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Paleoenvironmental changes during the late Quaternary as inferred from foraminifera assemblages in the Laizhou Bay

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Abstract
Controlled by climate changes, there were three large-scale transgressions and regressions around the Bohai Sea during the late Quaternary, which were accepted by most geologists. However, a big controversy still exists about the time when the transgressions occurred separately. In order to find out the process of the paleoenvironmental changes around the Bohai Sea in the late Quaternary, the foraminifera assemblages from a new borehole Lz908 in the southern coast of the Laizhou Bay were studied, and then the transgressive strata were indentified. Combined with accelerator mass spectrometry radiocarbon ^{14}C (AMS^{14}C) and optically stimulated luminescence (OSL) ages, the occurrence time of these transgressions were re-determined. The result showed that three major large-scale transgressions occurred separately at the beginning of marine isotopic stage 7 (MIS7), the last interglacial period (MIS5) and the Holocene. In addition, a small-scale transgression occurred in the mid-MIS6, and the corresponding transgressive stratum was deposited. The transgressive deposition of MIS3 was also discovered in this study. However, the characteristics of the foraminifera indicated the environment during this period was colder than that in the MIS5. By comparison with the global sea-level changes, the paleoenvironmental changes around the Bohai Sea in the late Quaternary can be consistent with the global climate changes.

Key words: foraminifera assemblage, late Quaternary, environmental changes, Laizhou Bay, Bohai Sea

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1 Introduction

The Bohai Sea is a semi-enclosed interior continental shelf sea of China with an average depth of 18 m and a connection to the Yellow Sea by the narrow Bohai Strait. Some 2000–3000 m of fluvial, lacustrine, and marine sediments have been deposited in the basin (IOCAS, 1985). The Bohai Sea sediments are frequently used to study ancient environments and geologic evolution, including the history of shelf evolution, monsoon climates and the environmental impact of ancient human activities (e.g., IOCAS, 1985; Liu, 2009).

The Bohai Sea and its surrounding areas deposited fluvial and marine sediments during the Quaternary period's glacial and interglacial alternating climates. Since the 1970s, hundreds of cores have been drilled and studied to understand the environmental and geological evolutionary histories surrounding the Bohai Sea (Zhao et al., 1978; IOCAS, 1985; Zhao, 1995; Wang and Tian, 1999; Zhuang et al., 1999; Yan et al., 2006; Liu et al., 2009). The classic pattern of previous studies suggest that transgressions were evident at the beginning of the interglacial stages, including the Holocene, MIS3 (marine isotope stage 3), and MIS5, and deposited three transgressive strata. Regressions occurred at the beginning of glacial stages such as MIS2 and MIS4.

No major disagreement exists concerning the three large-scale transgressions around the marginal seas of China (the Bohai, Yellow, and East China Seas), but researchers have divergent views regarding the times at which these three transgressions occurred. Yim et al. (1990) evaluated the age of mollusk samples in the South China Sea continental shelf sediments using two different methods, the AMS^{14}C and uranium series, and reported that old radiocarbon dates were likely to be minimum age estimates, then implying that transgressive sediments during the MIS3 as determined by ^{14}C dating should be considered MIS5. Similarly, Chen et al. (2012) studied two 80-m deep boreholes, BT113 and BT114, in the west coast of the Bohai Bay (Fig. 1), and identified three marine facies deposited in MIS7, MIS5, and MIS1. Unlike previous studies, they concluded that the marine transgression did not impact the studied area during the MIS3. Recently, information gathered from boreholes BZ1, BZ2, and CQJ4, all of which were drilled in the west coast of the Bohai Bay (Fig. 1), also significantly pushed back the age of the three transgression, as indicated by the magnetostratigraphy method (Yao et al., 2006; Xiao et al., 2008; Shi et al., 2009) and lumines-

