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Late Quaternary environmental change in Oujiang delta along the northeastern Zhe-Min Uplift zone (Southeast China)

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ABSTRACT

We present a history of late Quaternary coastal evolution based on the study of a 41.9-m-long sediment core from the Oujiang Delta. Multiple analytical methods are employed, including sedimentary facies analysis, radiocarbon dating, and the investigations of grain size, elemental, microfossil and pollen compositions. Two transgression-regression sequences, separated by a paleosol layer, are identified. Several lines of evidence indicate that the lower sequence was deposited during the mid-early MIS 3 stage, under a relatively warm and wet climate. An elevated MIS 3 highstand sea level (higher than − 24 m) is observed. The upper sequence was created after the paleosol was flooded during a marine transgression at ~9.5 cal kyr BP. Seven weak East Asian Summer Monsoon (EASM) events are identified with central years of ~8.4, 7.7, 6.3, 5.7, 4.7, 2.8 and 1.8 cal kyr BP. These coincide with those from the ECS sediment cores and the Dongge Cave $\delta^{18}O$ record, indicating that EASM precipitation is a major controlling factor of sedimentation rates in the region. The Oujiang Delta is also subject to typhoon impacts and East Asian winter monsoon (EAWM)-induced coastal currents. Active typhoons and a relatively enhanced EAWM occurred during the weak EASM period between 4.9 and 6.4 cal kyr BP, producing high sedimentation rates in the middle Holocene. We emphasize the high sensitivity of small Asian river deltas as archives of the EASM, EAWM and typhoons. Such environments merit further as a means to understand past changes as well as future responses to projected climatic and sea-level change.

1. Introduction

Monsoonal Asian coasts attract great attention for their extreme vulnerability to global change because of their typical dense populations and projected human impacts on climate and sea-level change on coastal evolution, albeit with large uncertainties (Syvitski et al., 2009; Fan et al., 2017). To reduce these uncertainties, late Quaternary coastal systems have been extensively investigated as analogues for contemporary and future coastal development. Numerous instructive findings have been extracted from research of mega-river deltas in the far-field, passive Asian coasts and their associated deposits on the broad shelves. However, debates on MIS 3 sea-level elevation and Holocene monsoon climate persist (e.g. Hanebuth et al., 2000, 2006; Li et al., 2002; Ta et al., 2002; Xiao et al., 2006; Liu et al., 2010, 2016a; Wang et al., 2013; Sun et al., 2015).

It is a challenging task to accurately determine the age and paleo-elevation of MIS 3 sea-level highstand markers (Hanebuth et al., 2000, 2006; Muhs et al., 2014; Murray-Wallace and Woodroffe, 2014; Liu et al., 2016a). Coastal sediments of the MIS 3 interstadial are commonly dated using the AMS ^{14}C method, but the reliability of dating results is questionable because of extreme sensitivities to contamination potentially introduced during burial, sampling, and/or laboratory processing of dating materials (d'Errico and Sánchez Goñi, 2003; Jull and Burr, 2006; Pigati et al., 2007). This apprehension has led some researchers to reinterpret MIS 3 interstadial deposits as MIS 5 (Yim, 1999; Hanebuth et al., 2006; Zong et al., 2009; Yi et al., 2012; Isla and Schnack, 2016). Other lines of evidence for age reinterpretation include additional age data by luminescence, uranium-series and other dating methods, and reconstructed MIS 3 sea-level elevations that are much higher than those from dated coral-reef sequences and oxygen-isotope records from deep-sea core sediments (Chappell et al., 1996; Yokoyama et al., 2001; Siddall et al., 2003). However, no dating method can guarantee absolute age accuracy (Murray-Wallace and Woodroffe, 2014). Moreover, it is difficult to accurately determine past sea-level

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elevations from limited geomorphic and sedimentological evidence, typically based on a few cores from the coast and shelf regions. Potential uncertainties include the estimation of paleo-water depths during deposition, vertical movement of the target strata by sediment compaction, tectonic movement, and differential responses to hydro-isostasy and sediment load. The latter effect is common in mega-river deltas and their adjacent broad shelves (e.g. Hanebuth et al., 2006; Wang et al., 2013; Sun et al., 2015; Liu et al., 2016a).

Coastal evolution during the late Quaternary is not only controlled by sea-level change, but also by sediment supply and coastal hydrodynamics. The latter two factors are driven by monsoon climate change in Asia. Asian summer monsoon-induced precipitation on land has been extensively studied due to its vital role in natural ecosystem development and agricultural production for human society (Wang et al., 2005; Yang and Scuderi, 2010; Zhang et al., 2011). Monsoon precipitation in the drainage basins controls river runoff and sediment discharge into the sea, consequently greatly influencing sediment dispersion and morphological development in the river mouths and adjacent shelves. The integrated catchment of mega-river systems may be controlled by different monsoon systems, complicating paleoenvironmental interpretations of their river deltas. For example, the upper reaches of the Yangtze and Yellow Rivers are influenced by Indian summer monsoon, but their lower reaches are dominated by the East Asian summer monsoon (EASM). However, small river systems in East and Southeast Asia are generally influenced exclusively by EASM, and they are highly sensitive to individual flooding events (Liu et al., 2016b; Wang et al., 2016). It is worth noting that flooding events may also be induced by typhoon landfalls in these small rivers. Furthermore, sedimentation in small river mouths and their adjacent shelves are strongly influenced by longshore currents, which are commonly linked with enhanced East Asian winter monsoons (EAWM) in East and Southeast Asia (Xiao et al., 2006; Liu et al., 2006). Therefore, small river deltas and their adjacent shelf deposits have high potential to register diverse climate change information in the Holocene, and different signals can be separated by sediment provenance analyses using clay mineral or geochemical methods (Li et al., 2015; Wang et al., 2016).

