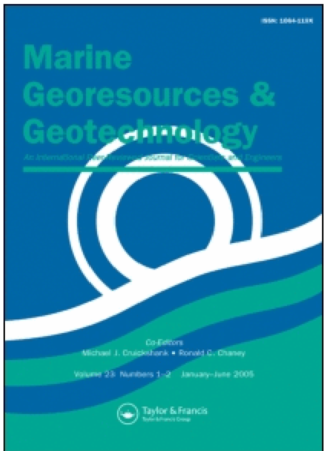

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Vertical Variations of Core Sound Velocity: Evidence of Paleooceanographic History Since the Pleistocene Epoch

Bo Lu [a]; Shaojian Huang [a]; Ganxian Li [a]; Fusheng Zhang [a]
[a] Laboratory of Marginal Sea Geology, South China Sea Institute of Oceanology and Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, P.R. China.

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BO LU
SHAOJIAN HUANG
GANXIAN LI
FUSHENG ZHANG

Laboratory of Marginal Sea Geology
South China Sea Institute of Oceanology and
Guangzhou Institute of Geochemistry
Chinese Academy of Sciences, Guangzhou, P.R. China

The vertical variations in the borehole core sound velocity (Cp) of the submarine sediments are related to the events of marine transgression and regression in the geologic history. This article establishes the vertical variation of Cp curve for the borehole sound velocity in the northern South China Sea continental shelf and the East China Sea continental shelf, thus providing evidence for revealing at least (3) sedimentary cycle events of marine transgression and regression occurring in the west Pacific marginal sea since the Pleistocene Epoch. The sound velocity of marine sediments brought in the course of marine transgression is lower (1450–1510 m/s) while that of continental sediments formed in the course of marine regression is higher (1650–1720 m/s).

Keywords northern South China Sea, East China Sea, continental shelf, marine transgression and regression, sound velocity in core sediment, sedimentary bedding

The vertical variations in the sound velocity of a borehole core of submarine sediments are mainly determined by its physical properties (Orio and Dunn 1990). The differences in the physical properties of the core are closely related to geologic historical changes, such as large-scale events of marine transgression and regression, and crustal tectonic movement. This article studies core data from eight geologic boreholes (A3, A7, A15, A22, N1, N2, B1A, B1B; see Figure 1) from the northern South China Sea continental shelf and the East China Sea continental shelf in China (hereinafter referred to as the sea areas). In addition, the vertical variation curve for measurements of borehole core sound velocity *Cp* are presented and used to identify the sedimentary

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Address correspondence to Lu Bo, South China Sea Institute of Oceanology, Chinese Academy of Sciences. 164 West Xingang Road, Guangzhou, 510301, China. E-mail: salu@scsio.ac.cn