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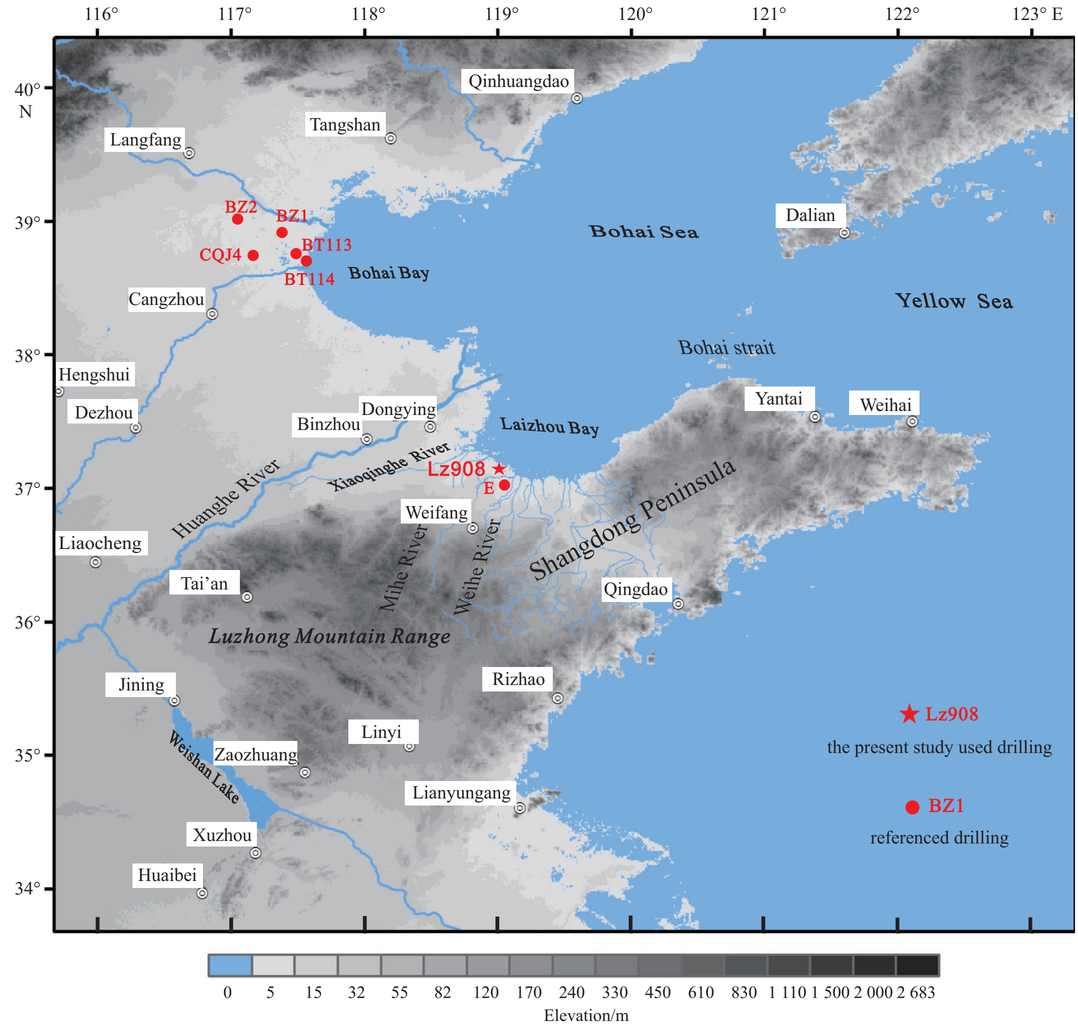

Fig.1. Location of Lz908 core.

cence (Chen, Li et al., 2008). If the proposal made by Chappell et al. (1996) is correct—that is, if the global sea level was 60–80 m lower than at present during 30–70 ka—then how the MIS3 transgression occurred in the Bohai Sea is questionable.

In the studies of the marginal seas of China, the Quaternary period's coastal plain transgression is of increasing interest and microfossils used to identify Quaternary transgressive strata have been reliable (Wang et al., 1981; Wang and Li, 1983; Wang et al., 1986, 2008). Specifically, foraminifera assemblage can be useful in reconstructing environmental changes and estimating the relative sea level (Zachos et al., 2001; Lisiecki and Raymo, 2005; Waelbroeck et al., 2002; Siddall et al., 2003). Even today, microfossils are crucial for coastal plain transgression research: they remain the primary means for assessing transgressive sediments (Wang et al., 1981; Wang et al., 2004; Wang et al., 2008).

To reconstruct the environmental changes during the late Quaternary period and to reassess the regional response in the Bohai Sea to global changes, a new core was drilled in the southern coast of the Laizhou Bay. Through identification of foraminifera assemblage and a combination of AMS^{14}C and OSL dating information, the past marine environmental changes were evaluated and their relations to the global changes were documented.

2 Materials and methods

2.1 *Study area*

The Laizhou Bay is the south part of the Bohai Sea (Fig. 1), located within the Yi-Shu Rift (Gao et al., 1980; Zhang et al., 2003), which formed in response to subsidence during the Cenozoic era (Allen et al., 1997; Hu et al., 2001; He and Wang, 2003). The period from the Neogene to the present has been marked by tectonic quiescence and stable sedimentation rates (Wu et al., 2006; Yu et al., 2008). The sediments in the Laizhou Bay were transported from the Luzhong Mountain Range by several local rivers including the Xiaoqinghe, Mihe, and Weihe Rivers (Xue and Ding, 2008). Depositional environments in the bay area have varied mainly among delta, estuarine, and tidal flat systems (Xue and Ding, 2008). During regressions, the exposed area might be replaced by diluvial fans (Chen et al., 1991), loess or sandy dunes (Chen et al., 1991; Zhao, 1995; Yu et al., 1999), or alluvial fans (Meng et al., 1999).

