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Application of electrical resistivity in determining diagenetic stage of deep-sea carbonate sediments : A new variable

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深海底 炭酸塩 堆積物의 續成作用의 程度를 決定할 수 있는 새로운 變數로서의 電氣 抵抗度의 應用 可能性

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Abstract

Laboratory investigations of physical (density and porosity), acoustic (velocity and velocity anisotropy), and electrical (resistivity and resistivity anisotropy) properties in deep-sea carbonate sequences at DSDP sites 288 and 289 in the western equatorial Pacific were made and correlated as a function of diagenesis. Profile of resistivity shows almost a mirror image of velocity indicating that electrical resistivity can be a useful variable to determine the diagenetic stage. Some fluctuations in acoustic and electrical properties near the zones of cherty and siliceous limestones for both sites imply significant changes in pore geometry due to interbedded silica. The significantly reduced pore throat size by the presence of silica which provides excess calcium carbonate to adjacent pore spaces is partly responsible for several jumps in acoustic and electrical properties of the zones. These observed geophysical data are interpreted as the result of silica diagenesis influencing carbonate diagenesis.

요약 : 적도 서태평양에 존재하는 심해저 탄산염 퇴적물(시추공번호 : DSDP 288과 289)에 대한 물리적 성질(밀도와 공극율), 음향학적 성질(속도와 속도성분 차이의 비), 그리고 전기적 성질(전기 저항도와 전기저항 성분 차이의 비)에 대한 실험실적 연구를 퇴적물의 속성작용의 관점에서 행하였다. 전기저항도의 깊이에 따른 변화는 속도의 변화양상과 거의 일치하며 전기저항도가 속성작용을 결정할 수 있는 변수의 하나가 될 수 있음을 보여주었다. 처트나 규산질 석회암 지대에서의 음향학적, 전기적 성질의 급격한 변화는 호층을 이루는 규산염광물 때문에 공극의 모양이 크게 변화함에 기인함을 시사한다. 규산염광물 때문에 만들어진 여분의 탄산칼슘이 주변의 공극사이를 채워 공극연결부가 급격히 감소하는데 이것이 처트와 규산염 석회암 지대의 음향학적, 전기적 성질이 크게 변하는 중요한 이유의 하나라고 생각된다. 이러한 자료는 규산염광물의 속성작용이 탄산염퇴적물의 속성작용을 가속화시킨 결과로 해석된다.

INTRODUCTION

Since the beginning of the Deep Sea Drilling Project (DSDP) diagenetic studies of deep-sea carbonate sediments as well as other types of marine sediments have been accelerated primarily due to the availability of a large number of cores. The continuous cores of various types of marine sediments provided a good opportunity to study the progressive diagenetic changes in terms of sediment depth and age. Efforts have been made to recognize the diagenetic stage as a quantity utilizing geochemical or geophysical parameters. For example, the amount of magnesium (Mg^{+2}) and strontium (Sr^{+2}), and stable isotope ratios ($^{18}O/^{16}O$, $^{13}C/^{12}C$) in carbonate grains, as well as interstitial water are documented with increasing depth and age. These parameters are used as indicators to determine the diagenetic stage (Matter et al., 1975; Manghnani et al., 1980; Garrison, 1981; Baker et al., 1982; Elderfield et al., 1982).

Various attempts have been made to correlate the geophysical parameters (i.e., physical, acoustic, and electrical properties) to sediment diagenesis. The general increases in density (ρ), compressional and shear velocities (V_P, V_S), and electrical resistivity (R), and decrease in porosity (ϕ) with depth and age are reported as a function of diagenesis (Boyce, 1976, 1980; Mayer, 1979; Hamilton, 1980). A number of studies have been conducted to correlate the physical and acoustic properties of deep-sea carbonate sediments to the degree of lithification (Schlanger and Douglas, 1974; Milholland et al., 1980).

Velocity anisotropy became an interesting topic since Hamilton (1970) predicted that marine sedimentary rocks are anisotropic. It is a phenomenon that an acoustic wave travels faster parallel to the bedding plane than the perpendicular to the bedding plane. In accordance with availability of DSDP cores increasing number of papers documented that the acoustic anisotropy is a common feature in marine sediments (van der Lingen and Packham, 1975; Boyce, 1976, 1980; Tucholke et al., 1976).

In order to understand the possible cause of anisotropy and its general increase with depth many researches have been carried out depending on different point of view (Carlson and Christensen, 1979; Kim et al., 1983, 1985). In many models, however, diagenesis is considered as a main mechanism in developing anisotropy with depth. Numbers of preferrably oriented flat and/or horizontally elongated pores and cracks are increased with progressive diagenesis (i.e., dewatering, cementation and recrystallization processes).