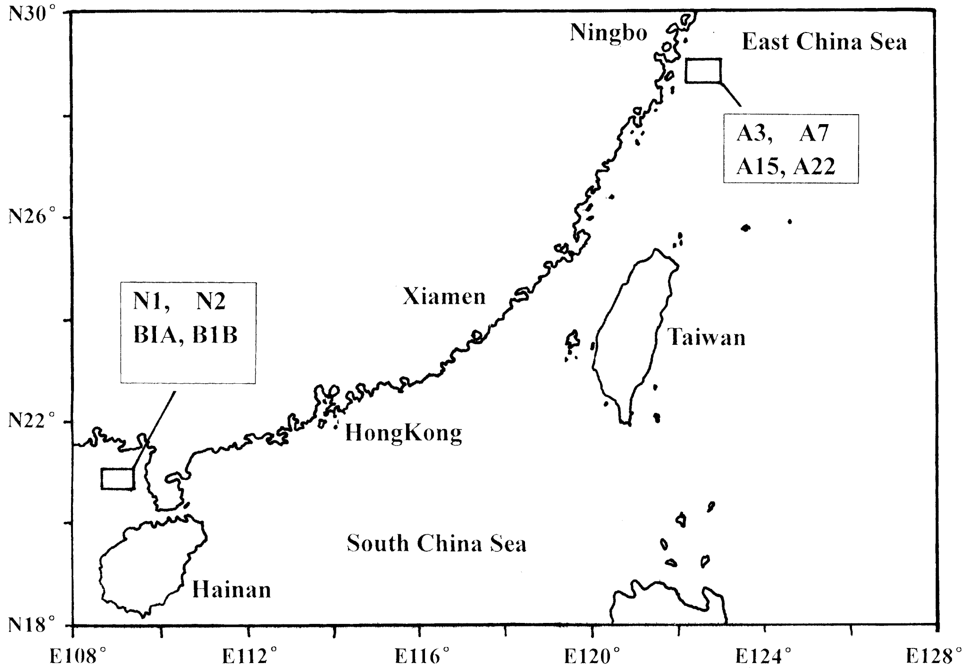

Figure 1. The map of core stations on continental shelf of the East China Sea and the part of the northern South China Sea.

bedding of the alternation and supraposition of marine and continental deposits in the two sea areas resulting from marine transgression and regression since the Pleistocene epoch. This makes a contribution to the research on the geologic events of marine transgression and regression in the marginal seas of the West Pacific.

Events of Marine Transgression and Regression Occurring in the Two Sea Areas Since the Pleistocene Epoch

The East China Sea continental cores (Figure 1: A3, A7, A15, and A22) were collected by the Zhejiang Academy of Geology Engineering Reconnaissance with a drilling boat, and the samples were prepared and measured by its Soil Test Laboratory. The cores of Northern South China Sea continental (Figure 1: N1, N2, B1A, and B1B) were collected by *Nanhai 503*, a drilling boat, of Exploration and Development Scientific Research Institute of China Offshore Oil Nanhai West Corp., and the samples were prepared and measured by its Soil Test Laboratory. The samples were processed and measured according to the China National Standard (Geotechnic Test Standard SD128–84,1987).

At the soil test laboratory, the samples' sound parameters were measured with a sound wave-measuring meter of SYC-3B model which connects the CJ-1 data processing system of acoustic parameters. At temperatures of 27°C–29°C, the samples were measured, in frequencies of 50 kHz . The sample length was measured with a dial gauge (range 10 mm, division value 0.01 mm). On each core, about 48–64 samples were collected approximately one sample per meter of core. Then a sound velocity curve for each core was drawn (Figures 2 and 3).