2.2 *Lz908 core*

The Lz908 core is located onshore near the south coast of the Bohai Sea in China (37°09′N, 118°58′E; elevation 6 m; Fig. 1). It was drilled to a depth of 101.3 m below the earth's surface by the First Institute of Oceanography, State Oceanic Administration of China during the summer of 2007. It had a recovery rate of 75%. The drilling site for the Lz908 core was submerged until the middle of the 20th century. Only the upper 50 m of sediment contained foraminifera, so it was chosen as the main subject of the present study. The core was subsampled at 20–50 cm intervals and 143 total samples were prepared for the foraminifera analysis described below.

2.3 *Chronology of Lz908 core*

An age control for core Lz908 was provided by radiocarbon dating and OSL of sediment grains (Fig. 2). Four foraminifera samples were radiocarbon-dated at the United States Woods Hole Oceanographic Institution at the NOSAMS Accelerator Mass (AMS) Spectrometry facility (Woods Hole, MA). OSL dating was performed using a Daybreak 2200 automated OSL reader at the Qingdao Institute of Marine Geology, Chinese Geological Survey, following an OSL protocol developed by Lu et al. (2007).

Conventional ^{14}C ages were converted to calendar ages using a Calib 6.0 radiocarbon calibration program (Stuiver and Reimer, 1993) and the Bohai Sea calibration dataset (Wang et al., 2004; Wang and Fan, 2005). When placed on the calibrated ^{14}C- and OSL-based age model, bulk sediment variations in grain size demonstrated potential modulation in response to the Asian monsoon intensity (Wang et al., 2001, 2008; Cheng et al., 2009). Using this information, Yi et al. (2012a) thus refined the preliminary chronology of Lz908 core by tuning it to the July insolation at 65°N synchronously. This orbital tuning significantly improved the core's chronology thus it was used here for further analyses. Results indicated that the upper 50 m sediment was deposited during the past 233 ka (Fig. 2).

2.4 *Foraminifera identification*

From each sample collected (described above) 5 g sediment then completely dried for 24 h or more at a temperature not greater than 50°C. An appropriate amount of distilled water was added to the dried sample which was soaked for at least 24 h and was repeatedly flushed with tap water passed through a 63-μm copper sieve. If the samples contained high levels of organic matter, a 30% hydrogen peroxide solution was added to the sample and allowed to react for 2 h. Then, the sample was rinsed. Material remaining on the sieve was dried at a temperature not greater than 50°C. Then the foraminifera were counted and identified under the microscope.

2.5 *Foraminifera indices*

(1) Abundance refers to the number of foraminifera per gram of dry sample (N/g).

(2) Diversity, as used here, was a quantitative description of the degree of diversity regarding the object in the study sample. Simple diversity (*S*) as used here is defined as the number of species found in the sample. Complex diversity, here abbreviated *H(S)*, can be calculated using the following formula:

$$H(S)=-\sum_{i=1}^{s} P_i \ln P_i ,$$

where P_i refers to the relative content of the *i*th individual in the group. *H(S)* not only reflects the absolute number of the species found within the samples, but also the relative number of species. Generally, diversity gradually increased from the shore to the outer edge of the continental shelf (Marine Geology Tongji University, 1978).

The foraminifera dispersity (*V*) here, is the number of species as arranged by relative abundance from greatest to least until

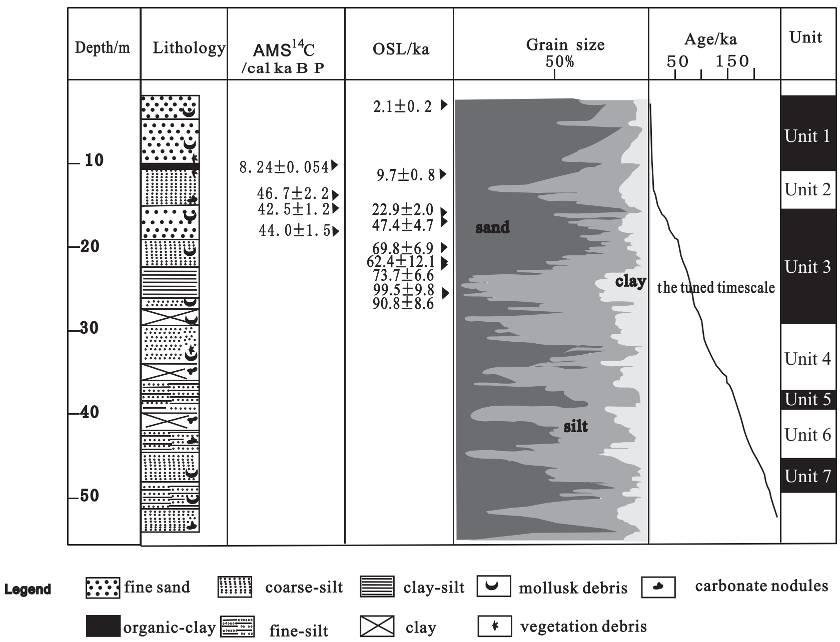

Fig.2. Lithology and timescale of Lz908 core. The tuned timescale data from Yi et al. (2012a).

the cumulative percentage reaches 95% or more. Dominance *D*, as used here, is the relative percentage of the species with the maximum quantity (IOCAS, 1985). From the shore to the sea, *V* increased and *D* decreased as depth increased (Zhuang et al., 1999).

