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Land-sea duel in the late Quaternary at the mouth of a small river with high sediment yield

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ABSTRACT

The transition between sedimentary environments is compressed along land-sea boundaries in space and time. At river mouths on high standing islands, sedimentary records with high temporal resolutions formed as a result of large sediment loads and pervasive post-glacial sea level rise. Here we report on sediment core records covering the late Quaternary from the mouth of a small mountainous river in Taiwan. Results show that the study site was initially terrestrial under fluvial control. Beginning at about 10,000 yr BP (before present) the site became inundated by the rising sea and the environmental facies transitioned from a floodplain/incised river valley to a succession of marine environments, from shoreface to offshore. As the rising sea level came to a pause at 6000 yr BP, fluvial processes became dominant and sediments began to aggrade at the river mouth. After 4500 yr BP, the accumulated sediment began to prograde seaward, taking on the form of a river delta, and subtidal sand ridges appeared in the nearshore. This also introduces the deltaic development, which was limited by topography of the receiving basin. The chronology expresses the duel between sea level and fluvial processes that determined the depositional environments along the land-sea boundary at the study site.

1. Introduction

The island of Taiwan is located on the collision boundary between the Eurasian and Philippine Sea plates. Small mountainous rivers on Taiwan deliver huge sediment loads as the combined result of steep terrain, extensive faulting and fracturing due to tectonism, and torrential rains from the monsoon and typhoons (Chen et al., 2004; Dadson et al., 2003; Liu et al., 2013). The orogenic uplift rate is about 1 cm/yr, and the denudation rate is about 0.5 cm/yr in Taiwan. Such high uplift/denudation rates make Taiwan well known for very rapid environmental changes (Liu et al., 2001). For example, the river channels of Taiwan's Western Foothills constantly shift on the Coastal Plain, affecting the coastal depositional environment.

The Zhuoshui River Basin located in central Taiwan has an area of 3156.9 km^2 and exports 54 × 10^6 tonnes of sediment per year (Dadson et al., 2003). The suspended sediment concentration in the river can reach to 11,000 mg/l – the second highest in the world (Eisma, 1998). On average, this river has a sediment yield (annual sediment load per unit drainage area) of 17,105 tonne/km^2/yr, which is among the highest in the world (Kao and Milliman, 2008). Unlike continental rivers, small mountainous rivers can experience sediment fluxes several orders of magnitude above normal during extreme weather events (Farnsworth and Milliman, 2003; Kao et al., 2008). Such large sediment loads preserve records of sedimentary environmental transitions with high temporal resolution at the river mouth.

Since the Last Glacial Maximum (LGM), the eustatic sea level rose about 120 m (Clark and Mix, 2002; Lambeck et al., 2002). Previous studies point out that the global trend of sea-level change is consistent with that of Taiwan in the Middle Holocene (Chen and Liu, 1996). The rising sea level provides accommodating space for sediment accumulation along the coast and in estuaries. Sediment accumulation can form a variety of coastal landforms due to different hydrodynamic processes driven by waves and tides (Orton and Reading, 1993). As the sea level rose, past coastal depositional patterns were recorded in the sediment stratigraphic sequences. Therefore, one can understand the characteristics of past depositional environments through sedimentary structures, facies, and environmental proxies in sediment records (Reading, 1996; Walker and Plint, 1992). Between ~8000 and 6000 cal. yr BP when the sea-level rise slowed down, many of the major modern deltas began to develop (Stanley and Warne, 1994). Deltaic deposition was dominated by aggradation in this period. After sea level reached a highstand, deltaic deposition turned to progradation, from 6000 to

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4000 cal. yr BP, e.g., Mekong River delta (Ta et al., 2002a), Red River delta (Tanabe et al., 2006), Yangtze River delta (Song et al., 2013). The sediment accumulation rate of the aggradation stage was generally higher than that of the progradation stage (Marriner et al., 2012; Song et al., 2013). However, there are relatively few studies of deltas of small mountainous rivers around the globe, as compared to deltas of large rivers (e.g., Mississippi River delta, Nile River delta, Yangtze River delta).

Sets of complex interacting fluvial and marine-related (land-sea duel) processes control the environment in which the morphology and sedimentary characteristics of river deltas are formed. Based on the relationship between deltaic characteristics and their controlling factors, modern deltas can be classified into several types, including fluvial-, tide-, and wave-dominated deltas (Orton and Reading, 1993). These types are applicable to paleo-deltas as well, including the paleo-Zhuoshui River delta in this study.

The ability to distinguish proximal facies from more distal deposits is an essential element of most sedimentary interpretations. However, this distinction is not equally viable for all environmental settings (Dalrymple and Choi, 2007). The distinction is especially difficult in a complex and dynamic setting where sedimentary environmental transitions took place abruptly, such as the fluvial plain of the Zhuoshui River on the west coast of Central Taiwan (Fig. 1).