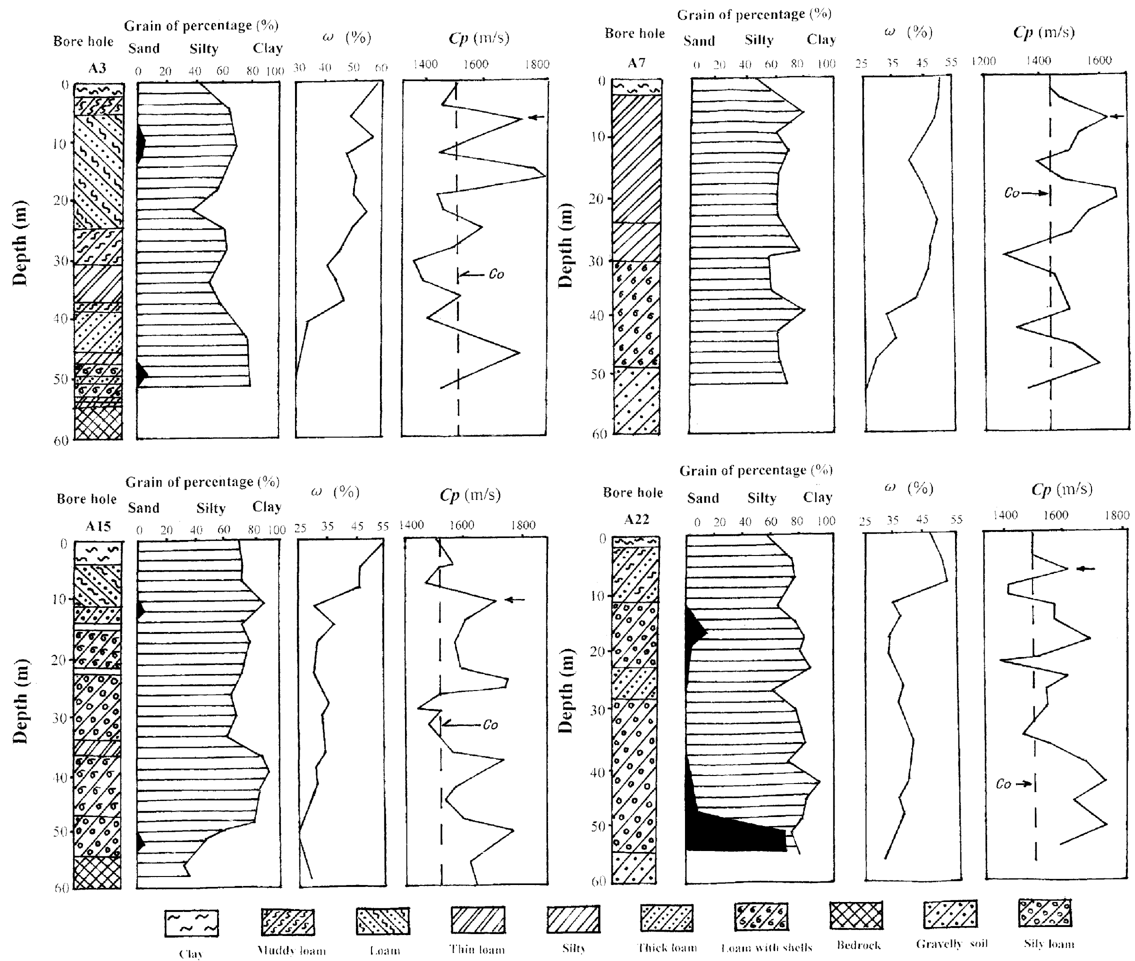

Figure 2. Comparison of Cp, ω, grain size distribution, and stratigraphic column among four seafloor sediment cores from continental shelf of the East China Sea.