3 Results

3.1 *Sedimentary changes*

Marine strata that were established on the basis of both the type and number of foraminifera species were large; the value of *H(S)* was greater than 1 (Zhuang et al., 1999). Thus the Lz908 core can be divided into seven units (Unit 7–1) from bottom to top (Fig. 2). Among these, Units 7, 5, 3, and 1 were found to be transgressive sediments. Units 6, 4, and 2 were regressive sediments, described as Units 1–7 in descending order.

Unit 7 (45.2–47.9 m)

Unit 7 contained yellowish grey coarse silt and mollusk debris in the upper areas and brick-red coarse/medium silt at the base. Unit 7 also had scattered shell fragments throughout. The average grain size varied mostly between 3 and 5 Φ. The abundance of foraminifera in Unit 7 was 8–68, with an average of 21.

Unit 6 (39.7–45.2 m)

Unit 6 contained yellowish-grey fine silt with olive-grey veins, and reddish mottles. Most of the grains averaged in size between 4 and 5 Φ. There were few foraminifera in this unit.

Unit 5 (37.5–39.7 m)

Unit 5 contained grey-brown and grey median silt and its base was a dark grey layer rich in organic material. This unit contained scattered shell fragments and rich veins of organic material. Most grains averaged in size between 4 and 4.5 Φ. The abundance of foraminifera was 2–68, with an average of 28.

Unit 4 (32.4–37.5 m)

Unit 4 contained dust-colored clay, yellowish grey fine sand to coarse silt, and also contains carbonate nodules and mollusk debris. Grains chiefly ranged in size between 3 and 6 Φ. There were also few foraminifera in this unit.

Unit 3 (16.2–32.4 m)

Unit 3 contained grey-brown and yellowish grey silt, fine sand, and scattered shell fragments. Most grains averaged between 4 and 5 Φ. The abundance of foraminifera was 3–826, with an average of 96 and this increased gradually from the base to the top.

Unit 2 (11.3–16.2 m)

Unit 2 contained yellowish grey coarse silt, red patches, and dark grey veins rich in organic material. The lower half of this layer contained calcareous concretions. The average grain size varied from 4 to 5 Φ. In this unit, at the intervals of 13.4–16.2 m, foraminifera were observed but classified as regressive deposits. For the specific reasons for this classification, see Section 4.

Unit 1 (2.3–11.3 m)

Unit 1 was subdivided into three subunits: the upper contained yellowish-grey fine sand, the middle was of dust-colored fine sand, and the base was dark grey and black clays rich in organic material and some vegetative debris. Unit 1 also contained scattered shell fragments throughout. The average grain size varied between 3 and 4 Φ. The abundance of foraminifera was 12–1 182, with an average of 168.

3.2 *Characteristics of foraminifera*

In the present study, 92 species across 30 taxa were identified. Nearly all were benthic foraminifera, only three planktonic foraminifera were found in the entire core. The major foraminifera were *Ammonia confertitesta*, *Elphidium advenum*, *Ammonia tepida*, *Ammonia beccarii*, *Cribrononion incertum*, *Protelphidium granosum*, *Elphidium limpidum*, *Ammonia limbatobeccarii*, and *Elphidium subcrispum*. The foraminifera characteristics of each transgression (Figs 3 and 4) were described as follows.

3.2.1 *Unit 7 (45.2–47.9 m, 204–221 ka)*

Benthic foraminifera were sparse with little diversity. The main components were *Ammonia*, *Elphidium*, *Cribrononion*, and *Protelphidium*. *Elphidium limpidum*, *Ammonia confertitesta*, *Elphidium subcrispum*, *Ammonia limbatobeccarii*, *Cribrononion incertum*, and *Protelphidium granosum* were the dominant species. *Elphidium limpidum* was the most common. *S* values ranged from 6 to 26 with an average of 14.57. *H(S)* values ranged from 1.4 to 2.7 with an average of 2.0. *V* values ranged from 5 to 18 with an average of 10.7. *D* values ranged from 13.8 to 54.2 with an average of 33.9.

