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The ratio V_p/V_s as a discriminator of pore geometry for pelagic carbonate sediment

Dae Cheol Kim[1] and Jeong Chang Kim[2]

[1]Department of Applied Geology, National Fisheries University of Pusan, Pusan 608-737, Korea
[2]Department of Shipboard Training, National Fisheries University of Pusan, Pusan 608-737, Korea

Abstract

The ratio of the velocity of compressional (V_p) and shear (V_s) waves in pelagic carbonate sequences (DSDP sites 288 and 289) were calculated to understand the changes in pore geometry with progressive carbonate diagenesis. Generally, the values of the ratio (V_p/V_s) decrease with increasing lithology (i.e., ooze-chalk-limestone). Although there are more or less scatterings, the ratio decreases with decreasing porosity. The relatively lower values of the ratio for siliceous and cherty limestones (1.67 - 1.72 at Site 288 and 1.72 - 1.76 at Site 289) compared to those of the adjacent limestones (1.79 - 1.82 at Site 288 and 1.96 - 2.05 at Site 289) suggest the importance of mineral composition for acoustic property. The increased number of low aspect ratio pores related with silica diagenesis is, however, considered to be partly responsible for lowering the ratio.

INTRODUCTION

The ratio of compressional wave velocity (V_p) and shear wave velocity (V_s) is an important tool to understand microstructure of sediments and rocks as well as their lithology (Hyndman, 1979; Robertson, 1983). Various attempts have been made to express V_p in terms of bulk porosity in water-saturated sediments. The elastic properties of rocks are also function of pore shape and fluid, effective pressure, mineralogy and temperature (Biot, 1956: Kuster and Toksoz, 1974: Mavko and Nur, 1979). For sediments and/or sedimentary rocks, mineralogy, degree of consolidation and cementation are also significant factors to determine acoustic velocity.

In general both V_p and V_s are strongly depends on porosity and saturation conditions. For a given fluid with same porosity, both V_p and V_s are also primarily controlled by pore geometry (Toksoz et al., 1976). It is also well known that V_p is more sensitive than V_p to the numbers of low aspect ratio pores. The aspect ratio (α) is defined as the minor to major axis of a spheroid. It is a measure of flatness of pores and/or cracks. The ratio V_p/V_s can be a valuable factor to understand the pore geometry because the value increases as the total volume of low aspect ratio pores increases in rock. Generally the silica content is considered as a major factor that controls the ratio for carbonate sediment, the pore geometry change related with burial diagenesis is also responsible for the ratio.

This paper reports the profiles of the ratio V_p/V_s to investigate the variations of pore geometry along the two selected pelagic carbonate sequences. The profiles are interpreted in terms of sediment composition and progressive carbonate diagenesis that results in changes in bulk porosity and pore geometry.

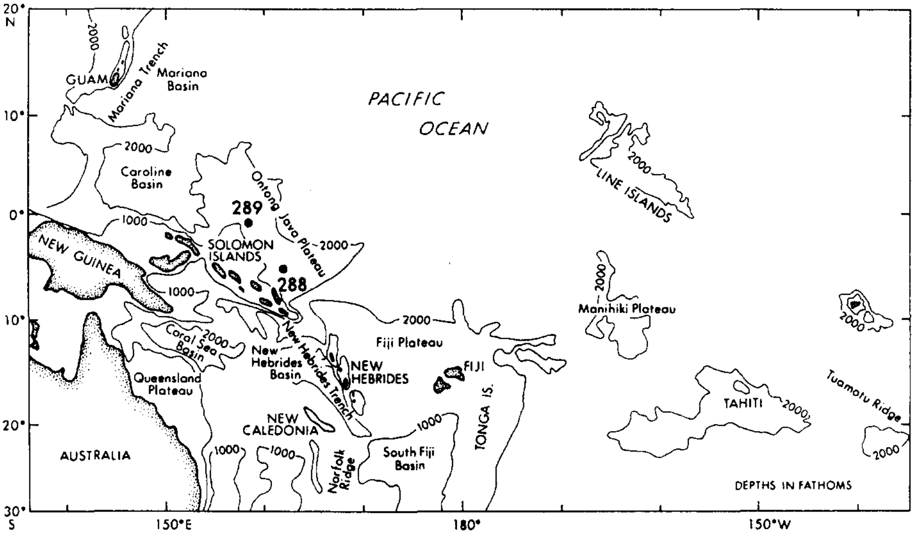

Fig. 1. Locations of DSDP Sites 288 and 289 on the Ontong-Java Plateau in the western equatorial Pacific.