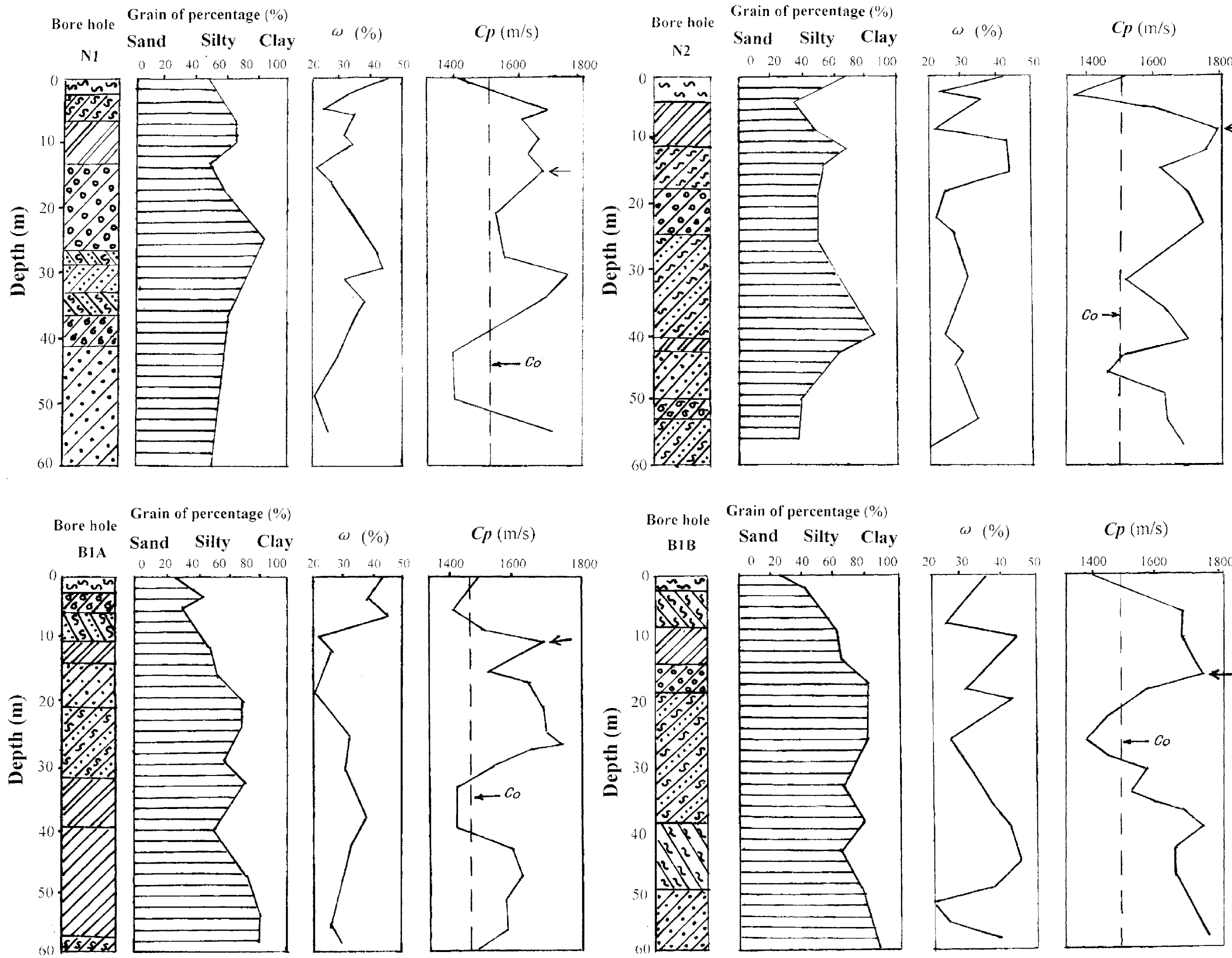

Figure 3. Comparison of Cp, ω, grain size distribution, and stratigraphic column among four seafloor sediment cores from continental shelf of the northern South China Sea.

In geological history, the two sea areas have undergone many events of marine transgression and regression. The occurrence and termination of these events have left features for later generations to interpret and identify. For example, biological features such as ancient organisms, foraminifera, and sporopollen may be used to identify the change in paleoclimate and ancient oceans (Wang 1992). What disciplinary features other than ancient organisms are there that can provide evidence for the changes in the ancient ocean? Manghnani and others (1980) used the sound compressional wave *Cp* and shear wave *Cs* velocities of sediments from DSDP site No. 289 and their anisotropic features to discriminate both the burial ages of core and the geologic environment, thus further revealing the characteristics of the ancient ocean and climate. Generally, the sedimentary indicator of marine transgression is that the sedimentary layer gradually transfers from below to above from the shallow-water facies to the deeper facies. The sediments are mostly blackish grey or brown with the very fine silt and silty clay as the dominant grain size. They are saturated with water, and their structure is loose and in fluid plastic shape. They have developed fine horizontal lamination and are rich in organic matter and interspersed with biological remains of shallow-sea facies. The sedimentary indicator of marine regression is that the sedimentary layer gradually shifts from deep-water to shallow-water facies as you go up through the sediment column. This process can be observed even in continental facies. In a large-scale marine regression, part of the original seabed is exposed and is mainly of composed continental sediments with quartz and feldspar as primary constituents. This layer will consist of compact bedding with low water content and contain coarse terrigenious minerals.

The references (Wang 1986; Feng et al, 1989; M. P. Chen et al, 1988) indicate that there have been three events of marine regression on the continental shelf of the northern South China Sea area of China since the late Quaternary period. The activity there has been as follows: a large marine regression in the late mid-Pleistocene epoch; a larger marine transgression in the early Late-Pleislocene epoch: and in the middle Late-Pleistocene epoch, first the marine regression and then a smaller marine transgression; a large marine regression in the late Late-Pleistocene epoch; and a marine transgression in the Holocene epoch. Wang (1986) and Lu and Liang (1991) suggested after testing several dozen boreholes that at least three marine sedimentary layers and three continental sedimentary layers could be found in the Quaternary stratum of the continental shelf of the East China Sea. He also indicated that the Quaternary deposits are about 100 m thick and include 3 marine layers. This shows that this area has undergone three marine transgressions, which may have appeared in 100,000–70,000 B.P., 37,000–29,000 B.P., 10,000 B.P., $\sim$0 B.P., respectively. In summary, there have been three marine transgressions and three marine regressions since the Pleistocene epoch with accumulation of marine and continental deposits resulting from these sedimentary cycles.

This article indicates that physical indicators may help to define boundaries of marine and continental sedimentary layers. This is in addition to boundary information being provided by paleobiological features.