Anisotropy studies in the electrical property, i.e., resistivity of marine sediments are very rare. Recently, Schoonmaker et al., (1985) related the acoustic and electrical properties to the mineralogy and diagenesis of DSDP clay-rich sediments. If the pore orientation is a main cause of acoustic anisotropy as indicated by Kim et al., (1983, 1985), it is also a main mechanism that can generate resistivity anisotropy because pore geometry determines the flow characteristics of electrical current in a saturated rock (Walsh and Brace, 1984). This paper relates the profiles of the electrical and acoustic properties of deep-sea carbonate sediments with depth and age and investigates the idea of pore orientation as an important cause of acoustic and electrical anisotropy.

STRATIGRAPHY OF SITES 288 and 289

Two DSDP sites (288 and 289) on the Ontong-Java Plateau in the western equatorial Pacific were chosen for this study (Fig. 1). These pelagic sediment sequences display one of the thickest and most complete ooze-chalk-limestone transition along the sediment column (Andrews et al., 1975; Berger et al., 1977). The $CaCO_3$ content is very high (usually higher than 90%) over most of the sequence. Biogenic calcite produced by calcareous nannofossils and foraminifera is a major component. Amount of other minor components such as interbedded biogenic silica and volcanogenic materials increases with increasing sediment depth (Andrew et al., 1975).

Site 288 was drilled on the eastern salient of the plateau (water depth 3,000 m). The oldest cored sediment is the Aptian cherty limestone (subbottom depth 988.5 m). The seismic basement is, however, pretty close to the core indicating that the oldest sediment is Early

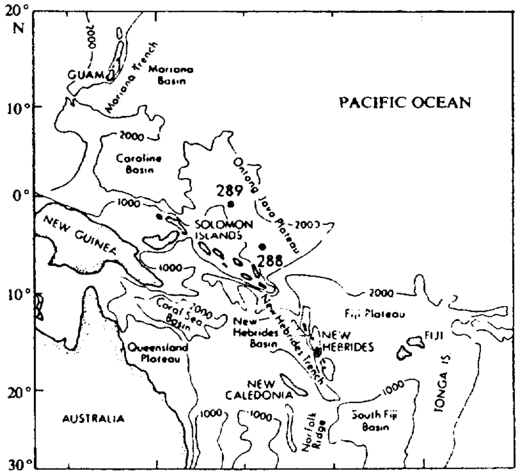

Fig. 1. Locations of DSDP Sites 288 and 289 in the Ontong-Java Plateau, western equatorial Pacific (depths in fathoms).

Cretaceous.

The sediment sequence is divided into two lithologic units (Fig. 2). The boundary corresponds to transition from ooze to chalk at around 500 m subbottom depth. Unit 1 can be subdivided into two subunits depending on the degree of induration and lithologic characteristics. Consolidation increases downward from soft ooze to semi-indurated chalk.

The major composition of Unit 2(533-988.5 m) is chalks and limestones interbedded with cherts and vitric siltstones. This unit is also subdivided into four subunits. Subunit 2A is nannofossil chalk and ooze with increasing amount of interbedded chert with depth. Subunit 2B is characterized by abundant volcanic materials and subunit 2C is similar to subunit 2A. Subunit 2D is dominated by the rhythmic sequences of partially silicified limestone interlaminated with vitric siltstone and interbedded chert.

Site 289 was drilled on the northern part of the plateau (water depth 2,206 m). The Early Cretaceous basaltic basement was encountered at 1,265.5 m subbottom depth (Andrews et al., 1975). This anomalously thick, pelagic carbonate sequence is divided into three lithologic units (Fig. 3). Compared to Site 288 the