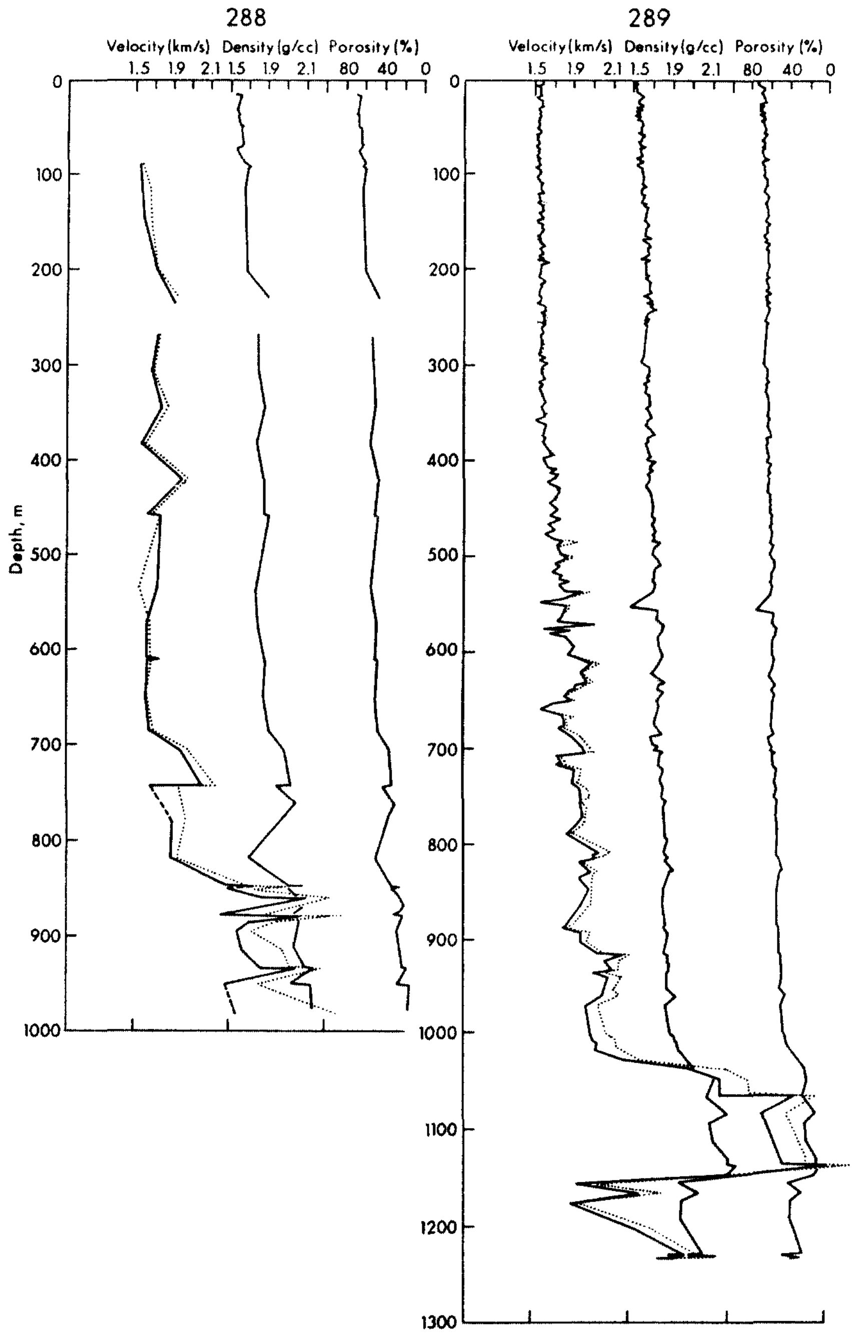

Fig. 2. Velocity, density and porosity profiles for Sites 288 and 289. The solid lines indicate horizontal velocity and dotted lines indicate vertical velocity (from Andrews et al., 1975).

