to be aggregate velocities. Christensen and Salisbury (1975) interpreted the velocities to be framework velocities.

The importance of water saturation on compressional-wave velocities is demonstrated by Figure 6, which shows the difference between velocities through water-saturated and air-dried samples [$\Delta V_P = V_P$ (saturated) $- V_P$ (air-dried)] versus the porosity of the sample. Site 446 samples are included in Figure 6, because only the difference in velocity is important, not the absolute values. Velocities measured at 0.5 kbar were used in Figure 6. Negative values of ΔV_P apparently reflect errors in measurement which are less than 3 per cent. Figure 6 demonstrates that the velocity difference between the water-saturated and air-dried samples is large for porosities greater than 2 and less

TABLE 2
Wet-Bulk Densities, Effective Porosities, Grain Densities, and Compressional-Wave Velocities for Air-Dried Basalts of DSDP Leg 58

Sample (Interval in cm)	Wet-Bulk Density (g/cm^3)	Effective Porosity (%)	Grain Density (g/cm^3)	Compressional-Wave Velocity (km/s) at Various Pressures (kbar)					
				0.2	0.4	0.6	0.8	1.0	1.5
442A-34-1, 82–85	2.395	20.70	2.759	3.710	3.922	4.026	4.096	4.152	4.235
442B-7-1, 49–52	2.529	12.61	2.750	4.351	4.555	4.690	4.784	4.855	4.945
442B-11-2, 123–126	2.471	17.72	2.788	4.025	4.149	4.242	4.313	4.369	4.458
442B-13-1, 38–42	2.350	23.77	2.771	4.030	4.154	4.226	4.272	4.307	4.364
442B-16-1, 121–124	2.657	8.47	2.810	4.560	4.643	4.703	4.746	4.775	4.843
443-49-3, 137–142	2.871	1.44	2.899	6.028	6.104	6.163	6.206	6.242	6.310
443-50-1, 117-120	2.873	1.08	2.893	6.328	6.385	6.426	6.457	6.483	6.542
443-53-1, 115–119	2.836	1.96	2.873	5.715	5.779	5.840	5.885	5.928	5.990
443-54-1, 90–92	2.872	0.72	2.885	6.174	6.214	6.238	6.254	6.267	6.288
443-54-3, 7–10	2.884	0.60	2.895	6.165	6.220	6.258	6.290	6.317	6.367
443-54-7, 64–67	2.907	0.37	2.914	6.133	6.174	6.200	6.222	6.244	6.296
443-58-3, 137–141	2.492	14.65	2.748	3.706	3.854	3.956	4.024	4.072	4.156
443-60-5, 113–116	2.821	0.95	2.839	6.018	6.085	6.131	6.164	6.194	6.243
443-61-4, 77–79	2.868	1.02	2.887	5.954	6.007	6.042	6.068	6.080	6.132
443-62-2, 43–45	2.690	4.40	2.769	4.668	4.742	4.802	4.850	4.884	4.953
443-64-1, 24–27	2.771	4.54	2.790	5.235	5.303	5.355	5.394	5.429	5.482
444A-25-1, 8–12	2.829	2.51	2.817	5.610	5.688	5.744	5.793	5.835	5.922
446A-5-1, 12–16	2.934	0.65	2.947	5.948	6.005	6.031	6.065	6.080	6.115
446A-7-3, 80–83	2.760	7.421	2.901	4.410	4.540	4.623	4.687	4.735	4.827
446A-10-5, 113–117	2.585	19.62	2.972	4.656	4.762	4.837	4.876	4.908	4.980
446A-15-3, 64–70	2.717	5.78	2.823	4.225	4.319	4.395	4.455	4.497	4.563
446A-20-1, 96–99	2.786	5.96	2.899	4.068	4.166	4.251	4.326	4.384	4.483
446A-23-2, 46–49	2.711	4.89	2.799	4.378	4.450	4.506	4.544	4.567	4.600

than 10 per cent. The difference is small to non-existent for higher porosities. The large magnitude of the velocity difference at low porosities is similar to the observations made by Nur and Simmons (1969) for low-porosity crystalline rocks. The difference between velocities for dry and saturated samples in the Nur and Simmons experiment was attributed to the influence of pores in the form of cracks rather than in the form of round holes. Leg 58 samples, however, are vesicular over the entire range of porosity. It is difficult, therefore, to separate the importance of crack porosity from vesicularity in this experiment. Gregory (1976) also found that the difference between velocities determined for water-saturated and dry sedimentary-rock samples was greatest for the low-porosity samples.