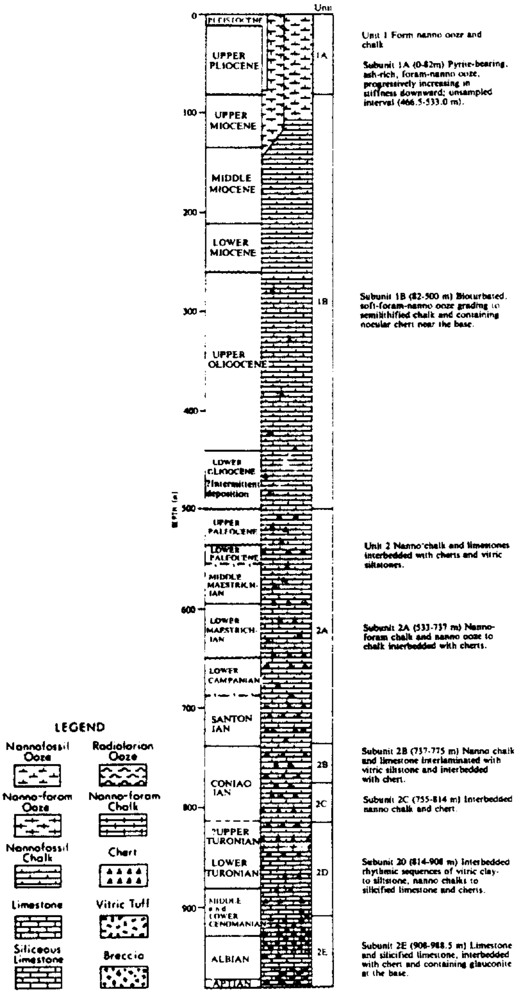

Fig. 2. Stratigraphic column of DSDP Site 288 (from Andrews et al., 1975).

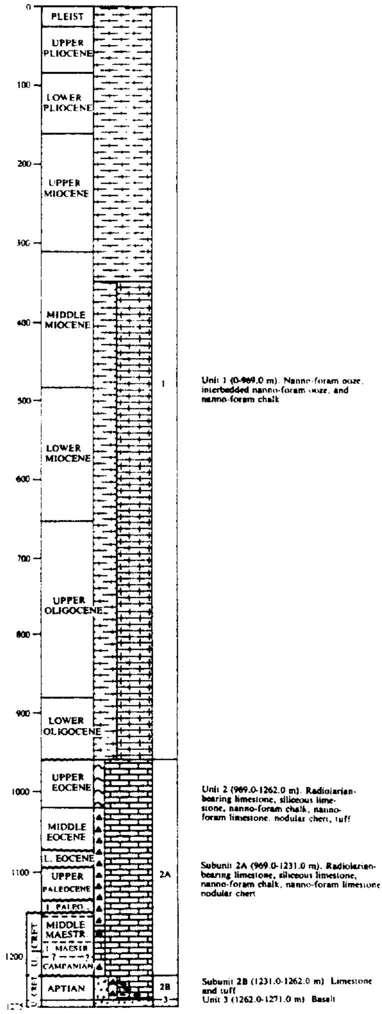

Fig. 3. Stratigraphic column of DSDP Site 289 (from Andrews et al., 1975).

lithology is rather simple. Unit 1 is nanno-foram ooze and chalk. Unit 2 is limestone, siliceous limestone, nanno-foram chalk, nodular chert, and tuff, and Unit 3 is basaltic basement. The sediment sequence is further divided into five units for the convenience of interpreting the physical properties.

EXPERIMENTAL TECHNIQUES

The magnitude of complex resistivity of specimen was measured by applying of the four-electrode technique similar to that described by Olhoeft (1980). This technique has an advantage of eliminating electrochemical polarization. Two pairs of current and potential electrodes therefore employed. To monitor the current a sinusoidal voltage source (HP 3325A synthesizer) was applied both to a sample and to a variable standard resistance (General Radio 1433H). The voltage across the sample and the standard resistor were measured using a digital processing oscilloscope (Nicolet 4094). The two digitized signals were processed by a mini-computer (HP 9920) which calculates the complex ratio of the Fourier amplitudes and phases of two signals (Fig. 4).

The measurements were made on two orthogonal directions of the sediment samples (i.e., parallel and perpendicular to the core axis) to observe differences in resistivity values (resistivity anisotropy). The resistivity anisortropy is definded by (Schoonmaker et al., 1985)

$$A_R = \frac{R_V - R_H}{R_M} \times 100\ (\%)$$

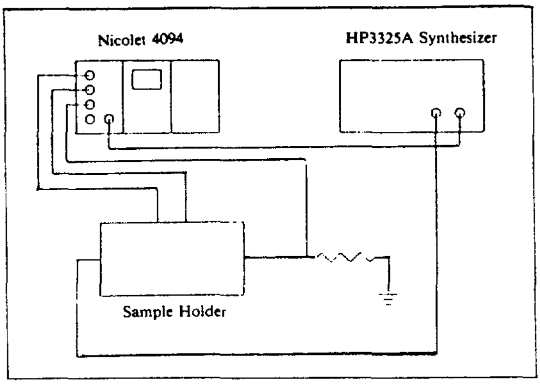

Fig. 4. Schematic diagram of 4-electrode method for electrical resistivity measurement.

where R_V is vertical resistivity (parallel to the core axis), R_H is horizontal resistivity (perpendicular to the core axis) and R_M is mean sample anisotropy. Usually R_V is greater than R_H (i.e., $R_V > R_H$).

