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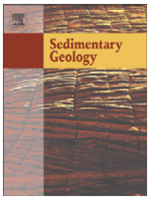

Sequence stratigraphy of the subaqueous Changjiang (Yangtze River) delta since the Last Glacial Maximum

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ABSTRACT

This study focuses on sedimentary research at the subaqueous Changjiang (Yangtze River) delta, based on five high-resolution seismic profiles and seven borehole cores with accurate AMS ^{14}C datings. Three distinct seismic units were identified from the seismic profiles according to seismic reflection characteristics, and five sedimentary facies were recognized from borehole cores. These facies constituted a fining upward sedimentary sequence in relation to postglacial sea-level transgression. Three sequence surfaces (sequence boundary (SB), transgressive surface (TS), and maximum flooding surface (MFS)) demarcate the boundaries between early transgressive system tract (E-TST), late transgressive system tract (L-TST), early highstand system tract (E-HST) and late highstand system tract (L-HST), which constitute the sixth order sequence. These system tracts were developed coevally with postglacial sea-level rise. E-TST (~19–12 ka BP) corresponds to an incised-valley infilling in the early stages of postglacial transgression whereas L-TST (~12–7.5 ka BP) was formed during the last stage of postglacial transgression. The progradational structure of L-TST reflected in seismic profiles is possibly related to the intensification of the East Asian summer monsoon. E-HST (~7.5–2 ka BP) was deposited in response to the highstand after maximum postglacial transgression was reached, while L-HST (~2 ka BP–present) was initiated by accelerated progradation of the Changjiang delta.

1. Introduction

The Changjiang (Yangtze River) is characterized by its large drainage basin (1.8×10^6 km^2), high amounts of runoff (9550×10^8 m^3) and high annual sediment load (4.86×10^8 t) debouched into the East China Sea (Milliman and Meade, 1983). An extensive delta developed in the Changjiang estuary has been prograding since the Holocene sea-level highstand (Chen et al., 2000; Li et al., 2014). Its delta plain is 4.2×10^4 km^2 and the subaqueous delta front and prodelta cover an area more than 1.9×10^4 km^2, extending down to the 50 m bathymetric contour (Li, 1986; Qin et al., 1987; Chen and Zong, 1998).

More than 600 cores have been drilled in the present Changjiang delta plain during the last five decades, providing an excellent database for the understanding of its stratigraphic framework (Li and Wang, 1998). Based on 30 analyzed cores and >100 published core data records, Li et al. (2002) concluded that its late Quaternary stratigraphic framework consists of an incised-valley infill, roughly coinciding with the present Changjiang delta, and two interfluvial sequences (Li et al., 2002). Hori et al. (2001a, b) clarified the sedimentary facies, sedimentary architecture and Holocene progradation rates following analysis of three boreholes drilled in the Changjiang delta plain. Subsequently, these authors discussed the evolution of the depositional systems of the incised-valley infills by applying sequence stratigraphic concepts (Hori et al., 2002a, 2002b). They attributed the stacking pattern of the system tracts to step-like, postglacial sea-level rises (Hori et al., 2002b). However, little was known about the eastward extension of this incised-valley to the East China Sea (ECS) shelf. Wellner and Bartek (2003) reported the presence of an extremely broad and deep incised-valley complex across the ECS shelf in Marine Oxygen Stage (MIS) 2. They proposed a diagram illustrating the development and fill of the MIS 2 through the incised-valley system. None of the boreholes or seismic profiles was shown at the subaqueous delta, though an incised valley was conspicuously illustrated. In contrast to those in the delta plain, only <10 boreholes and sparse seismic data were obtained from the subaqueous delta front and prodelta (Huang et al., 1985, 1996; Yuan, 1986; Qin et al., 1998). Chen et al. (2000) summarized

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these data which defined four sediment belts from the sea-bottom sediment distribution, and discussed the late Quaternary stratigraphy and sedimentary facies of the subaqueous delta. Sub-bottom acoustic profiles were also interpreted and three acoustic facies were differentiated, but these acoustic facies were not chronologically constrained and its relationship to the sedimentary facies was not revealed, mainly due to the lack of dated boreholes. In recent years, several age-controlled boreholes obtained from the subaqueous delta were reported (Liu et al., 2010; Wang et al., 2010, 2011, 2015; Xu et al., 2013). This research mainly focused on the relationship between sedimentary facies and sea-level fluctuation, without any corresponding seismic profiles. Thus, the chronostratigraphic correlation between these boreholes and the spatial distribution of the sedimentary facies is still not well understood. For this reason, neither boreholes nor seismic data from the subaqueous delta were cited in recent review by Li et al. (2014).

In order to depict the detailed sedimentary architecture of the subaqueous Changjiang delta, it is necessary to conduct a comprehensive research on boreholes and their corresponding seismic profiles. In this study, seven boreholes, containing sediments deposited after the Last Glacial Maximum (LGM) and their related seismic profiles from the subaqueous Changjiang delta (Fig. 1) were analyzed in order to (1) recognize sedimentary facies in these boreholes; (2) propose a sequence stratigraphy frame for the study area; and (3) reveal the relationship between the sedimentary sequence and the postglacial transgressive processes.