Figure 6 also shows that the nature of the fluid in the pore space has very little influence on the aggregate velocity. This is surprising, because Figure 4 demonstrates that the time-average equation works well for the water-saturated basalts studied here. The time-average equation, however, does not work for air-filled pore space, as demonstrated by Nur and Simmons (1969). Wyllie et al. (1958) noted similar behavior of the Berea sandstone when different saturating fluids were used. They noted little difference between the velocities for the water-saturated, porous sandstone and the dry sandstone, although the data for the water-saturated sample followed the predictions of the time-average equation.

CONCLUSION

Data presented in this study demonstrate that compressional-wave velocities of basalts recovered during DSDP Leg 58 are primarily dependent upon the porosity of the samples. The strong negative correlation between velocity and porosity and the second-order influence of grain density clearly document this dependence. Porosity is mainly in the form of vesicles, although the influence of crack porosity can not be neglected. The influence of water-saturated pore space can be large. Velocities of samples with porosities around 20 per cent, for instance, can be reduced by as much as 30 per cent. The time-average equation (Wyllie et al., 1956) adequately describes the variation of compressional-wave velocities of Leg 58 basalts as a function of porosity.

The influence of water saturation is most pronounced for samples with porosities less than 10 per cent. At greater porosities, the quantitative effect of water-filled pore space and air-filled pore space is about the same. This effect is similar to that observed for porous sedimentary rocks (Gregory, 1976) and low-porosity crystalline rocks (Nur and Simmons, 1969).

The results discussed here support the idea that fractures in oceanic crustal layer 2a will considerably reduce the seismic-refraction velocities through the layer (e.g., Hyndman, 1976). Although the scale of porosity and the frequency of waves used in this study differ tremen-

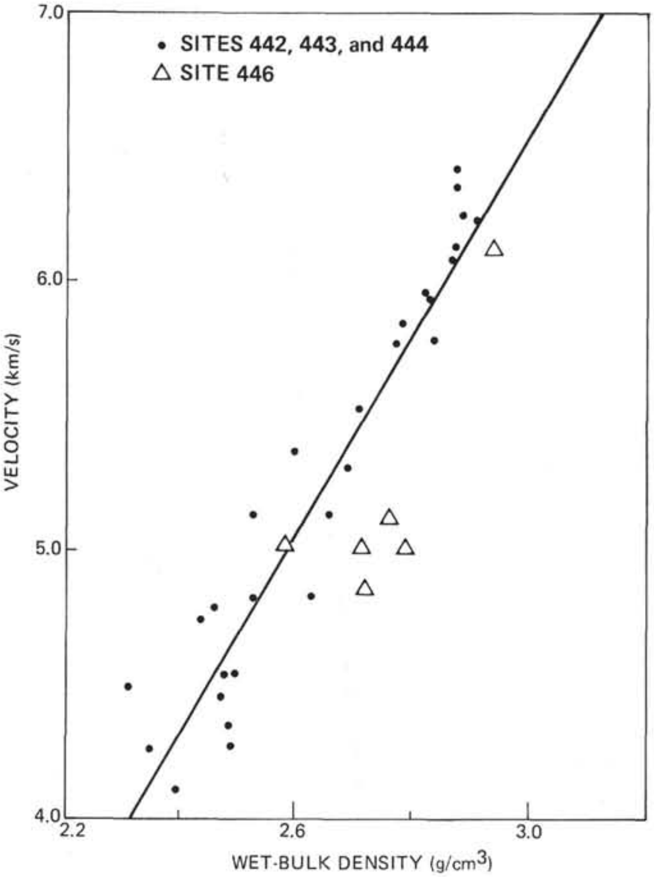

Figure 1. *Compressional-wave velocity at 0.5 kbar versus wet-bulk density for Leg 58 basalts. The linear relationship for Sites 442, 443, and 444 is* $V_p = 3.74\varrho - 4.69$, *with a correlation coefficient of 0.905.*