This study used two drilled cores with high-resolution AMS ^{14}C dating to establish the land-sea transition changes that occurred as the sea level rose above the Zhuoshui River paleo-fluvial plain in the late Quaternary. The objective is to expand our knowledge of rapidly changing sedimentary environments caused by rising sea level, using the river mouth of a small mountainous river as a detailed example. We aim to provide a case study from which we can compare with other deltaic systems in the world and anticipate the rapid environmental changes that may result from global climate change.

2. Methods

2.1. Core analyses

Core JRD-S (104 m long, at 120° 14.44′E 23° 49.94′N) was taken on the south side of the river delta at an elevation of 4.072 m; and a second core, JRD-N (98 m long, at 120° 18.15′E 23° 54.17′N), on the upper tidal flat at an elevation of 7.94 m in the tidal basin north of the river mouth (Fig. 1). A rotary drill with PVC casing was used to ensure high recovery rates (80% and 85%, respectively) and sample continuity. In the laboratory, each sediment core was first split, and the archived half was photographed and described. The core descriptions contained sedimentary structures, color, and inclusions, and grain-size classification based on the Udden-Wentworth scale. After sub-sampling, the samples were freeze-dried and then 2 g of each subsample was prepared for grain-size analysis as described in Section 2.3 below. For foraminiferal analysis, 10 g of each subsample was wet sieved through a 150-μm sieve. The coarse fraction (> 150 μm) was examined under a binocular microscope and individual foraminifera were picked out. The foraminiferal abundances provide evidence for the marine sedimentary environment. There were 182 samples for grain-size analysis and 192 samples for foraminiferal analysis in JRD-S, 504 samples for grain-size analysis and 64 samples for foraminiferal analysis in JRD-N (There are at least two grain-size analysis data points per meter).

2.2. Age model based on AMS ^{14}C dating

Samples containing organic carbon, such as tree branches, carbon chips, peat, and shells, were picked out from the cores and sent to the University of Arizona for Accelerator Mass Spectrometer (AMS) ^{14}C analysis. Samples were treated with a standard acid-alkali-acid pretreatment and carbonates were subjected to stepwise dissolution in phosphoric acid to remove potential contamination (Burr and Jull, 2010). The cleaned samples were oxidized to CO_2 under vacuum, and subsequently reduced to graphite, the target material for the accelerator. For organic samples we employed a stepped-temperature combustion at 400 °C and 1100 °C. Eight standards were run on the AMS along with the unknowns and the reported uncertainties include uncertainties in chemical processing, blank uncertainties and AMS machine uncertainties (Burr et al., 2007). The ^{14}C dating results were calibrated with the CALIB 7.0.0 program, according to the sample types either the IntCal 13 or Marine 13 calibration curve was used. A ΔR (difference between the regional and global marine ^{14}C age) value of 87 yr was used for the calculation of marine shell dates (Reimer et al., 2013).

For the age model we selected organic samples that used the 400 °C combustion temperature fraction. Some samples in the bay-head delta facies in the upper part of the cores show conspicuously older dates when compared to the trend established by numerous samples lower in

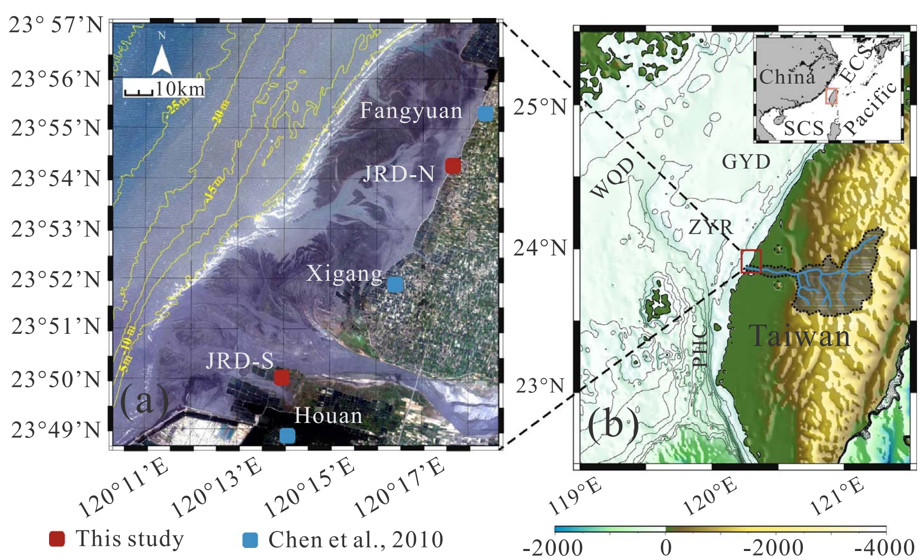

Fig. 1. (a) A composite map combing a FORMOSAT II satellite image taken on Oct. 18, 2007 and bathymetric contours of the Zhuoshui River mouth, showing the topography of the river mouth and the nearshore at low tide. The red squares are the coring locations of this study and the blues squares are the drilling locations of previous studies. (b) A relief map of Taiwan, in which the blue lines are the Zhuoshui River and its tributaries, and the black dotted line delineates the boundary of the river basin. The inset shows the study area (pink rectangle) in the western Pacific (see Supplemental material for image processing).