Sample holder was designed to measure resistivity for different size and shape of samples. Platinum electodes were used on the sample holders. Although the measured frequency range was 100 Hz to 18 KHz, the resistivity values at 100 Hz were used as data.

The velocity was measured using the pulse transmission technique under ambient condition similar to that of Birch (1960). Ultrasonic frequency (1 MHz) was applied to improve the accuracy of measurement (Kolsky, 1953). Measurement errors less than 2% possibly arise from variations in sediment temperatures (Hamilton, 1974) and poor coupling between transducers and the soft sediment.

Similar to the case of electrical resistivity the velocity measurements were carried out two orthogonal directions of the specimens. The velocity anisotropy for compressional waves (A_P) is defined by (Kim et al., 1983)

$$A_P = \frac{V_{PH} - V_{PV}}{V_{PM}} \times 100\ (\%)$$

where V_{PH} represents compressional velocity in the horizontal direction, V_{PV} represents compressional velocity in the vertical direction, and V_{PM} is the mean for the two velocities. Beacuse horizontal velocities are generally faster than vertical velocities (i.e., $V_{PH} < V_{PH}$), A_P is usually positive.

Porosity and bulk density were measured using mercury injection porosimetry (Micromeritics 9300). This technique, however, is accurate only for consolidated or semi-consolidated specimens such as chalk and limestone because of volume loss in unconsolidated samples during the drying step of the preparation process. Thus, porosity data on shallowly buried soft sediments were obtained from DSDP.

RESULTS AND DISCUSSION

Figure 5 shows the profiles of age, bulk density (ρ), porosity (ϕ), compressional velocity (V_P), velocity anisotropy (A_P), electrical resistivity (R), and resistivity anisotropy (A_R) for Site 288 in terms of depth of burial. A

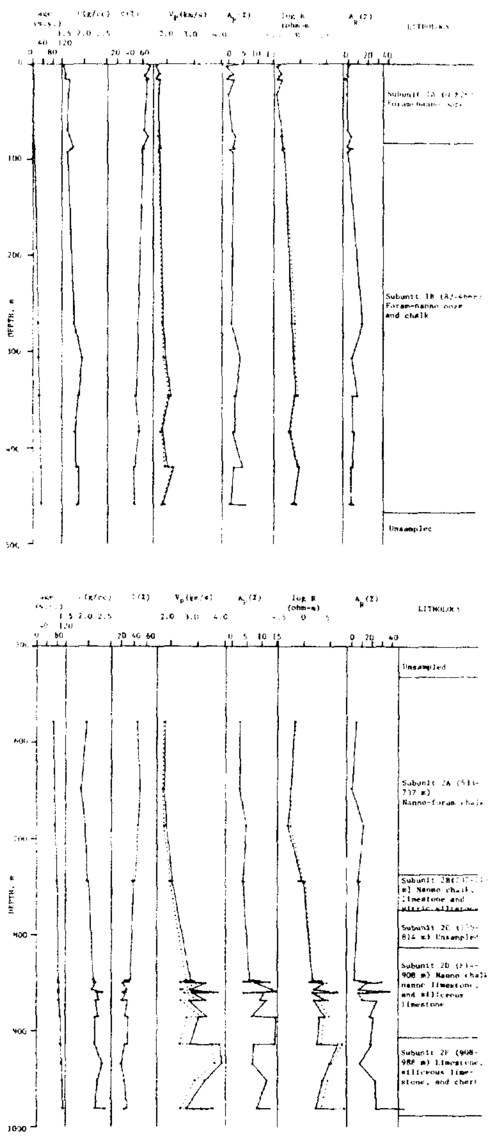

Fig. 5. DSDP Site 288 physical properties: age, density, porosity, compressional velocity, velocity anisotropy, electrical resistivity, and resistivity anisotropy. Solid lines for V_P and log R indicate horizontal direction and dotted lines indicate vertical direction. Note the fluctuations at subunit 2D.

small fluctuation in physical properties near the bottom of subunit 1B appears to be related to the increasing bioturbation and appearance of nodular chert. Except for subunit 2D, however, generally ρ,V_p and R in the stratigraphic column increase more or less systematically with depth.