dously from the scale of fractures in the oceanic crust and frequencies of seismic-refraction experiments, this study demonstrates that porosities between 0 and 25 per cent can significantly reduce compressional-wave velocities in oceanic crustal rocks. In particular, the time-average equation appears to adequately describe the porosity dependence of velocity in basalts saturated with sea water for frequencies which are sensitive to the open pore space.

This study is only a preliminary examination of the influence of porosity and water saturation on seismic velocities in deep-sea basalts. Further work on this problem should focus on the possible frequency dependence of the relationships discussed here, the relative importance of crack porosity versus general volume porosity, the importance of the percentage of water saturation, and the role of pore pressure.

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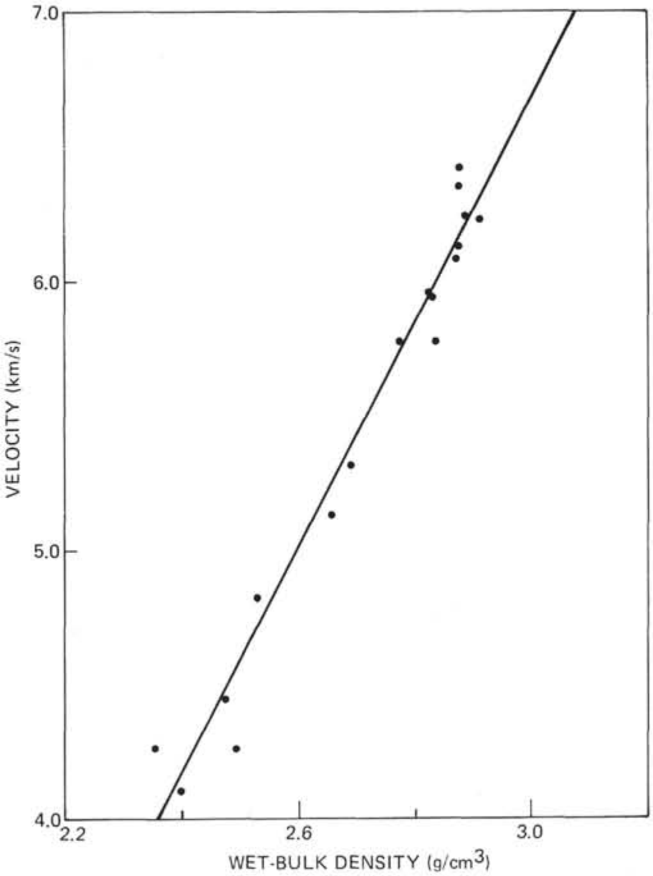

Figure 2. *Compressional-wave velocity at 0.5 kbar versus wet-bulk density for selected samples (no filled vesicles, minimum apparent alteration) from Sites 442, 443, and 444. The linear relationship is* $V_p = 4.17\varrho - 5.84$, *with a correlation coefficient of 0.982.*