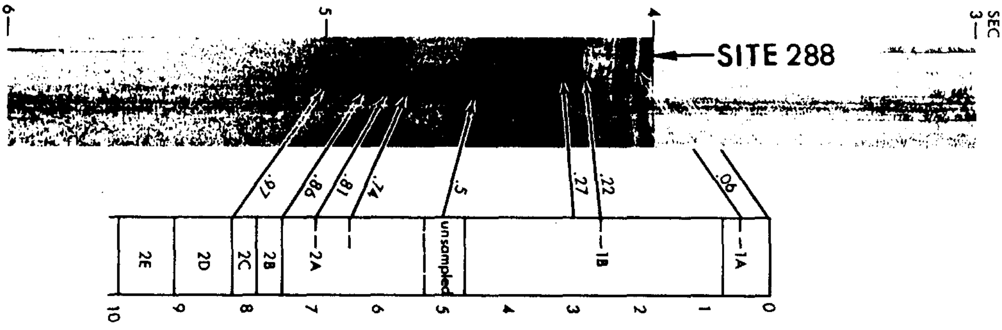

Fig. 3. Correlations of Glomar Challenger seismic reflection profile with the lithologic units at Site 288.

SAMPLES AND EXPERIMENTS

Two pelagic carbonate sequences, drilled by Deep Sea Drilling Project (DSDP Sites 288 and 289), were selected to obtain the almost pure carbonates. The sites are located on the Ontong-Java Plateau in the southwest equatorial Pacific (Fig. 1). The calcium carbonate content is high (mostly more than 90%). Amount of interbedded biogenic and nonbiogenic (mainly volcanogenic) silica increases with subbottom depth for both sites (Andrews et al., 1975). The sites are considered as an ideal model of progressive pelagic carbonate diagenesis showing ooze-chalk-limestone transition (Schlanger and Douglas, 1974).

Site 288 is located on the eastern flank of the Ontong-Java Plateau at water depth of 3000 m (Andrews et al., 1975). The oldest sediments recovered are Lower Cretaceous (Aptian) limestones at 989 m subbottom depth. The basement was not encountered. The calcium carbonate content generally decreases with depth because of increasing amount of chert and volcanic material (Zemmels et al., 1975).

Generally both velocity and density increase gradually with depth. The abrupt changes in physical property at levels below 650 m subbottom depth are believed to be related to compositional variation and induration of the sediments (Fig. 2). For example, the occurrence of dolomite below the depth coincides with the beginning of sharp increase in velocity from 1.6 to 2.4 km/s. This abrupt change is recorded as a prominent seismic reflector (Fig. 3). Several jumps in velocity (2.5 - 3.5 km/s) were also reported in the siliceous zone down below 820 m subbottom depth.

Site 289 is one of the thickest and complete ooze-chalk-limestone sequence drilled in the Pacific Basin. The basal Aptian limestone and tuff lies on basaltic basement at 1271 m subbottom depth (Andrews et al., 1975). Generally the physical property changes gradually with depth. The sudden change in physical property below 1000 m subbottom depth is closely related to the occurrence of chert (Fig. 2).

Each sample for velocity measurement was cut into rectangular parallelepipeds with one pair of faces perpendicular to core axis and two pairs of faces parallel to core axis. A precision wafering saw was used to obtain flat surfaces suitable for the ultrasonic tests. Lengths of the samples range from 15 to 20 mm.

A pulse transmission technique suggested by Birch (1960) was applied to measure both compressional and shear wave velocities. One MHz piezoelectric crystals were used to record transmitted ultrasonic signals through the samples. Water and very viscous poly-(a-methyl)-stylene were used as contact grease to provide strong coupling between the specimen and transducers for VP and VS measurements, respectively (Williams and Lamb, 1958).