The lithologic composition of subunit 2D is dominated by the rhythmic sequences of partially silicified limestone and interbedded chert. The several jumps in velocity (2.6-3.8 km/s) and resistivity (1.3 - 3.8 ohm-m) as well as density (2.1 - 2.3 g/cm^3 and porosity (35 -23%) in the subunit imply the strong correlation between physical and acoustic properties and sediment composition. The very high velocity and resistivity values in the layers of siliceous limestone and chert near the top and bottom of subunit 2E can be interpreted as the same idea.

In the light of the foregoing observations the behavier of velocity profile matches very well with that of resistivity. The result is more encouraging in Site 289 (Fig. 6). The mirror image exists between velocity and resistivity in the zones of complicated lithology (Units 4 and 5). Similar to Site 288 the several jumps in density, velocity, and resistivity at the top of Unit 4 and at the boundary between Units 4 and 5 are correspond to the occurrence of cherty and siliceous limestone.

These abrupt jumps in physical and acoustic properties in layers of cherty and/or siliceous limestone are result of diagenetic effect rather than the composition itself. Van der Lingen and Packham (1975) suggested the possibility of silica diagenesis affecting carbonate diagenesis. In their model the surplus

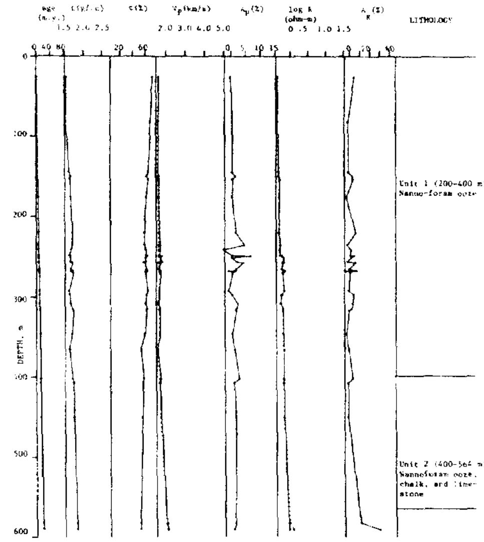

Fig. 6. DSDP Site 289 physical properties: symbols and lines are the same as in Fig. 5. Note the fluctuations at Units 4 and 5.

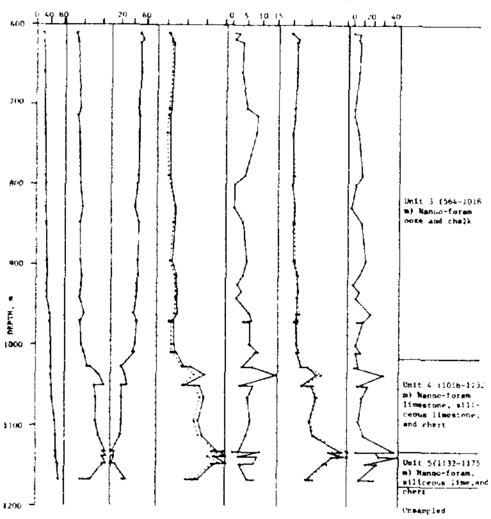

Fig. 6. (continued)

calcium carbonate released from the chert nodules by replacement of calcite by silica is precipitated the adjacent pore spaces. Recently, Kim et al., (1985) found a supporting evidence of the idea by observing dramatic changes in pore geometry in zones of high silica content (i.e., siliceous and cherty limestones) which result in fluctuations of velocity and velocity anisotropy in deep-sea carbonate sequences.

It is interesting to compare the profiles of velocity and resistivity anisotropy (A_P, A_R) in terms of possible causes. It is not an accident that both A_P and A_R follow the similar profiles if the anisotropies originate from the same mechanism. Preferred vertical orientation of calcite c axes was considered the main cause of velocity anisotropy after the high pressure experiment of Carlson and Christensen (1979). Kim et al., (1983) were skeptical about the result because they did not control the pore pressure accurately. Using the improved high pressure technique, which means newly designed sample holder that can control both confining and pore pressure independently, and ultrasonic attenuation (Q_P^{-1}, Q_S^{-1}), Kim et al., (1983) concluded that the horizontally elongated flat pores (i.e., pore orientation) are the main cause of the observed anisotropy. Recently, Kim et al., (1985) further support this idea by observing the flat pores which aligned dominantly in horizontal direction in the Scaning Electron Microscope (SEM) photographs.

Quantification of diagenesis by physical, acoustic, and electrical properties is based on the concept that changes in pore geometry are related with progressive diagenesis. Pores and pore connections (throats) become flatten and elongated horizontally due to the overburden pressure. In deep-burial diagenesis solid solution process can intensify development of the sheet-like pore connections (Wardlaw, 1976; Scholle, 1979). This variation in pore geometry determines both acoustic and electrical properties because narrow pore connections not only decrease elastic moduli but also prevent the flows of electrical current.