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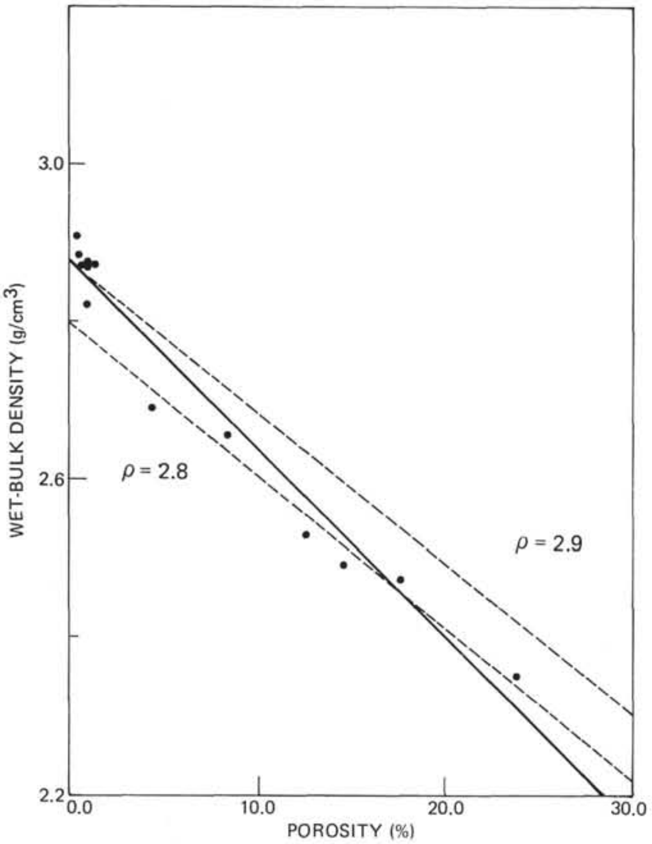

Figure 3. *Wet-bulk density versus porosity for selected samples from Sites 442, 443, and 444. The linear relationship is* $\varrho = -0.024\,\phi + 2.88$*, with a correlation coefficient of* -0.985*. The dashed lines describe the theoretical relationship between porosity and wet-bulk density for grain densities of 2.8 and 2.9 g/cm*^{3}*.*

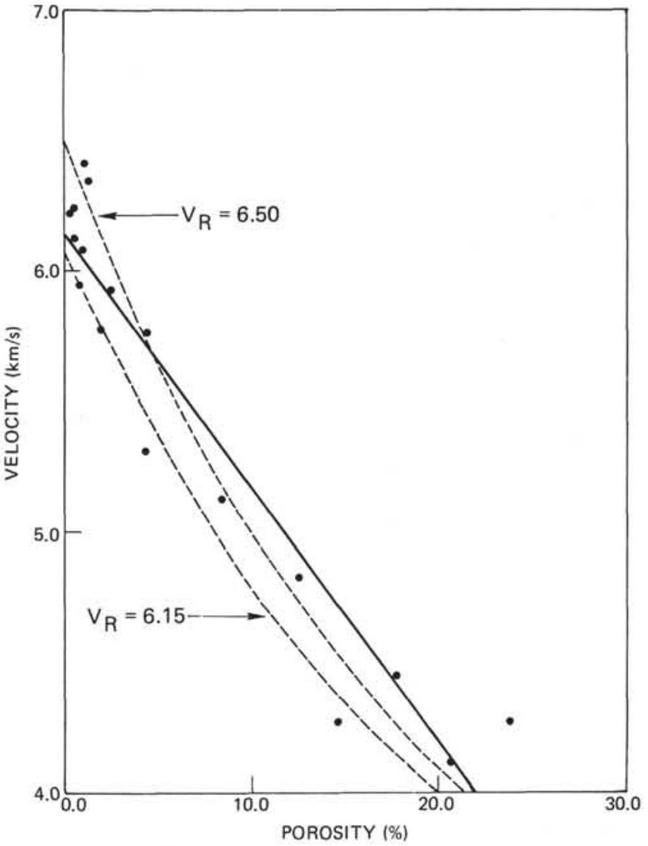

Figure 4. *Compressional-wave velocity at 0.5 kbar versus porosity for selected samples from Sites 442, 443, and 444. The linear relationship is* $V_p = -0.985\,\phi + -0.954$*. The dashed curves are the theoretical curves predicted by the time-average equation for solid-rock seismic velocities of 6.15 and 6.5 km/s.*