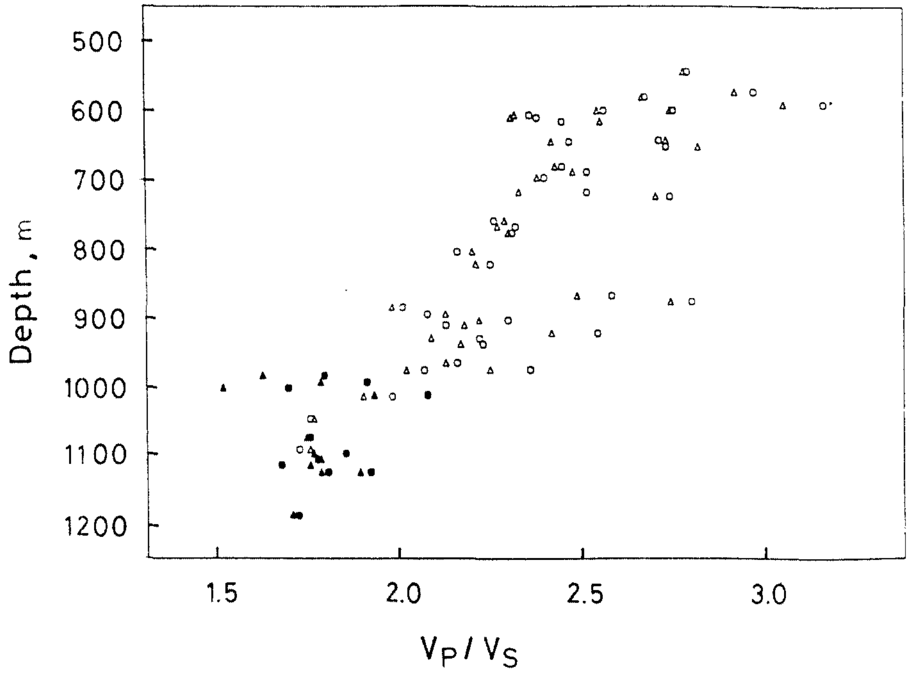

Fig. 4. The V_p/V_s change according to subbottom depth at Site 289. Squares indicate the horizontal velocity and triangles indicate the vertical velocity. Solid symbols represent cherty and siliceous limestones. Note the more scattered values for the ratio for cherty and siliceous limestones than limestones.

To improve the reproducibility of the measurements and to provide high damping, aluminum buffer rods and backing pieces of nearly the same impedance as the transducers were used (Sears and Bonner, 1981: Kim et al., 1983). Bulk porosity and pore-size distributions were measured with a mercury injection porosimeter (Micromeritics 9300).

RESULTS AND DISCUSSION

The ratio of velocity of compressional waves, V_P, to the velocity of shear waves, V_S, (V_P/V_S) is an important parameter to investigate the distribution and shapes of pores and cracks as well as the lithology (Tatham, 1982). for

Table 1. Subbottom Depth, Lithology, V_{PH}/V_{SHH}, and V_{PV}/V_{SHV} at DSDP Site 288

Depth(m)	Lithology	V_{PH}/V_{SHH}	V_{PV}/V_{SHV}
850	Siliceous limestone	1.60	1.62
850	Siliceous limestone	1.74	1.73
851	Siliceous limestone	1.86	1.76
857	Limestone	1.72	1.60
859	Nannofossil limestone	1.79	1.77
859	Limestone	1.85	1.88
859	Limestone	1.84	1.80
868	Nannofossil limestone	1.79	1.74
868	Nannofossil limestone	1.86	1.79
876	Limestone	1.93	1.94
877	Limestone	1.82	1.72
879	Limestone	1.82	1.70
886	Nannofossil limestone	1.80	1.74
914	Nannofossil limestone	1.81	1.87
934	Cherty limestone	1.68	1.66
952	Cherty limestone	1.74	1.60
971	Limestone	1.89	1.86
981	Limestone	1.76	1.80
average for limestone		1.82	1.79
average for siliceous and cherty limestone		1.72	1.67

fully saturated marine sediment that has little variation in composition enhance the significance of crack and pore geometry in determining the value of the ratio.