Geological Implications of Physical Indicators of Sediments

The physical features of modern marine deposits are generally: small sediment particles, plastic consistency, high water content, high porosity (i.e., low density) and high degree of saturation. Relatively speaking, their mechanical properties are poor, and are mainly manifested in the low bearing capacity and compressive strengths, and higher sensitiveness. In contrast, the continental sedimentary layers are composed of coarser particles, low water content, lower degrees of porosity (i.e., higher densities), and low degree of saturation. The continental shelf deposits are mainly composed of terrigenous-derived particles that exhibit relatively better mechanical properties, resulting in higher bearing capacity and compressive strength than those of the marine deposit. The vertical variations in the above-mentioned sediments may be indicated by the vertical variation of the sound (compressional) velocity (*Cp*). Generally speaking, the sound velocity (*Cp*) of the marine sediments is lower, varying in the range of 1400–550 m/s. The sound velocity in individual sections from this layer (the sedimentary layer since the Holocene epoch) is even lower than the sound velocity (*Co*) of sea water ($\sim$1460 m/s). The sound velocity (*Cp*) of the continental sediment is higher, varying in the range of 1550–700 m/s. The curve of the core sound velocity versus depth reveals the superposition boundary of the events of marine transgression and regression.

The general trend of the vertical variations of the core sound velocity *Cp* is that the velocity is lower at the surface (the modern marine sedimentary layer) and gradually increases with depth. This is confirmed by the authors' measurement of the boreholes in the Beibu Gulf and Zhujiang River mouth in the South China Sea and the continental shelf of the East China Sea as shown in Figures 2 and 3. Such a global variation tendency also exists in the core of reef limestone from the Nanyong Well No. 1 in the Yongshu Reef of Nansha Islands in the southern South China Sea. Similarly, the above-mentioned DSDP site No. 289 presents the vertical variation of sound velocity (*Cp*) gradually increasing with the depth. A review of the borehole cores shows that the sound velocity (*Cp*) does not increase downwards linearly. There are anomalous low sound velocity values in individual horizons, which are 100–150 m/s lower than those in the overlying and underlying layers.

A series of eight boreholes were drilled, to a depth of 60 m below the seafloor, by rotary slurry drilling method with Japan driller (M2-32), installed on main deck and boat deck of Nanhai 503 drilling boat. Four of the boreholes were located in the East China Sea and the remainder in the northern part of the South China Sea as shown in Figure 1. Results of the four boreholes drilled in the East China Sea are presented in Figure 2. This figure shows a comparison between the vertical variation of the sound velocity (*Cp*), water content of sediment (ω), particle components' percentage, and stratigraphic column. A review of this record shows the physicogeographical and geological evolutionary history of the site. A review of Figure 2 shows the physicogeographical and geological evolutionary process of the area. There have existed at least four high velocity continental sedimentary layers and three low velocity coastal sedimentary layers. The one corresponding to the burial depth of 7.5–10 m is the first high velocity layer, the second at 15–23 m, the third at 25–37 m, and the fourth at 42–50 m. The sediment in these high velocity layers is dominated by loam and silty loam. The rest are the low velocity horizons, and the sediment in these low velocity horizons is dominated by sludge, muddy loam, and loam with shells. Therefore, it may be preliminarily concluded that in the geologic historical period (about 120,000–100,000 B.P.) for burial depths shallower than 60 m, there had occurred three events of marine transgression and four events of marine regression.

Results of four boreholes drilled to a depth of 60 m in the Beibu Gulf on the continental shelf of the northern South China Sea are shown in Figure 2. Figure 2 presents comparative results between the vertical variations of their sound velocity (*Cp*), the water content of sediment (ω), particle size percentage, and stratigraphic column, from which it can be seen that in this area there have existed three high velocity layers and two low velocity layers. In the high velocity layers are hidden some lower velocity layers, indicating that in the continental horizons there have occurred transient marine or coastal sedimentary environments (or continental fluvial deposit) and that in the core shallower than 60 m there have been three events of marine transgression and three events of marine regression.

Discussion and Concluding Remarks

In summary, in the geologic history since 120,000 B.P. there exists sediment in the two areas of the west Pacific marginal sea studied that is due to many events of marine transgression and regression, and the boundary lines of these sedimentary cycles may be found from the sound velocity variation curves.

