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Sedimentary environment and paleo-tidal evolution of the eastern Bohai Sea, China since the last glaciation

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ABSTRACT

Numerical simulation suggests that the Holocene sediments re-suspension and distribution in the Bohai Sea was mainly controlled by tidal current regime, which was closely related with sea-level change. Study on sediments in the Bohai Sea thus can provide insights into the evolution of tidal-influenced sedimentary environment and its links with sea-level change. Our understanding of this issue remains incomplete, however, owing to the lack of comprehensive study on sediment core with high-resolution proxies to test such inference. In this study, analyses of sedimentary facies, proxies (grain size, total organic carbon and total nitrogen, X-ray fluorescence scanning Sulfur and Chlorine ratio) and accelerator mass spectrometry ^{14}C dates of a sediment core recovered from the eastern Bohai Sea were carried out to clarify the Holocene sedimentary environment, tidal current change and its relation to the sea-level. The results indicate that the eastern Bohai Sea was dominated by fluvial-coastal environment prior to 12,400 cal a BP due to the sea-level lowstand and changed to tidal-influenced environment from 12,400 to 6700 cal a BP following the rapid sea-level rising. Thereafter shelf environment with minor tidal influence dominated the eastern Bohai Sea under the condition of a deceleration of sea-level rise. The significant change at ~6700 cal a BP both in sedimentary environment and sediment proxies, indicating an environmental transition from strong tidal-influenced to less tidal-influenced setting. With the sea-level rising from the early Holocene to the mid-Holocene, tidal-current was much strong due to the low sea-level stand and became weak after the maximum transgression at ~6700 cal a BP. These results are consistent with the numerical simulation, which suggested that less strong tidal current were the consequence of the most highstand sea-level since the mid-Holocene. Our study thus provides a sedimentary record to support the interpretation of numerical simulation-based tidal-influenced depositional process in the eastern Bohai Sea since the deglacial period.

1. Introduction

The Bohai Sea is a semi-enclosed sea of China that connects to the northern Yellow Sea by the narrow Bohai Strait. The sedimentary environment in the Bohai Sea has been strongly affected by the sea-level fluctuations and sediments supply due to the shallow water depth (average: ~18 m; Qin et al., 1990). The tidal current is one of the most energetic oceanic components of the present Bohai Sea, especially in the eastern area close to the Bohai Strait, and thus plays an important role in sedimentary processes such as deposition, erosion, and re-suspension (Liu et al., 1998; Zhu and Chang, 2000; Chen and Zhu, 2012). Therefore exploring the links between tidal current and the sedimentary process is crucial to understand the sedimentary environment change in this region.

Both field data (Qin et al., 1990; Liu et al., 1998; Qiao et al., 2010) and numerical simulation results (Uehara and Saito, 2003; Chen and Zhu, 2012) show that tidal-current field is the dominant

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factor for controlling the sediment types and distribution in the Bohai Sea. The model results are fairly consistent with the investigation on modern sediments distribution in the Bohai Sea (Qin et al., 1990; Liu et al., 1998; Shi, 2012). However, how the tidal current regime evolved to influence the sedimentary process since the last deglacial period, as well as its underlying causes remains poorly understood. Numerical simulations suggested that sediment types in the Chinese shelves were closely related to tidal-current regime during the Holocene transgression (Uehara and Saito, 2003; Chen and Zhu, 2012), while the latter was mainly dominated by the postglacial sea-level rise and resultant changes in coastline configuration (Chen and Zhu, 2012). This inference is very important to understand the sedimentary process in the Bohai Sea, because the Bohai Sea was exposed subaerially during the last glacial maximum (LGM), and then was followed by a large-scale Holocene transgression which can be found in coastal region worldwide (Violante and Parker, 2004; Gao and Collins, 2014), responding to the global sea-level rising from −120 m to the present level (Siddall et al., 2003). However, there is still lacking of sedimentary record spanning the last deglacial period to test the model results up to now, in spite of its paleoenvironmental significance.

Recently, a 212.4-m core (BH08) was recovered from the eastern Bohai Sea, close to the Bohai Strait. In this study, we focus on the upper ~8 m portion, which has been well dated using accelerator mass spectrometry (AMS) ^{14}C method and proved to be spanning the last deglacial period. We present the sedimentology and proxies (grain size, XRF core scanning elements, carbon and nitrogen content) records of the core sediments. The specific objectives of the current research are (1) to perform detailed facies analyses and establish the sedimentary history in the eastern Bohai Sea and (2) to tentatively discuss the tidal current evolution of the eastern Bohai Sea since the deglacial period as well as its relation to the sea-level change.