In general the ratio can be expressed as a function of fluid content and rock fabric under the assumption of the rock with fully saturated pores and almost homogeneous chemical composition. Figure 4 shows the decreasing of the ratio with increasing subbottom depth.

The idea of changes in pore geometry related to the silica diagenesis can be manifested by comparing the ratio of the velocity of compressional (V_p) and shear (V_s) waves. The value of V_p/V_s is an importance indicator to study the crack and pore geometry for a rock particularly that has little variation in composition (Tatham, 1982). Since V_s is more sensitive than V_p for the pores of low aspect ratio (α = minor axis / major axis), the value of Vp/V_s increases as the pores of low aspect ratio increase in a rock.

Table 2. Subbottom Depth, Lithology, V_{PH}/V_{SHH}, and V_{PV}/V_{SHV} at DSDP Site 289

Depth(m)	Lithology	V_{PH}/V_{SHH}	V_{PV}/V_{SHV}
1009	Nanno-foram limestone		2.21
1010	Nanno-foram limestone	2.07	2.02
1017	Nanno-foram limestone		2.28
1018	Cherty limestone		1.62
1027	Nanno-foram limestone		2.16
1037	Siliceous limestone		1.63
1037	Siliceous limestone	1.69	1.51
1050	Nanno-foram limestone		1.78
1050	Nanno-foram limestone	1.85	1.84
1065	Siliceous limestone		1.82
1084	Siliceous limestone	1.75	1.76
1094	limestone		2.23
1112	limestone		1.90
1132	Cherty limestone	1.72	1.75
1138	Cherty limestone	1.85	1.76
1147	Siliceous limestone	1.77	1.78
1167	Siliceous limestone	1.80	1.78
average for limestone		1.96	2.05
average for siliceous and cherty limestone		1.76	1.71

Wilkens et al., (1984) measured V_P and V_S for a set of siliceous limestone from Oklahoma to investigate the effect of pore geometry and composition on the ratio V_P/V_S. Although they concluded that the ratio V_P/V_S is more sensitive to the composition, pore geometry also controls the ratio to some extent. In other words, the ratio increases with increasing carbonate content (i.e., V_P/V_S=1.5 for quartz, and 1.8< V_P/V_S < 2.0 for calcite and dolomite).

Tables 1 and 2 list subbottom depth, lithology, and the ratios in two different directions (i.e., V_{PH}/V_{SHH} and V_{PV}/V_{SHV}) for limestone samples at Sites 288 and 289, respectively. Note the higher average values of the ratio for limestone (1.79 - 1.82 at Site 288 and 1.96 - 2.05 at Site 289) than for siliceous limestone and chert (1.67 - 1.72 at Site 288 and 1.71 - 1.76 at Site 289). These results agree with those of Wilkens et al., (1984).