3.2.2 *Unit 5 (37.5–39.7 m, 160–171 ka)*

Benthic foraminifera were sparse with little diversity. The most common components were *Ammonia*, *Elphidium*, *Cribrononion*, *Protelphidium*. *Ammonia confertitesta*, *Elphidium advenum*, *Cribrononion incertum*, *Ammonia takanabensis*, *Protelphidium granosum*, and *Ammonia beccarii* were the dominant species. *S* values ranged from 16 to 19 with an average of 16.8, *H(S)* values ranged from 1.9 to 2.1 with an average of 2.0. *V* values ranged from 10 to 13 with an average of 11.7. *D* values ranged from 41.5 to 50 with an average of 46.0.

3.2.3 *Unit 3 (16.2–32.4 m, 114–29 ka)*

Ammonia, *Elphidium*, *Cribrononion*, and *Quinqueloculina* were the dominant taxa in this unit, and *Elphidium* comprised the largest content and greatest varieties in this section. As indicated by the abundance of foraminifera and the identities of the dominant species deposited in the sediments, two different sections could be divided at a depth of 20.6 m.

From 20.6 to 32.4 m, *Elphidium advenum*, *Ammonia beccarii*, *Ammonia tepida*, and *Ammonia confertitesta* were the dominant species. The material found at this depth also contained more *Cribrononion incertum*, *Elphidium magellanicum*, and *Ammonia convexidorsa* than other species. *S* values ranged from 6 to 26 with an average of 16.4. *H(S)* values ranged from 1.3 to 2.6 with an average of 2.2. *V* values ranged from 8 to 19 with an average of 12.2. *D* values ranged from 15.5 to 71.8 with an average of 28.0.

From 16.2 to 20.6 m, *Ammonia tepida*, *Elphidium advenum*, *Ammonia confertitesta*, *Cribrononion incertum* and *Pseudorotalia gaimardii* were the dominant species. The material found at this depth also contained more *Ammonia beccarii*, *Elphidium subcrispum*, and *Elphidium limpidum* than other layers. *S* values ranged from 21 to 31 with an average of 24.3. *H(S)* values ranged from 2.2 to 2.8 with an average of 2.5. *V* values ranged from 13 to 20 with an average of 16.7. *D* values ranged from 12.6 to 35.7 with an average of 22.3.

3.2.4 *Unit 1 (2.3–11.3 m, 8.5 ka to the present)*

Benthic foraminifera were numerous and highly diverse. *Ammonia*, *Elphidium* and *Quinqueloculina* were the dominant