Figures 7 and 8 plot log resistivity versus velocity for Sites 288 and 289 separating according to lithology (ooze-chalk-limestone). On one hand, strong positive correlations between velocity and resistivity for both sites suggest the possibility that resistivity can be a

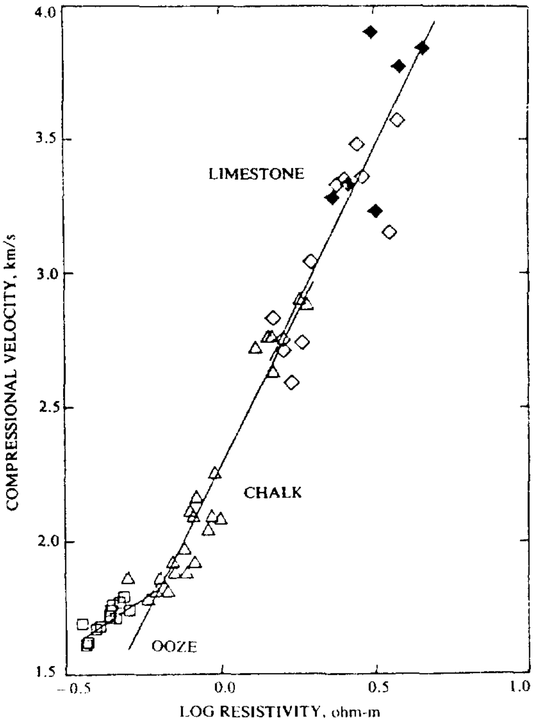

Fig. 7. Log resistivity versus compressional velocity for DSDP Site 288. Solid lines represent the least-squares fits for each lithologic group (ooze-chalk-limestone). Square represent ooze, triangles represent chalk, and diamonds indicate limestone. Solid diamonds represent siliceous or cherty limestones.

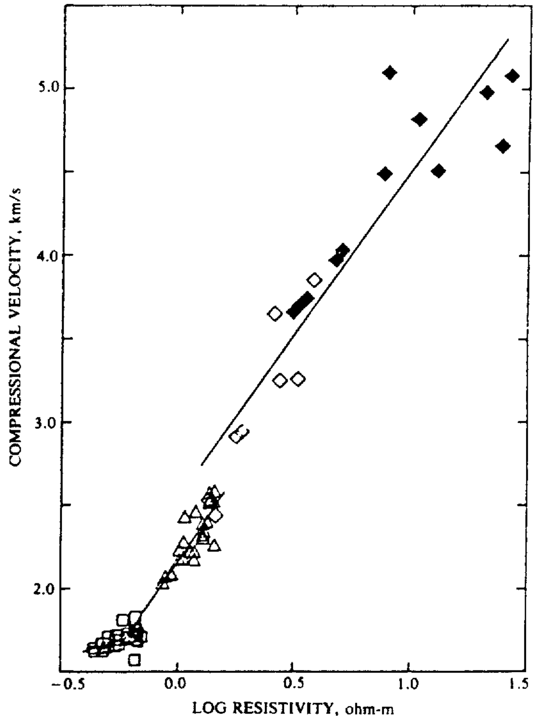

Fig. 8. Log resistivity versus compressional velocity for DSDP Site 289. Symbols are the same as in Fig. 7. Note the highly scattered data points for siliceous or cherty limestones.

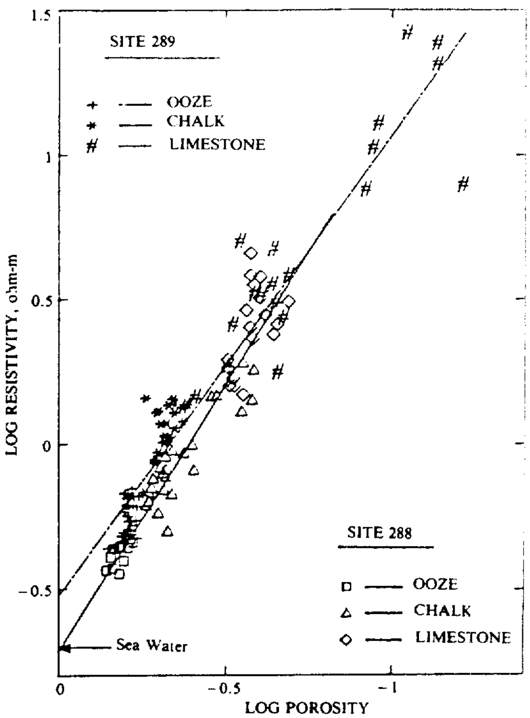

Fig. 9. Log porosity versus log resistivity for DSDP Sites 288 and 289. Solid line indicates the least-squares fits for Site 288 and brocken line represents the least-squares fits for Site 289.

