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Spatial and temporal variations and controlling factors of sediment accumulation in the Yangtze River estuary and its adjacent sea area in the Holocene, especially in the Early Holocene

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ABSTRACT

The sub-bottom and collected borehole data provide insight into the transport and accumulation processes of the Yangtze-derived sediment in the study area since ~11 kyr BP. Five seismic units were identified according to six major acoustic surfaces. The sedimentary strata consist of fluvial, estuarine and deltaic systems from the bottom up, characterized by two different trends in sediment accumulation rates, i.e., low-high-low, and high-low-high. On the inner shelf of the East China Sea, the terrain with trough and ridge was formed by the Early Holocene transgression strata (formed in ~10 to 12 kyr BP) scoured by the later rectilinear tidal current due to postglacial sea-level transgression, and the sharply protruding seismic units are interpreted to be bedrocks outcropping on the seafloor. An analysis of the sedimentary characteristics in the boreholes and such factors as difference in accumulation rates, and tectonic subsidence led us to conclude that the paleo-coastline was located not far away from and to the east of Core ZK09 at ~9 kyr BP, and the southern bank of the Yangtze River estuary was located to the south of Core ZK09. At ~9 kyr BP, the Yangtze-derived sediments were transported eastwards along the southern bank of the Yangtze River and the barrier due to the influence of the paleo-coastal current from the north, the direction of the Yangtze-derived sediment transport was split on the northeast of the Zhoushan archipelago, and the sediments covered the terrain with trough and ridge. During the high sea level period (7 kyr BP–present), the eastward migration of paleo-coastline had resulted in the increase in accumulation rate. We also conclude that the sharp increase in accumulation rate near the Yangtze River estuary after ~2 kyr BP was not primarily caused by human activities. The position shifts of the estuary caused by the paleo-coastline migration and sea level oscillations since the Holocene is the main cause controlling the Yangtze-derived sediment distribution, and the difference in accumulation rate at different locations in the study area.

1. Introduction

Rivers transport plentiful soluble materials and up to 15–20 billion tons of sediments annually into the global oceans, in which over 70% of global river sediments are from Asian rivers (Huang et al., 2001; Milliman and Meade, 1983; Milliman and Syvitski, 1992; Xu et al., 2009b). Historically the sediments transported into the East China seas by the Yangtze and Yellow rivers account for 10% of global sediment discharge (Liu et al., 2007a; Xu et al., 2012; Zhou et al., 2014). The Yangtze River is a link connecting mainland China and the East China Sea, and more than half of the Yangtze-derived sediments have been sequestered in the Yangtze River estuary and inner shelf over the past 7 kyr BP, thus to form a mega-delta near the current Yangtze River estuary and a muddy area on the inner shelf along the coasts of the Zhejiang and Fujian Provinces (Wang et al., 2010; Xu et al., 2009b). As the main fate of the sediments, the Yangtze River estuary and inner shelf have potential to record abundant geological information, the use of archives enables the identification of stratigraphic architecture, sedimentary characteristics and buried landforms for the study of paleo-environmental evolution and land–sea interaction (Atahan et al., 2008; Innes et al., 2014; Wang et al., 2012).

In recent years, research efforts on scientific aspects related to the transport and deposition of the Yangtze-derived sediment

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have mainly included the following: (1) the Yangtze River delta initiation and evolution were studied using large quantities of onshore borehole data, coupled with the current development trend of the Yangtze River estuary (Dai et al., 2015; Hori et al., 2001a; Song et al., 2013; Xu, 2013; Zhao et al., 2008). It is worth noting that the rapid increase in accumulation rate in the last 2 kyr BP has been extensive studied, and previous researchers mostly linked it to the influence of human activities (Hori et al., 2001b; Xu et al., 2012; Yi et al., 2003); (2) the muddy area on the inner shelf was identified using the seismic and borehole data (Liu et al., 2007b, 2013; Xu et al., 2015, 2012, 2009b), and its formation causes were further explored, to have a common understanding about the mode of southward transport of sediments (Liu et al., 2006, 2007b); (3) the modern sediment dispersal and distribution characteristics were analyzed based on the test and analysis results of large quantities of gravity and box cores, coupled with the distribution of tidal currents in the region (Liu et al., 2015; Xu and Milliman, 2009). Most of these studies were concentrated in the high sea level period. Besides, some scholars have studied the Holocene deposition process as a whole (Chen et al., 2000; Li et al., 1991; Li and Li, 1983). Research results from Chen et al. (2000) showed that, since the Holocene, large volume of sediments had been accumulated on the inner shelf near the Yangtze River estuary, and suggested that the gravity caused subsidence, providing accommodation space for accumulating sediments. Xu et al. (2009a) suggested that the Yangtze-derived sediment started to be transported southwards at 12 kyr BP due to the effect of the coastal current. However, the directions of the paleo-coastline migration were completely reverse in the Early Holocene (7–11 kyr BP) and high sea level period, which determines that the sediment transport process might be different between these two periods. The sea level rose in the Early Holocene and reached to the east of the Yangtze River estuary, the sedimentation at that time had a potentially profound influence on the later sedimentary evolution at the estuary. However, owing to the limitation by previous study conditions, studies dealing with the sedimentary evolution in the inner shelf during the Early Holocene are sparse.