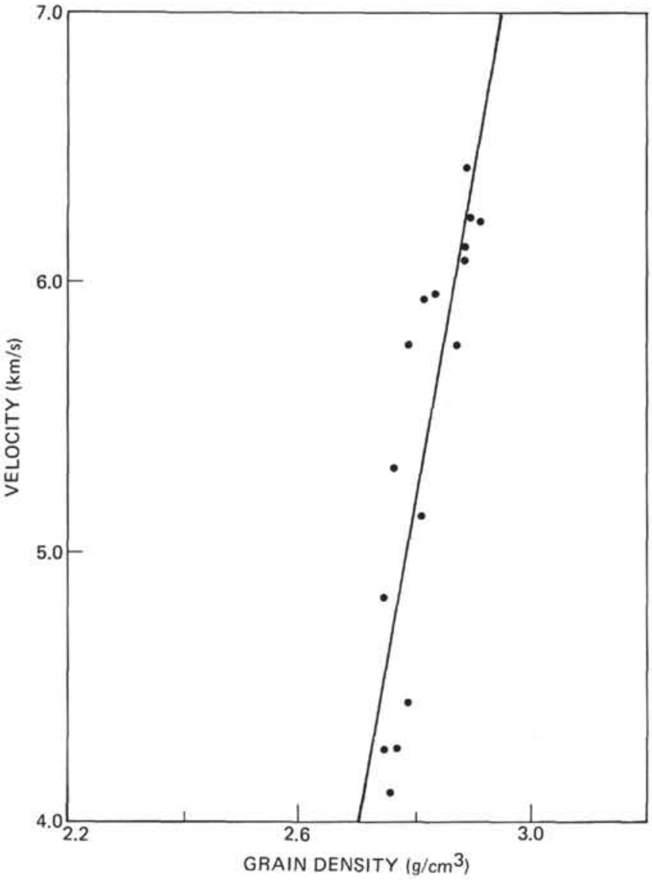

Figure 5. *Compressional-wave velocity versus grain density for selected samples from Sites 442, 443, and 444. The linear relationship is* $V_p = 11.87\varrho - 28.09$, *with a correlation coefficient of 0.873.*

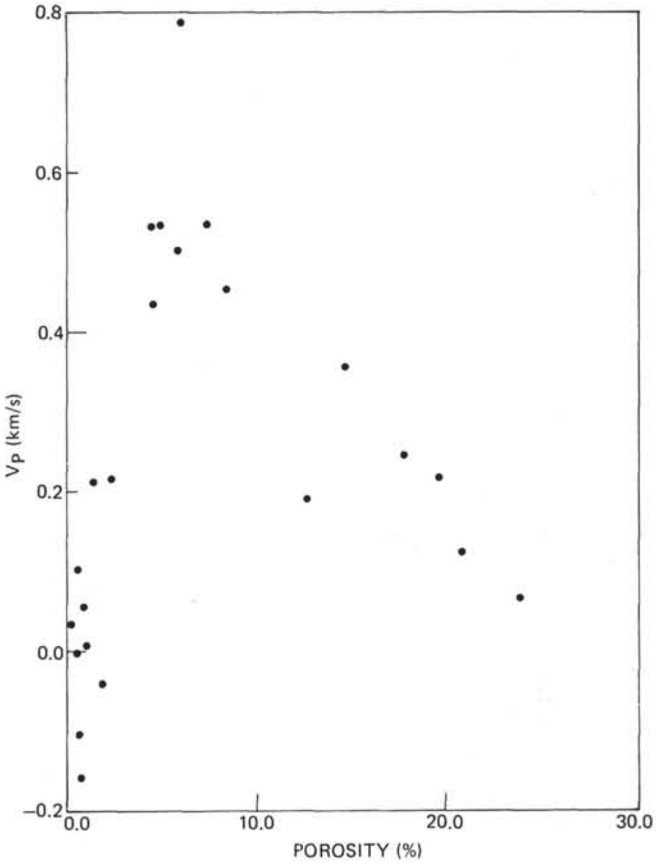

Figure 6. V_p *versus porosity of selected samples from Sites 442, 443, 444 and 446.* ΔV_p *is the difference between the seismic velocity at 0.5 kbar of the water saturated sample and the velocity after the sample has been air-dried.*