good indicator to determine the diagenetic stage as well as acoustic velocity. On the other hand, the relatively scattered data points for limestones of high silica content at Site 289 can arise an argument because the high values of velocity and resistivity can be considered due to differences in lithologic composition rather than silica diagenesis affecting carbonate diagenesis. By synthesizing laboratory data on deep-sea carbonate sediments, however, recently Kim et al., (1985) concluded that diagenesis is a primary factor controlling elastic moduli which govern acoustic property. They used the plots between different parameters such as porosity, pore geometry (modal pore size), velocity, and ultrasonic attenuation. The results consistently support the importance of pore geometry determining physical and acoustic properties.

However, this effect of silica diagenesis on the resistivity and velocity is weaker at Site 288 than at Site 289 because of relatively smaller amount of silica content at Site 288. Figure 9 compares log porosity-log resistivity for Sites 288 and 289. Note the differences in the slopes of least-square fit lines. For Site 288 the linear fit match well with the estimated sea water resistivity (−0.70) whereas the linear fit for Site 289 crosses a high value. Probably the abnomally high resistivity in cherty and siliceous limestones caused by their thin pore connections results in higher Y-intercept value for Site 289 because both the Y-intercept and slope are function of cementation, textures, and mineralogy of sediment (Winsauer et al., 1952). However, the flowage of electrical current is primarily controlled by the pore geometry rather than the rock matrix (Walsh and Brace, 1984).

CONCLUSIONS

Electrical resistivity as well as other physical and acoustic properties reveal as an important variable to determine the diagenetic stages of deep-sea carbonate sediments. The good correlations for velocity versus resistivity, and/or velocity anisotropy versus resistivity anisotropy are very encouraging.

Along the sediment column geophysical parameters such as density, velocity, velocity anisotropy, resistivity, and resistivity anisotropy increase with depth of burial and age. These overall changes are interpreted in terms of progressive diagenesis. In order to explain the several fluctuations in physical, acoustic, and electrical properties, the idea of silica diagenesis enhancing carbonate diagenesis is introduced. The exceptionally high values in velocity and resistivity reflect the dramatic decrease of pores and pore connections which cannot be explained by simple progressive carbonate diagenesis. Although the possibility of the influence of mineralogical change on resistivity cannot be ruled out, the accerleration of carbonate diagenesis induced by interbedded silica is considered as the major mechanism for the observed high resistivity values in the zones of cherty and siliceous limestones.

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REFERENCES

Andrews, J.E. et al., 1975. Initial Reports of the Deep Sea Drilling Project, **30:** 753 pp.

Baker, P.A., J.M. Gieskes, and H. Elderfield, 1982. Diagenesis of carbonate in deep-sea sediments-evidence from SrlCa ratios and interstitial dissolved Sr^{+2} J. Sed. Petrol., **52:** 71-82.

Berger, W.H., T.C. Johnson, and E.L. Hamilton, 1977. Sedimentation on Ontong-Java Plateau: observations on a classic 'carbonate monitor'–in The Fate of Fossil Fuel CO_2 in the Oceans, N.R. Anderson and A. Malahoff (eds.), 543-567, Plenum, New York.

Birch, F., 1960. The velocity of compressional waves in rocks up to 10 kilobars. J. Geophys. Res., **65:** 1083-1102.

Boyce, R.E., 1976. Sound velocity-density parameters of sediment and rock from DSDP drill sites 315-318 on the Line Islands Chain, Manihiki Plateau, and Tuamotu Ridge in the Pacific Ocean, in Initial Reports of the Deep Sea Drilling Project. **33:** 695-728.

Boyce, R.E.. 1980. Determination of the relationships of electrical resistivity, sound velocity, and density/porosity of sediment and rock by laboratory techniques and well logs from Deep Sea Drilling Project Sites 415 and 416 off the coast of Morocco, in Initial Reports of the Deep Sea Drilling Project. **50:** 305-318.

Carlson, R.L., and N.I. Christensen, 1979. Velocity anisotropy in semi-indurated calcareous deep-sea sediments. J. Geophys. Res., **84:** 205-211.