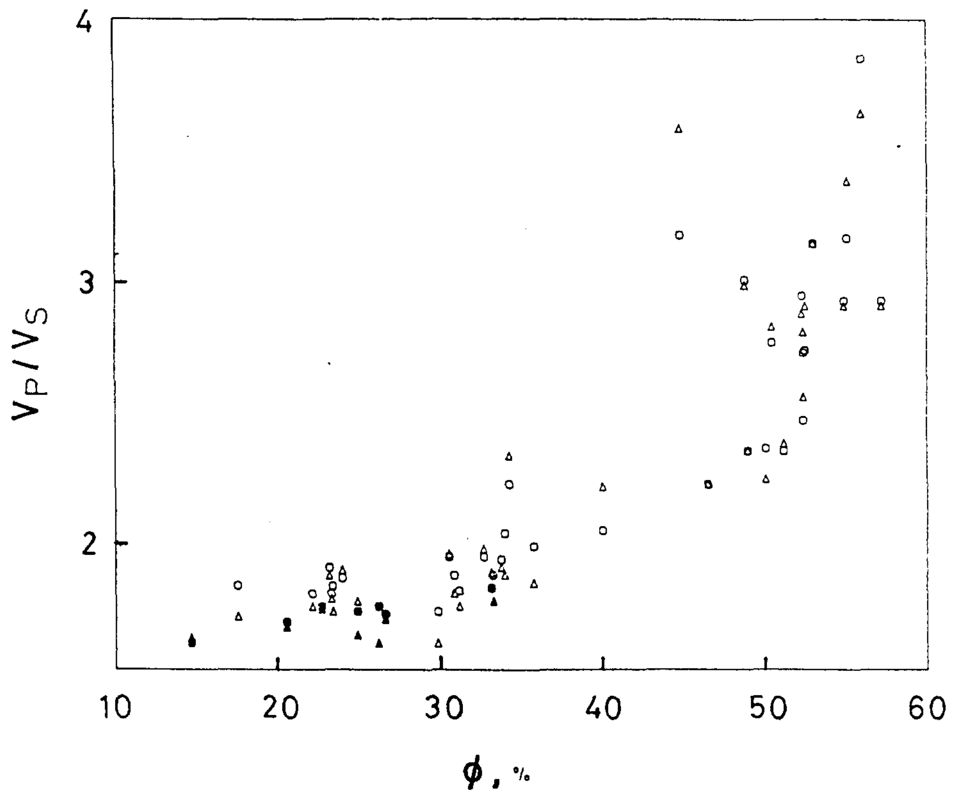

Fig. 5. The ratio versus porosity (ϕ) at Site 288. Symbols are the same as in Figure 4. Note the relatively low values for cherty and siliceous limestones.

The trend is also observed in the plot the ratio against porosity (Fig. 5). The ratio decreases with decreasing porosity. The V_p/V_s values for cherty and siliceous limestones are lower than limestones.

The scatterings can be interpreted in terms of the influence of silica diagenesis on carbonate diagenesis. Van der Lingen and Packham (1975) suggested that surplus calcium carbonate outside the chert nodules, which is released from the replacement of calcite by silica, can be precipitated in adjacent inter- and intraparticle pore spaces. Addition of even a small amount of excess calcium carbonate from outside the small pores will cause the pore connection to decrease faster than the pore spaces. This effect may result in a significant change in pore throat size without a big change in bulk porosity.

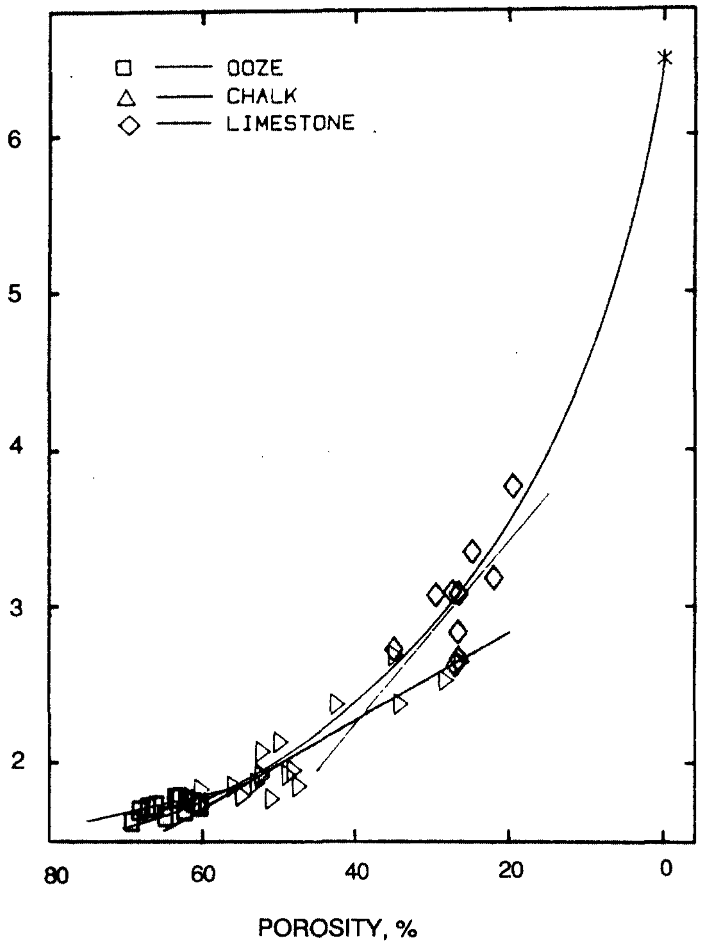

Fig. 6. Porosity versus mean compressional velocity at Site 288. Straight lines represent the least-squares fits for each lithologic group and a curved line extends to a single crystal (marked by an asterisk).