In this study, the seismic-stratigraphical features within the study area have been well studied in terms of large quantities of acoustic profiles and the latest published borehole data, which never been investigated before in such a detail. And we calculated the sediment accumulation rate and marked out the sedimentary systems in boreholes. In addition, we found some special geologic phenomena in some acoustic profiles and analyzed their causes. Based on these research results, we examined the sedimentary characteristics of the Yangtze-derived sediment, and analyzed the control factors. We also identified the spatiotemporal distribution in the Holocene using these published borehole data associated with dating data, and special internal reflections in some acoustic profiles, which revealed a complex deposition process. To address these, the key point of this study is the transport and accumulation processes of the Yangtze-derived sediment in the Early Holocene, and we presented a complex pattern for the first time. These research results are beneficial supplements to study on the sedimentary evolution in the Yangtze River estuary and its adjacent sea area in the Early Holocene, trying to drive the deepening of understanding of the process of sediment "source to sink" under the background of river-sea interaction.

2. Geological background

The Yangtze River originates from the Tibetan Plateau, and flows eastwards into the East China Sea, with an overall length of 6300 km, an annual runoff of 876.7×10^9 m^3, and an annual sediment transport rate of 460×10^6 t (Milliman and Meade, 1983). In terms of sediment load and water discharge, the Yangtze River is a world class large river (Yi and Saito, 2004). In the last glacial period, the sea level declined to 135 m below the present seal level (Li et al., 2014; Park et al., 2000). At that time, the riverbed in the lower reaches of the Yangtze River was cut strongly, forming an incised river valley (Li et al., 2002). In the last deglacial period, the climate turned warm; affected by the paleo-climate events in different periods, the sea level rose with rapid-slow alternated speed, or even stagnated (Li et al., 2014, 2004; Xue, 2014). The sea water invaded the paleo-river valley first, and the base level of the river was lifted, causing retrogressive aggradation (Li et al., 2002). During about 11–12 kyr BP, the sea level rose to the inner shelf of the East China Sea, and there was river-sea interaction occurring in the area (Xu et al., 2012; Xu et al., 2016b). At about 7 kyr BP, the sea level rose to the maximum marine flooding surface, and the high sea level period started from then on (Clark et al., 2012; Yoo et al., 2002). At that time, the Yangtze River estuary was formed with Zhenjiang-Yangzhou area as vertex, and the development of a delta was started (Li et al., 2009). Since 7 kyr BP, the delta has been transformed from aggradation-dominated stage to seaward progradation-dominated stage, and the coastline has moved eastwards, with coastal markers, including shell embankment formed, according to which the locations of the paleo-coastline in different times after 7 kyr BP were delineated (Li et al., 2014; Zhu et al., 1996, Fig. 1b).

The inner shelf near the Yangtze River estuary, as an important component part of the East China Sea shelf, is also influenced by current systems, including the Yellow Sea coastal current, the East China Sea coastal current, and the Taiwan warm current (Bian et al., 2013; Chen and Zhu, 2012). These current systems act on the sediments and the sedimentary strata, building the current geomorphology high in the north and low in the south (Fig. 1a). The Yellow Sea coastal current acts on the northeast of the Yangtze River estuary, forming the Yangtze shoal with water depth of 30–40 m; the coastal current transports the bulk of sediments southwards and few sediments eastwards, so that the underwater terrain differs significantly on the inner shelf near the Yangtze River estuary; due to strong tidal effect, there is radial sand ridges along the Jiangsu Coast developed in the north of the Yangtze River estuary, and thus the delta at the Yangtze River estuary is a tide-controlled delta (Hori et al., 2002; Song et al., 2013; Sun et al., 2015; Xu et al., 2016a).

The Zhenjiang-Yangzhou area is a transition zone, on the west of which tectonic uplift occurs, and on the east of which tectonic subsidence occurs and it exhibits a trend of extending seawards gradually (Li et al., 2000). The study area is located in the tectonic subsidence zone, with subsidence rate of 1–3 mm a^{-1} (Li et al., 1991; Stanley and Chen, 1993; Wang et al., 2013). Moreover, the burial depth of the bedrock increases seawards gradually, and it is less than 100 m in Zhenjiang area but reaches 350–400 m at the Yangtze River estuary (Li et al., 2000). The Zhejiang-Fujian uplift zone passes through the East China Sea shelf from the part to the south of the Yangtze River estuary, and extends to the Korean Peninsula (Wageman et al., 1970; Zhao et al., 2008). The Zhoushan archipelago is seen to the southeast of the Yangtze River estuary, they are parts of the Zhejiang-Fujian uplift zone, which outcrop over the sea level, and the altitudes of these islands decrease gradually from south to north (Fig. 1a).

3. Data sources

The sub-bottom profiles collected for this study included: (1) CHIRP sub-bottom profiles, acquired by the First Institute of Oceanography, SOA in 2010 with 0512i towed profilers; (2) CHIRP