2. Study area

The Changjiang estuary is 120 km long and 90 km wide at its outer limit where the river is divided into four distributaries by Chongming Island, Changxing Island, Hengsha Island, and Jiuduan Shoal with three-ordered bifurcation (Fig. 1a, b). Before the 18th century, its North Branch was the main discharge channel. Since that time, the main flow has shifted gradually to the South Branch as the North Branch discharge decreased dramatically. At present, the South Branch accommodates about 98% of the river runoff and the North Branch only discharges river water during low tides during flood seasons (Wang et al., 2003; Yang et al., 2003). Sandy material from the Changjiang River accumulates primarily within the estuary, where the water depth is less than 10 m and forms the delta front (Fig. 1c). Muddy sediment disperses seawards, suspended as a fresh-water plume floating over a salt-water wedge. Part of the muddy sediment is deposited in the prodelta and some is transported southeastward, being met by the north-directed Taiwan warm current (Chen et al., 2000).

Since 7 ka BP, sediments from the Changjiang River began to fill the incised valley that had formed during the late Pleistocene sea-level lowstand. As a result, the modern Changjiang River delta formed with its apex located around Zhenjiang and Yangzhou (Huang et al., 1996; Hori et al., 2001a, 2002c; Li et al., 2002; Liu et al., 2007a). At the present time, the Changjiang River delta can be divided into the subaerial delta and subaqueous delta in relation to the average low tide level (Hori et al., 2001a, 2002c). The subaqueous delta can be further subdivided into subtidal flats (subaqueous delta plain), delta front, and prodelta, according to the sediment types and topography (Fig. 1c). The subaqueous delta is mainly composed of fine-grained sediments except for the river-mouth bars that consist of sandy sediments (Fig. 1c). The subtidal flats are located in water depths of about 5–10 m and the gradient is very gentle (0.006°) (Fig. 1c). The prodelta is the distal part of the Changjiang River delta, where the water depth is about 15–30 m. The delta front lies between the subtidal flats and prodelta with a slope of 0.03–0.05° (Fig. 1c). East of the study area, there are relict sand ridges and transgressive sandy ridges distributed at a water depth of >30 m (Huang et al., 1996; Liu, 1997; Chen et al., 2000; Berné et al., 2002; Uehara et al., 2002; Wang et al., 2005; Liu et al., 2007b) (Fig. 1c).

3. Methods

3.1. Borehole core analysis

During the period 2008–2010, seven borehole cores, ranging from ~30 m to ~70 m in penetration depth, were obtained from the subaqueous Changjiang delta by R/V *Kan 407* (Fig. 1b). Detailed information on these cores is summarized in Table 1. The sedimentary facies of each core have been described previously on the basis of lithological characteristics, sedimentary structures, and fossil assemblages (Table 1).

In addition to the eight new ^{14}C dates (Table 2), which were tested at Woods Hole Oceanographic Institute, USA, by accelerator mass spectrometry AMS ^{14}C dating method, forty previously reported AMS ^{14}C dates were collected (Table 2). These AMS radiocarbon dates were obtained from molluscan shells, foraminifera, bivalve shells, shell debris, wood, plant materials, and sedimentary organic matter within the cores (Liu et al., 2010; Wang et al., 2010, 2015; Wang, 2011; Xu, 2013; Xu et al., 2013), and were calibrated using CALIB6.0.1 (http://intcal.qub.ac.uk/calib/). An ocean surface reservoir correction (45 ± 71 a) was applied according to the weighted mean of the data around the Changjiang River estuary.

For the gravel and coarse sand deposits in the lowermost part of some cores, it is not possible to find materials suitable for ^{14}C dating. Therefore, 9 samples were selected for Optically Stimulated Luminescence (OSL) dating (Table 3). To ensure the accuracy of the OSL test, two different methods were used for comparison. Three samples were calibrated using the Single-aliquot regenerative-dose procedure (SAR) method (Wintle and Murray, 2006). Concentrations of U, Th, and K were analyzed at the China Institute of Atomic Energy and the other parameters were measured in the OSL lab of the China University of Geosciences (Wuhan). The other 6 samples were calibrated by the Sensitivity-corrected multiple-aliquot regenerative-dose protocol (SMAR) method (Lu et al., 2007). Concentrations of K were measured at the Institute of Earth Environment, Chinese Academy of Sciences, and the other parameters were analyzed at the Institute of Geology, China Earthquake Administration.

3.2. High-resolution seismic data

Five high-resolution seismic profiles, approximately 400 km long in total, were conducted in the study area during July–August 2010 using a SB-0512i CHIRP acoustic profiler (Fig. 1b) and passing through the aforementioned boreholes. The operation frequency of this acoustic profiler was between 0.5 and 12 kHz. Acoustic penetration depth ranged from ~30 to ~70 m, and the vertical resolution was ~0.1 m. Boat speed was 4 nmph during the survey. The three longitudinal seismic lines were labeled as Line 1, Line 2, and Line 3 from north to south (Fig. 1b), whereas the other two latitudinal seismic lines were labeled Line 4 and Line 5 (Fig. 1b). In accordance with previous studies (Huang et al., 1996; Chen et al., 2003), an acoustic velocity of 1600 m/s was assumed to calculate the water depth and sediment thickness. Gas-bearing deposits prevail in the study area within a water depth of ~30 m.

4. Results

4.1. Seismic structure

The shallow gas-bearing deposits and multiple reflections prevailing in the area at <30 m water depth seriously reduced the precision of the acoustic profiling (Figs. 2–6). Thus, acoustic profiles with relatively unambiguous reflectors can only be observed in the deeper sea area. On the basis of the truncated surfaces and the characteristics of the reflectors, the seismic profiles were divided into three units.

Unit I is the uppermost unit and no more than 10 m in thickness, showing a wedged shape in each profile, with a seaward thinning