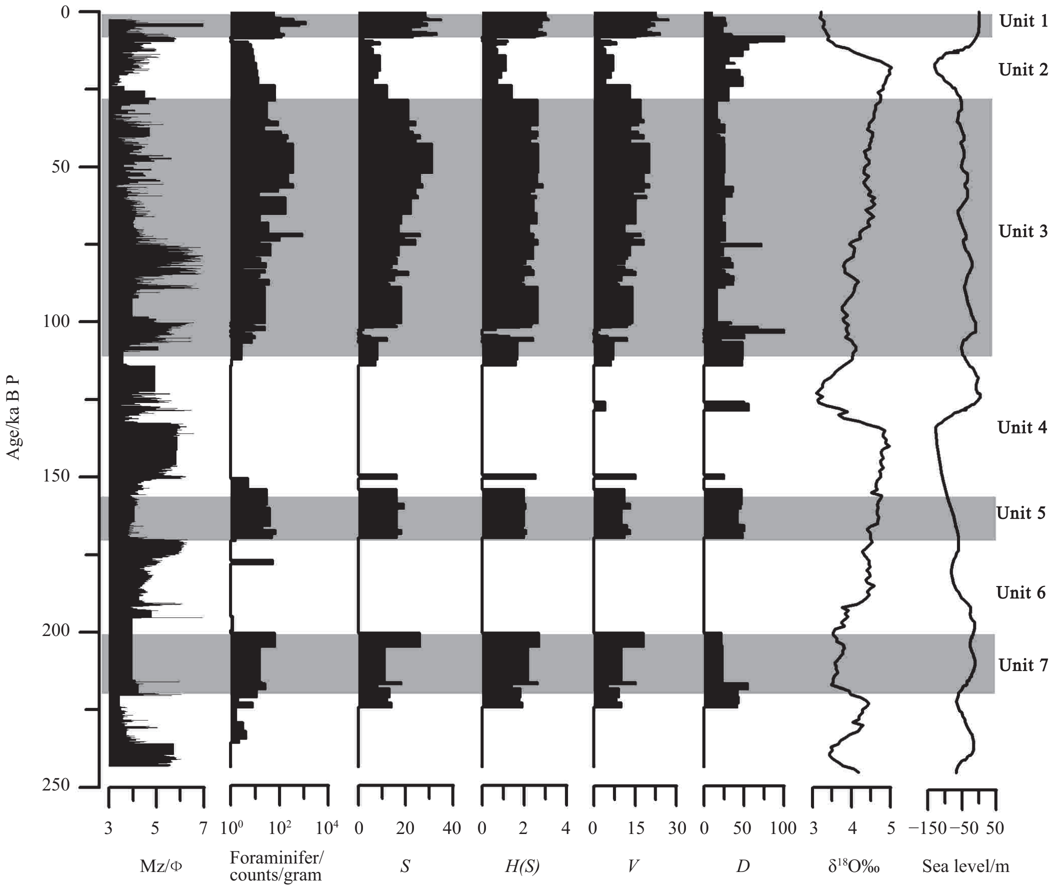

Fig.3. Foraminifera variation through the whole Lz908 core, deep sea sediment $\delta^{18}O$ records (LR04 stack, Lisiecki and Raymo, 2005) and detailed sea level curve for Huon Peninsula (Chappell and Shackleton, 1986).

taxa. Based on the abundance and identities of the dominant species deposited in the sediments, two different sections were divided at a depth of 9.5 m.

From 9.5 to 11.3 m, *Ammonia multicella*, *Ammonia confertitesta*, *Ammonia beccarii*, *Ammonia tepida*, *Stomoloculina multangula*, *Ammonia limbatobeccarii*, and *Pseudononionella variabilis* were the dominant species. The sediment also contained more *Pseudoeponides anderseni* than other species. *S* values ranged from 10 to 33 with an average of 20.8. *H(S)* values ranged from 1.9 to 3.0 with an average of 2.4. *V* values ranged from 10 to 24 with an average of 15.3. *D* values ranged from 14.4 to 44.4 with an average of 24.9.

From 2.3 to 9.5 m, *Protelphidium granosum*, *Elphidium advenum*, *Ammonia confertitesta*, *Cribrononion incertum*, *Ammonia limbatobeccarii*, and *Ammonia beccarii* were the dominant species. The sediment also contained more *Pseudorotalia gaimardii* than other species. *S* values ranged from 22 to 35 with an average of 27.7. *H(S)* values ranged from 2.5 to 3.1 with an average of 2.8. *V* values ranged from 17 to 27 with an average of 20.8. *D* values ranged from 11.3 to 27.0 with an average of 19.1.

4 Discussion

Many extant foraminifera species have long histories, and many serve as geomorphologic and environmental indicators. As such, foraminifera are widely used in stratigraphic correlation and paleoenvironmental studies. Here, the abundance, variations and combinations of foraminifera were used to evaluate changes in the sedimentary environment of the Laizhou Bay dating back to the late Quaternary period.

4.1 *Marine isotopic stage 7–6 (MIS7-6, 243–130 ka)*

Changes in the abundance and composition of the foraminifera population (Figs 3 and 4) indicated that two transgressions occurred during this period (Units 7 and 5).

In Unit 7, the presence of *Elphidium limpidum* indicated a low-salinity environment (Wang et al., 2008). This was the most abundant species in this layer. *Cribrononion incertum* and *Ammonia limbatobeccarii* were usually found in shallow water (Lin et al., 2005; Li et al., 2010).

In Unit 5, the presence of *Ammonia confertitesta* indicated a coastal, shallow-water environment (Cheng et al., 1991; Li and He, 1983; Li, 1986). *Elphidium advenum* and *Cribrononion incertum* are usually found in shallow seawater environments (IOCAS, 1985; Lin et al., 2005). As can be seen from Fig. 3, global sea level slightly increased during this period, which also occurred in the Laizhou Bay.

In addition, the foraminifera population had less diversity abundant than one in other transgressions. These data indi-