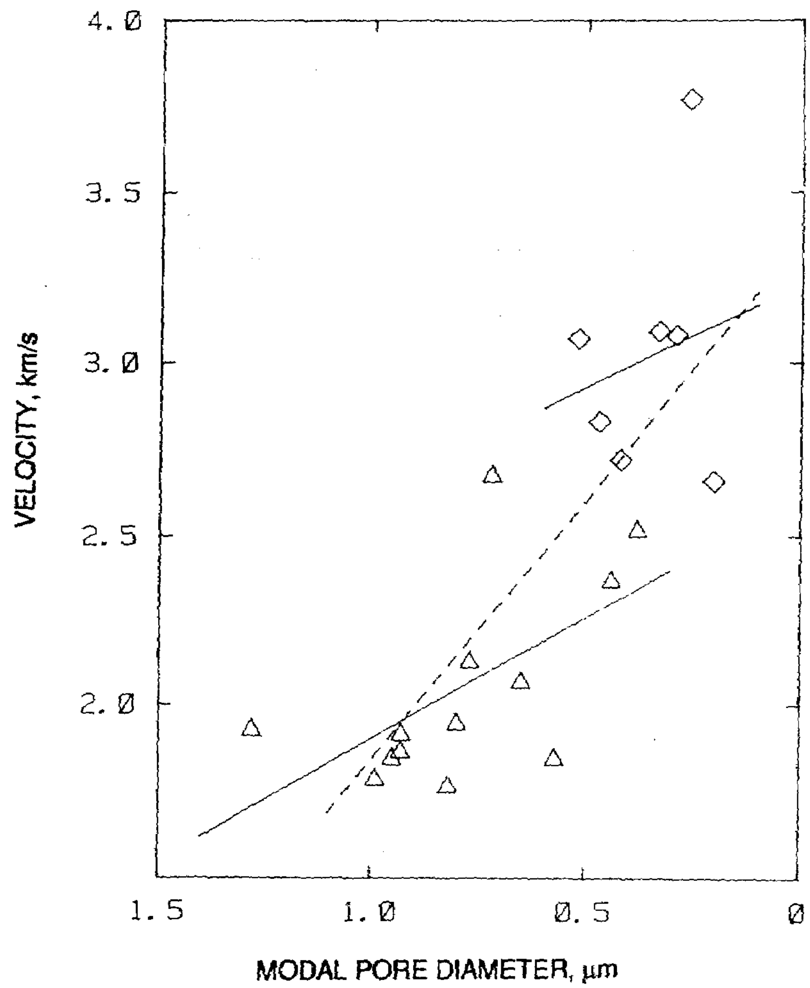

Fig. 7. Modal pore diameter versus mean compressional velocity at Site 288. Symbols are the same as Figure 6. Solids lines indicate the least-squares fits for chalk and limestone, respectively, and the dotted line is the least-squares fit for all the data.

Consequently, the data points in the velocity-porosity plot for Site 288 (Fig. 6) are less scattered than in the velocity-modal pore size plot (Fig. 7). The modal pore size for ooze was unavailable. This trend seems reasonable if we consider that modal pore size is more sensitive to the diagenetic environment than porosity is. Moreover, some highly scattered points in Figure 7, i.e., less than 0.7 mm size range, coincides with the depth of high silica content. There is, however, a general increase in velocity with decreasing modal pore size.

SUMMARY

The ratio of compressional and shear wave velocity (V_p/V_s) in pelagic carbonate sediment decreases with subbottom depth. The ratio also decreases with decreasing porosity. The values for cherty and siliceous limestones are lower than those of limestones with similar subbottom depth. These low values are partly related to silica diagenesis enhancing carbonate diagenesis that results in low aspect ratio pores. The importance of mineral composition for the ratio particularly for the amount of silica, however, should not be ruled out.

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