2. Regional setting

The Bohai Sea is a semi-enclosed sea of China connecting to the northern Yellow Sea by the narrow Bohai Strait (Fig. 1). The water depth is less than 30 m throughout the Bohai Sea with a mean value of ~18 m (Fig. 1a, b; Qin et al., 1990). The main rivers flowing into the Bohai Sea are the Yellow River, Luanhe, Haihe and Liaohe Rivers, which originate from the Tibetan Plateau, Taihang and Yanshan Mountains (Fig. 1). Among them, the Yellow River is the largest and is the main source of sediments in this region. As the second largest river in the world in terms of sediment loads, the Yellow River discharges eastward huge amounts of sediments into the Bohai Sea (Milliman and Meade, 1983).

The circulation in the Bohai Sea is mainly composed of the predominant extension of the Yellow Sea Warm Current (YSWC), the Liaonan Coastal Current (LCC) and the southern Bohai Sea Coastal Current (BSCC) (Fig. 1a, Guan, 1994; Fang et al., 2000). The saltier water enters the Bohai Sea from the northern Yellow Sea through the northern Bohai Strait, circulating as LCC and BSCC along the Bohai Sea coastal area (Fig. 1a). Although the direction of LCC follows the clockwise and anticlockwise during the winter and summer season, respectively, the water finally flows out through the southern part of the Bohai Strait (Guan, 1994).

In addition to the current circulation, the modern Bohai Sea is also affected by tidal currents (Qin et al., 1990), with the strongest tidal currents in the eastern part close to the Bohai Strait (Xie et al., 1990). The tidal regime is dominated by semi-diurnal tides (M2). The absolute ellipticities values of the M2 tidal are less than 0.4 in the study area, dominated by reciprocating-current (Liu et al., 1998). The mean velocity of tidal currents varies from 20 cm/s to 80 cm/s with the strongest value in the northern Bohai Strait and the eastern part of Liaodong Bay (Huang et al., 1999). In the Bozhong Shoal close to the core location, the maximum speeds of flood currents are ~58–79 cm/s with an average of 68.5 cm/s and the maximum ebb current speeds are ~50–65 cm/s with an average of 57.5 cm/s (Liu et al., 1998). The flood current enters the Bohai Sea along the northern part of the Bohai Strait and leads to the counterclockwise tidal circulation in Liaodong and Bohai Bays, due to the Coriolis force, while the ebb current flows out of the Bohai Sea along its southern part (Qin et al., 1990; Liu et al., 2009).

The sediments distribution in the Bohai Sea varies with tidal-current energy under the influence of tidal current field, because sediments erosion and re-suspension in the Bohai Sea are mainly controlled by tidal currents (Milliman et al., 1985; Liu et al., 1998). Modern sediments distribution in the Bohai Sea (Qin et al., 1990; Shi, 2012) show that muddy deposits composed of silts/sandy silts dominated in the estuarine and the central part, while sandy deposits (mainly sand/silty sand) dominated in the north-eastern Bohai Sea, close to the Bohai Strait where strong tidal currents occurs. The north-eastern Bohai Sea is mainly composed of mixed sediments with sand fraction ranging from 20% to 60% (Shi, 2012).

3. Material and methods

The BH08 core (212.4 m) was recovered in the eastern Bohai Sea (119.99° E, 38.28° N; Fig. 1) with a mean recovery of 86% in length. The current water depth at the site location is ~25 m. In laboratory, the core was split into two sections, photographed, described and subsampled. In the present study, we have selected the above ~8 m portion with well-constrained AMS ^{14}C dates for study.

Grain-size analysis was performed at ~5–10 cm intervals throughout the core to characterize the sediment texture using Malvern Mastersizer 2000. We have used the chemical procedure introduced by Konert and Vandenberghe (1997) in the experimental pretreatment to remove carbonate and organic material before the measurements.

A total of 60 samples have been selected at ~10 cm intervals for total organic carbon (TOC) and total nitrogen (TN) analyses. After samples being freeze-dried, homogenized and pulverized, sediments were treated with 1 N HCl to remove carbonate and subsequently rinsed with deionized water to remove salts. The residue was centrifuged and oven dried at 60 °C. Then the carbonate-free samples were analyzed for TOC and TN in duplicates in a Vario EL-III Elemental Analyzer.

Elemental abundances, given in peak area (count per second; cps), were obtained at 1 cm resolution using the Itrax XRF core scanner, using 20 s count times, 30 kV X-ray voltage. Although elemental concentrations are not directly available from the micro-XRF measurements, the obtained values can be used as estimates of relative concentrations. All the above analyses were performed at the First Institute of Oceanography, State Oceanic Administration, China. We here focus on the sulfur (S) and chlorine (Cl) which are obtained directly from the XRF scanning.

A total of six foraminifera samples and well-preserved mollusks (Table 1) were taken for AMS ^{14}C dating at the Woods Hole Oceanographic Institution, USA. Radiocarbon ages were corrected for the regional marine reservoir effect ($\Delta R = -139 \pm 59$ years, a regional average value determined for the Bohai Sea; Stuiver et al., 2005) and calibrated using Calib 6.0.1 program (Stuiver et al., 2005) with a one standard deviation (1σ) uncertainty (Table 1).

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