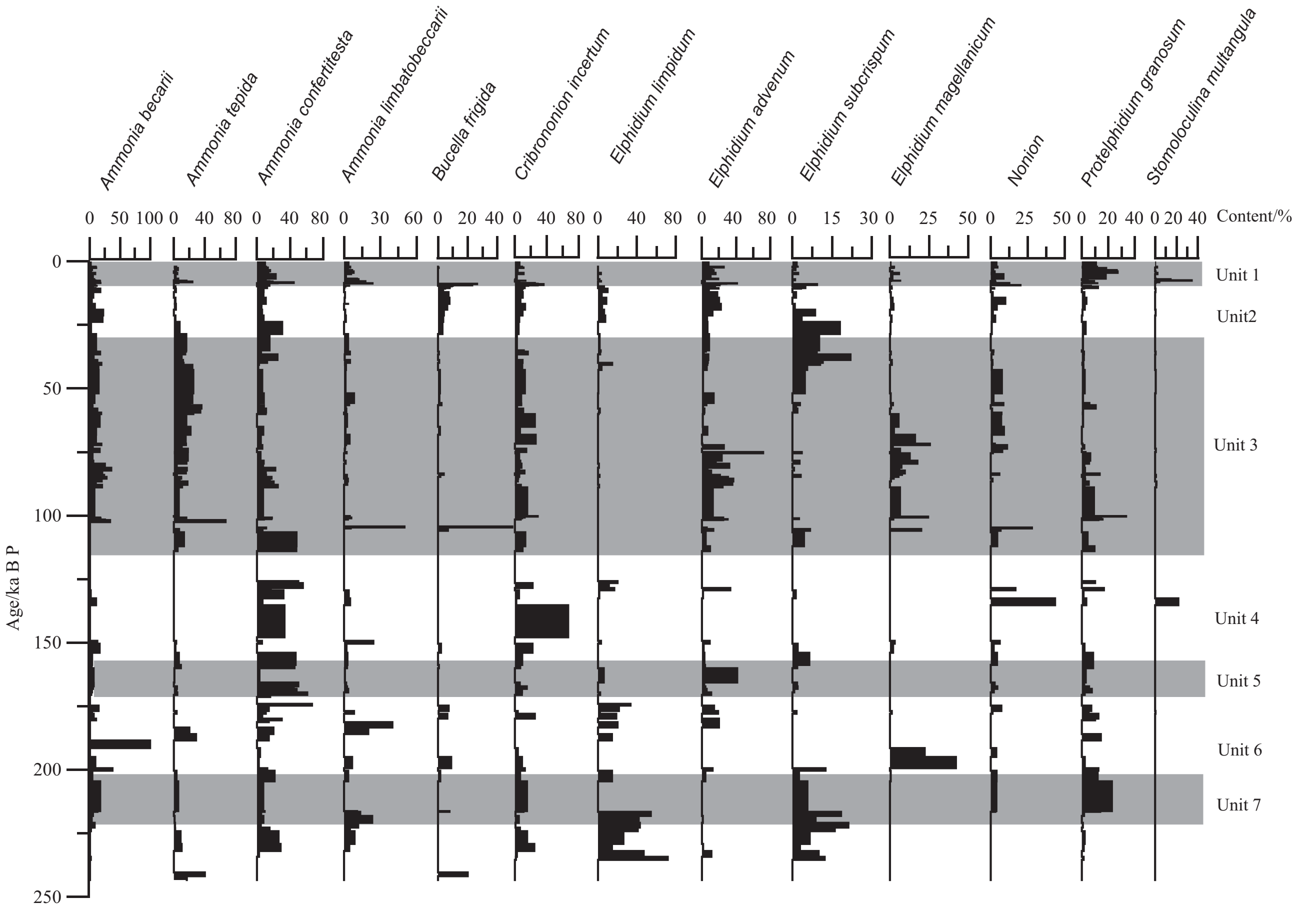

Fig.4. Foraminifera species content (%) of Lz908 core.

cated that these two transgressions were less developed with smaller influence. Recent studies of the Bohai Bay coasts (Chen, Liu et al., 2008; Chen et al., 2012) were consistent with our results, indicating relatively small transgressions during this period. After these two transgressions, a significant sea-level retreat occurred which deposited Unit 4.

4.2 *MIS5-3 (130–29 ka)*

The abundance of foraminifera (Unit 3) indicated a continuous transgression without any major regression during this period. However, two different foraminifera assemblages were observed in this period (Fig. 4).

(1) In the lower section, the presence of *Elphidium advenum* and *Cribrononion incertum* indicated a shallow sea environment (IOCAS, 1985). The optimum environmental conditions of *Ammonia tepida* were 25–30°C with a water depth of about 20 m or less (Chen and Zhu, 2004; Lin, 1983; Chen, Liu et al., 2008; Wang et al., 2009). The presence of *Elphidium magellanicum* indicated a near-shore environment (Wang et al., 1988) and this organism can usually be found in water depths of 5–10 m or more (Zhuang et al., 2004; Zheng et al., 1978). These findings demonstrated that the temperature of the water during this period was very warm and the water depth was less than 20 m.

(2) In the upper section, the presence of *Ammonia beccarii* indicated a euryhaline and shallow sea environment (Wang et al., 2009). *Buccella frigida* was present in some parts of this section, and this species usually lives in cold-water estuarine environments (e.g., Hayward, 1993; Newton and Rowe, 1995). This raises questions regarding the environmental conditions during the MIS3. According to Yi et al. (2012b) who reconstructed late Pleistocene relative sea level in the southern Bohai Sea based on sediment grain-size analysis of Lz908, sea level fell gradually from 79 to 60 ka, and then entered a prolonged, low period from 60 to 17 ka. Changes in the global sea level during this period had the same trend (Siddall et al., 2003), indicating that regional and global patterns of sea level changes were somewhat consistent. The characteristics of the foraminifera present in this layer indicated that MIS3 transgression occurred in the Bohai Sea, but that the environment during this period was colder than that in the MIS5.