Elderfield, H., J.H. Gieskes, P.A. Baker, P.K. Oldfield, C.J. Hawkesworth, and R. Miller, 1982. ^{87}Sr/^{86}Sr and ^{18}O/16O ratios, interstitial water chemistry and diagenesis in deepsea carbonate sediments of the Ontong-Java Plateau. Geochim. Cosmochim. Acta, **46:** 2259-2268.

Garrison, R.E., 1981. Diagenesis of oceanic carbonate sediments, A review of the DSDP propective. SEPM spec. publ., No. **32:** 181-207.

Hamilton, E.L., 1970. Sound velocity and related properties of marine sediments, North Pacific. J. Geophys. Res., **75:** 4423-4446.

Hamilton, E.L., 1974. Prediction of deep-sea carbonate properties: state-of-the-art, in Deep Sea Sediments, physical and mechanical properties, A.L. Inderbitzen (eds.), 1-43, Plenum, New York.

Hamilton, E.L., 1980. Geoacoustic modeling of the sea floor. J. Acoust. Soc. Am., **68:** 1343-1340.

Kim, D.C., K.W. Katahara, M.H. Manghnani, and S.O. Schlanger, 1983. Velocity and attenuation anisotropy in deep-sea carbonate sediments. J. Geophys. Res., **88:** 2337-2343.

Kim, D.C. M.H. Manghnani, and S.O. Schlanger, 1985. The role of diagenesis in the development of physical properties of deep-sea carbonate sediments. Mar. Geol., **69:** 69-91.

Kolsky, H., 1953. Stress waves in solids. Clarendon Press, Oxford, Great Britain.

Manghnani, M.H., S.O. Schlanger, and P.D. Milholland, 1980. Elastic properties related to depth of burial, strontium content and age, and diagenetic stage in pelagic carbonate sediments. in Bottom-Interacting Ocean Acoustics, W.A. Kuperman and F.B. Jensen (eds.), 41-51, Plenum, New York.

Matter, A., R.G. Douglas, and K. Perch-Nielson, 1975. Fossil preservation, geochemistry and diagenesis of pelagic carbonates from Shatsky Rise, northwest Pacific, in Initial Reports of the Deep Sea Drilling Project, **32:** 891-922.

Mayer, L.A., 1979. Deep sea carbonates: acoustic, physical, and stratigraphic properties. J. Sed. Petrol., **49:** 819-836.

Milholland, P.D., M.H. Manghnani, S.O. Schlanger, and G. Sutton, 1980. Geoacoustic modeling of deep-sea carbonate sediments. J. Acoust. Soc. Am., **68:** 1351-1360.

Olhoeft, G.R., 1980. Initial reports of the petrophysics laboratory: 1977-1979 addendum. U.S. Geol. Survey Open File Rept., 80-522, 9 pp.

Schlanger, S.O., and R.G. Douglas, 1974. The pelagic ooze-chalk-limestone transition and its implication for marine stratigraphy. spec. publ. Intl. Assoc. Sedimentol., **1:** 117-148.

Scholle, P.A., 1979. Porosity prediction in shallow versus deep water limestone-primary porosity preservation under burial conditions: in Geology of Carbonate Porosity. A.A.P.G. Continuing Education Course Note Series #**11**: D1-D12.

Schoonmaker, J., F.T. Mackenzie, M.H. Manghnani, R.C. Schneider, D.C. Kim, A. Weiner, and J. To., 1985. Mineralogy and diagenetic characteristics and their effect on acoustic and electrical properties of pelagic clays, DSDP Leg 86, in Initial Reports of th Deep Sea Drilling Project, **86**: 549-570.

Tucholke, B.E., N.T. Edgar, and R.E. Boyce, 1976. Physical properties of sediments and correlations with acoustic stratigraphy, leg 35, Deep Sea Drilling Project, in Initial Reports of the Deep Sea Drilling Project, **35**: 229-249.

van der Lingen, G.J., and G.H. Packham, 1975. Relationships between diagenesis and physical properties of biogenic sediments of the Ontong-Java Plateau (Sites 288 and 289, DSDP), in Initial Reports of the Deep Sea Drilling Project, **30**: 443-481.

Walsh, J.B., and W.F. Brace, 1984. The effect of pressure on porosity and the transport properties of rock. J. Geophys. Res., **89**: 9425-9432.

Wardlaw, N.C., 1976. Pore geometry of carbonate rocks as revealed by pore casts and capillary pressure. A.A.P.G., **60**: 245-257.

Winsauer, W.D., H.M. Shearing, Jr., P.H. Mason and M. Williams, 1952. Resistivity of brine-saturated sands in relation to pore geometry, A.A.P.G. Bull., **36**: 253-277.

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