The recent marine regression in the East China Sea continental shelf occurred in the late Pleistocene epoch about 15,000–20,000 B.P. As the glacier volume throughout the world reached 70 million km^3, the sea level once dropped to about -130 m at the minimum and the East China Sea continental shelf emerged above the sea surface due to marine regression. At this point, it bahaved as a continental sedimentary environment consisting mainly of loessial sediment at the burial depth of approximately 7.5–10 m. The second velocities of the core range between 1650 m/s and 1720 m/s (pointed at by the arrow in Figure 2). Around 18,000 B.P., the glacial period gradually came to an end, the sea surface slowly rose and the sea water again invaded the East China Sea continental shelf. The marine regression of the Holocene epoch occurred up to about 5,000 B.P., when sea water submerged today's East China Sea continental shelf and its nearby areas. The seabed was today's marine deposit, and the sound velocities of the core varied in the range of 1450–1510 m/s. The maximum thickness of this marine sedimentary layer was 10 m. In some places, the seabed was only a very thin marine deposit (less than 1 m) due to scouring by the Kuroshio current, and even the continental sediment in the late Pleistocene epoch was left over due to lack of marine deposit. The sound velocity of submarine sediment was about 1600 m/s. In the sea area to the north of Taiwan, which the Kuroshio current from open waters flowed through, the sound velocity of submarine deposits was very high, reaching 1600–1770 m/s (Chen et al. 1988).

Since the early Pleistocene epoch, the majority of the Beibu Gulf sea area on the continental shelf of the northern South China Sea has emerged as land due to new tectonic movement and glacial periods. The Qiongzhou Strait has become the continental bridge connecting the south China continent and Hainan Island. In the late Pleistocene epoch 15,000–20,000 B.P., the sea level of the Beibu Gulf dropped, and the Gulf became a continental sedimentary environment. The burial depth of this deposit is 10–25 m (pointed at by the arrow in Figure 3) and the sound velocity (*Cp*) is about 1700 m/s. Similar to the situation in the East China Sea continental shelf, in 18,000 B.P., the action of the glacial period began to disappear and the sea water gradually entered the Beibu Gulf via the Qiongzhou Strait. In the Holocene epoch of the postglacial period, the Beibu Gulf was filled with sea water and again became a marine sedimentary environment while the sound velocity of cores (*Cp*) changed gradually from 1700 m/s to 1460–1500 m/s.

It can be seen from the analysis above that in the course of the recent sedimentary cycle, the sound velocity (*Cp*) of the core, changed from the high sound velocity character (1650–1700 m/s) of continental sediment to the low sound velocity character (1450–1500 m/s) of marine sediment. In view of the above, it is not difficult to identify the existence of at least three sedimentary cycle events of the marine transgressions and three marine regressions in the submarine sedimentary layers of the two areas from the sites shallower than the burial depth of 60 m in the curves of vertical acoustic velocity variations shown in Figures 2 and 3.

In Figures 2 and 3, the burial depths of the vertical variations of sound velocity of core are not consistent probably for the following reasons: First, the thickness of marine sediment in the Holocene epoch is not consistent. There are many factors affecting the sea level change and the marine sedimentation rate: glacier, crustal change, sea basin contraction, the scouring effect of the Kuroshio current when passing and so on. Secondly, the rates of sedimentation of the two sea areas are different. Feng and others (1989) reported that the average rate of sedimentation of marine sediment in the East China Sea continental shelf (in the off-sea area of Beilun Port) measured with the 210 Pb method is 0.28 cm/a; Chen and others (1988) reported that in the continental shelf of the northern South China Sea (Beibu Gulf) the average rate of sedimentation measured with the ^{14}C method is 0.408 cm/a. Thirdly, the events of marine transgression and regression in the marginal sea of West Pacific may have not occurred synchronously. When the East China Sea continental shelf was changing from a continental sedimentary environment to a marine sedimentary environment, the Beibu Gulf on the continental shelf of the northern South China could have evolved into the sedimentary environment earlier. This would have resulted in the Beibu Gulf receiving more marine sediment than the East China Sea continental shelf. This study of geological events in the ancient ocean uses the method of physical properties. This method establishes the boundary between marine transgression and regression events using the curve of vertical variation of the core sound velocity *Cp*. The research findings here indicate that the use of this method has provided evidence for studying the change of the ancient ocean.

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