4.3 *MIS2 (29–14 ka)*

The lower section of this layer contained some foraminifera, but relatively few species. The most common components were *Elphidium advenum*, *Ammonia confertitesta*, *Cribrononion incertum*, *Ammonia beccarii* and *Buccella frigida*, and *Buccella frigida* was present in large numbers throughout this entire section. Foraminifera indices *S* and *H* (s) values were low, and foraminifera shells were rust colored. In addition, the sediments contained more calcareous concretions which indicated that the climate was cold and dry. Also, the sea level was very low during this period (Fig. 3), but the presence of foraminifera raised intriguing questions.

In the last glacial period, a large-scale regression occurred, and the main continental shelf of the west Pacific was exposed during the LGM (Liu, 2009). Under the effects of frequent storm winds, the original marine stratum disintegrated. Winds transported and deposited some fine-grained sediments to distant places. During this process, micro-organisms in the original marine stratum redeposited together with sediments. Thus, fossil foraminifera may have been mixed into a younger terrestrial stratum (Zhao, 1995; Yu et al., 1999). This phenomenon may also cause by abnormal old radiocarbon dates (foraminifera-based) at similar strata around the marginal seas of China (Liu, 1987; Zheng, 1989; Zhao, 1995; Yu et al., 1999; Yi et al., 2013).

According to foraminifera characteristics in the MIS2, all foraminifera species were present in the MIS3 stage, and thus a hypothesis was raised here that foraminifera in the MIS2 might be redeposited from the MIS3 marine layer's redeposition after disintegration in the glacial age. Therefore, sediments at this stage should still be classified as terrestrial stratum which deposited in the glacial age; although, there were foraminifera within it.

4.4 *The Holocene period*

The Holocene period could be characterized as being largely influenced by transgression because both the abundance and diversity of foraminifera peaked at this time. *Stomoloculina multangula* and *Pseudononionella variabilis,* which live in brackish environments (Lin, 1983), were common in the sediments (Fig. 4). *Stomoloculina multangula*, *Pseudononionella variabilis*, and *Pseudoeponides anderseni* usually live in a coastal or offshore area (Zheng et al., 1978), and these foraminifera assemblages revealed that the Laizhou Bay environment during the Holocene period was similar to the present environment.

5 Conclusions

The environmental conditions of the late Quaternary period were reconstructed by studying a core drilled from the southern coast of the Laizhou Bay, identifying the foraminifera assemblages, and combining dating information. Three major transgressive events have been identified by previous work in the same study area, which might have occurred during the MIS5, MIS3, and the Holocene period (Han et al., 1994; Zhao, 1995; Zhang et al., 1996). However, based on foraminifera assemblages and dating information of Lz908, together with comparisons with the Shouguang E core (Zhao, 1995; Yao et al., 2010; Fig. 1), three major transgressive events could be related to the four marine/coastal sedimentary units, and their ages were related to MIS7, MIS6, MIS5–3 and the Holocene period, respectively. The timing of transgressions support previous along the Chinese marginal seas (e.g., Yim et al., 1990; Chen et al., 2012, Yao et al., 2006, Xiao et al., 2008, Shi et al., 2009), but these data differ significantly from work described by Han and his colleagues (Han et al., 1994), Zhao's group (Zhao, 1995) and Zhang's laboratory (Zhang et al., 1996).

The main processes during the late Quaternary period then can be summarized as follows:

At the beginning of MIS7, when the global ice volume decreased and the global sea level rose (Lisiecki and Raymo, 2005; Chappell and Shackleton, 1986; Fig. 3), a transgression occurred around the Bohai Basin, and then sea water retreated from the Bohai Sea at the beginning of MIS6. A small-scale transgression also occurred during MIS6, which was followed by seawater withdrawal from the Bohai Sea.

When global warming began during the last interglacial period (MIS5), sea water again dominated the Bohai Basin. Because the global ice volume and temperature during MIS7 had not reached the MIS5 level, the transgressions that occurred in MIS7 and MIS6 had less influence on the evolution of the Bohai Sea than the transgression that took place during MIS5.

At the beginning of MIS4, sea water again retreated from the Bohai Sea. However, this retreat was likely incomplete, possibly because of uplift movements and volcanic activity (Xu et al., 2005). For this reason, some sea water remained in the Bohai Sea. The transgressive deposition of MIS3 was observed in our study. However, the characteristics of the foraminifera indicated that the environment during this period was colder than that in the MIS5.

In the last glacial period, a large-scale regression occurred, the main continental shelf of the west Pacific was exposed during the LGM. The MIS3 marine stratum disintegrated, and some of the fine-grained sediments redeposited under the action of frequent winds, which caused the terrestrial stratum in the MIS2 partly contain foraminifera.

Finally, after the last glacial stage (MIS2), seawater again invaded the Bohai Sea due to the decrease in global ice volume and the increase in global temperature during the Holocene period.

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