Mega-river deltas have been intensively studied for the late Quaternary environmental change in East and Southeast Asia during the past decades, including the Yellow River (Saito et al., 2000; Liu et al., 2009), the Yangtze (Hori et al., 2002; Li et al., 2002; Yi et al., 2003; Song et al., 2017), the Pearl River (Zong et al., 2009), the Red River (Schimanski and Stattegger, 2005; Tanabe et al., 2006), and the Mekong (Ta et al., 2002; Schimanski and Stattegger, 2005). However, small-river deltas in this region have received much less attention. As a typical representative of small Asian river deltas, the Oujiang Delta is developed in an embayment coast along the Zhe-Min Uplift zone (Fig. 1). The chenier plain is widely developed along the southern deltaic flank, which is actively shaped by complex interactions of fluvial and marine processes, including tides, waves and longshore currents. The 41.9-m-long borehole core YQ0902 was retrieved from the central (cross-shore) chenier plain, where the previous highstand deposition experienced erosion by sea-level lowering incision. The core sediments were investigated in detail using multiple methods of sedimentology, sequence stratigraphy, radiocarbon dating, elemental analysis, and microfossil and pollen identification. The specific objective of this paper is to examine the second marine transgression sequence in the core as an MIS 3 or MIS 5 highstand deposit, and its corresponding sea-level elevation, and to examine Holocene EASM, EAWM and typhoon activities and their correlations in the region.

2. Study area

2.1. Geological setting

The study area belongs to the eastern Cathaysia Block in southeast China (Xu et al., 2007). The basement is composed mainly of Paleoproterozoic rocks. These were folded and highly reworked during Yanshanian magmatic activities in the Jurassic and Cretaceous, resulting in the Zhe-Min Uplift zone (Fig. 1A). This tectonic unit has remained relatively stable since the Cenozoic, undergoing continuous erosion in the mountainous area (Xu et al., 2007). Several rivers drained the central-western Zhe-Min Uplift zone into the East China Sea (ESC) through graben valleys. Their present sediment discharge is very low in comparison with those in Taiwan (Wang et al., 2016). Deltaic plains are generally narrow (Fig. 1A) and about 150–180 m thick of Quaternary strata lie directly over the Mesozoic basement. Roughly half of these strata have been deposited in the late Quaternary (Wang et al., 1982a).

2.2. Oujiang river-estuary-coastal system

The Oujiang River drains a small area of $\sim 1.80 \times 10^4$ km^2 in the northeastern Zhe-Min Uplift zone. Its headwaters are on Baishanzu Mountain (peak mountain elevation of 1856.7 m) in the southwest Zhejiang Province. The river winds through the mountainous area for 388 km before debouching into Yueqing Bay. The bay stretches northeast with several rocky islands that separate it from the East China Sea (ECS). The river carries mean annual water and sediment discharges of 1.67×10^{10} m^3 and 2.22×10^6 tons, respectively, ranking it the second largest river in the Zhejiang Province.

The Oujiang drainage basin experiences a subtropical monsoon climate, highly influenced by typhoons in summer. The present vegetation is principally dominated by middle subtropical evergreen broadleaved forests. Annual precipitation varies from 1100 to 2200 mm, and most of the rainfall is concentrated in summer (April to September). The river runoff in summer accounts for 78% of the annual total (Xie et al., 1994; Zhang et al., 2012). Heavy rainfall induced by typhoons produces mega-flood events, and a relevant peak discharge has been reported to be one fourth that of the Yangtze River, despite the watershed difference approaching one percentile. This rapid flooding event characterizes numerous coastal mountainous rivers in low latitudes.

The Oujiang river-mouth is a macro-tidal setting with a mean and maximum tidal range of 4–5 m and 7.15 m, respectively (Li et al., 1994; Xie et al., 1994). Waves are generally quite low with a multi-year mean wave height < 0.5 m, but the maximum wave height reaches over 2.4 m during typhoon strikes. On average, four typhoons make landfall or exert significant impacts on the coast every year (Xie et al., 1994).

The present delta and chenier plain formed since the mid-Holocene maximum transgression with an extreme landward boundary near Qingtian (Zhang, 1990; Zhu, 1993; Fig.1B). Two large alluvial islands outcrop at the present river-mouth. The south flank of the delta includes four shore-parallel chenier ridges. They are the Siqian, Ningcun, Wuxi and Jiangding ridges and trend in a seaward direction (Zhu, 1993; Fig. 1B). Sandy ranges and bars have also developed on the modern intertidal flat and subtidal flats (Li et al., 1994; Xie et al., 1994). The Holocene strata is about 30–50 m thick in the study area (Wang et al., 1982a, 1982b; Yang and Chen, 1982).

3. Methods

3.1. Core logging and grain-size analysis

Borehole core YQ0902 (27°55′27″ N, 120°50′35″ E, and 3.15 m in elevation) was drilled in June 2009 with a rotary drill on the Wenrui chenier plain, a part of the southern flank of the Oujiang Delta (Fig. 1B). The core is 41.9 m long, and the average recovery of core sediments is ~95%.

In the laboratory, the cores were split lengthwise into two halves, and the surfaces of the working core halves were carefully smoothened with stainless steel knives to reveal any sedimentary structures. They were then photographed, described, and nondestructively analyzed by