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Sediment trapping in deltas of small mountainous rivers of southwestern Taiwan and its influence on East China Sea sedimentation

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ABSTRACT

Taiwan's setting of high mountains, steep gradients, frequent earthquakes, erodible lithology, and heavy rainfall represents an ideal site to focus on sedimentary processes of the deltas of small mountainous rivers (SMRs). Several SMRs in southwestern Taiwan have deposited a thick sedimentary succession in the composite Southwest Taiwan Delta (SWTD) since the middle Holocene. Evidence from the SWTD can help to determine its trapping efficiency and assess the role of SMRs in sediment transport to the sea. We used historical nautical charts, bathymetric data, satellite radar data, and ^{14}C dates to calculate the sediment volume of the SWTD on millennial and decadal scales. The ^{14}C dates of core samples indicate deposition of thick deltaic sediment in subsiding areas since the time of the maximum flooding surface about 7 cal ka BP. The paleo-shoreline changes of the SWTD suggest a steady westward progradation since 7 cal ka BP. In contrast, the nautical charts suggest minor volume reduction of the offshore part of the SWTD, with a deepening trend and retreating shorelines, during the last seven decades. The results show that at least 201.72 ± 13.90 km^3 (~3.23×10^5 Mt) of sediment has been trapped in the SWTD since 7 cal ka BP, and that the delta has shifted to a destructive phase during the past seven decades as human influences such as construction of reservoirs, dams, and weirs in the hills have reduced the sediment supply. The birth of the Taiwan Warm Current and following continuous sediment supply from the western rivers of Taiwan to the East China Sea since ~7.3 cal ka BP have played a crucial role in the sedimentation of the East China Sea, particularly in the Okinawa Trough, and the Japan Sea through the Tsushima Warm Current.

1. Introduction

Deltas form in coastal environments where river-borne sediment builds sedimentary bodies that extend by aggradation into receiving basins. Wright (1977) defined deltas as “coastal accumulations, both subaqueous and subaerial, of river-derived sediments adjacent to, or in close proximity to, the source stream,” and Elliott (1978) defined them as “discrete shoreline protuberances formed where rivers enter oceans, semi-enclosed seas, lakes or barrier-sheltered lagoons and supply sediment more rapidly than it can be redistributed by indigenous basinal processes.” Modern deltas are widely variable in terms of scale, processes and the nature of the sediment deposits. Deltas are commonly classified as dominated by rivers, waves or tides (Galloway, 1975) and are also classified using grain-size factors (Orton and Reading, 1993).

Most modern deltas have been built since 7.5–8.0 cal ka BP, following the decrease of Holocene sea-level rise (Stanley and Warne, 1994; Olariu, 2014). High-resolution studies of deltas and sea-level changes have revealed that delta initiation occurred after a rapid rise of sea level during 9.0–8.2 cal ka BP, and the timing of delta initiation depended on the sediment supply between 8.2 and

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6.5 cal ka BP (e.g., Tamura et al., 2009; Hijma and Cohen, 2010; Smith et al., 2011; Li et al., 2012b; Wang et al., 2013; Song et al., 2013; Tjallingii et al., 2014). Large deltas are major sinks of terrestrial sediment in coastal areas (e.g., Bianchi and Allison, 2009), and deltas usually have higher accumulation rates than other marine environments (Syvitski, 2003).

Rivers in Asia and Oceania deliver huge amounts of sediment, amounting to ~70% of the global discharge of suspended sediment (Milliman and Farnsworth, 2011), with large rivers on the Asian continent and small rivers on islands contributing roughly equal portions. Many recent studies of the Holocene deltas of large Asian rivers have focused on delta evolution, sediment facies, paleoenvironments, and sediment flux and fate (e.g., Woodroffe et al., 2006; Liu et al., 2009; Woodroffe and Saito, 2011; Wang et al., 2011; Wilson and Goodbred, 2015). The East Indies (Oceania) constitutes one of the largest regional sources of sediment to the global ocean (Milliman et al., 1999). The Fly River delta of New Guinea, one of the largest deltas in Oceania in terms of sediment discharge, is comparable to large river deltas and has been well characterized (Dalrymple et al., 2003). However, deltas associated with small mountainous rivers (SMRs) are not well studied. In this study we examined the large composite Holocene delta of southwestern Taiwan, which is a good example of SMR deltas, to characterize its sediment trapping and delta evolution at millennial and decadal time scales.

Taiwan's natural setting of high mountains, steep gradients, frequent earthquakes, erodible lithology, and heavy rainfall makes it a natural laboratory for studying the fate of sediment transport by SMRs. For example, events including typhoons, earthquakes and extreme rainfall trigger erosion and weathering of rocks that in turn promote sediment output. Landslides induced by earthquakes mobilize large volumes of sediment that is susceptible to erosion during typhoon and monsoon seasons (Dadson et al., 2004; Milliman et al., 2007). Consequently, the mountain ranges of Taiwan deliver very large quantities of sediment to the coast. Estimates of the average amounts of sediment delivered to the ocean by Taiwanese rivers include one of 384 Mt/y during 1970–1998 (Dadson et al., 2003) and another of 180 Mt/y of sediment between the 1980s and 2005, with a range of 16–440 Mt/y (Kao and Milliman, 2008). These estimates rival the sediment discharges of the Mekong (160 Mt/y) and Red (130 Mt/y) rivers, as well as that of the Yangtze River (~150 Mt/y) after completion of the Three Gorges Dam and the Yellow River (~150 Mt) after completion of the Xiaolangdi Dam (Wang et al., 2011). This study focused on sediment trapping in the Chianan Plain, a wide compound delta plain (Fig. 1) in southwestern Taiwan, and the influence of sediment from this area on sedimentation in the East China Sea.

2. Geological background

The Taiwan orogen, resulting from oblique collision between the Luzon Arc and the Eurasian continent (Fig. 1), manifests as a mountain belt reaching elevations of 4 km (Bowin et al., 1978; Ho, 1988; Teng, 1990). The denudation rate of the Central Range of Taiwan has averaged at least 1.4 g/cm^2/y since the Pliocene (Li, 1976). Furthermore, the erosion rate ranges from 3 to 6 mm/y for an average annual sediment yield of 500 Mt/y, and much of the bedload in Taiwanese rivers is trapped in floodplains before reaching the sea (Dadson et al., 2003). Under precipitation totals of ~2500 mm/y, the SMRs of Taiwan are strongly affected by periodic floods, typhoons, and earthquakes (Dadson et al., 2003; Kao and Milliman, 2008). Sediment transport in SMR catchments is substantially influenced by landslide debris produced by hillslope mass wasting (Hovius et al., 2000). The SMRs of western Taiwan run perpendicular to the strike of the Taiwan orogen in short, straight routes across low-gradient deltaic plains (Fig. 1) and thus tend to discharge larger percentages of their sediment loads directly to the sea than do larger rivers. However, eight of these SMRs (the Choshui, Peikang, Potzu, Pachang, Chishui, Tsengwen, Yenshui, and Erhjen rivers; see Table 1) have collectively built up a compound delta, called here the Southwest Taiwan Delta (SWTD), in the western and southwestern coastal plains (Fig. 1). The Choshui and Tsengwen rivers are major rivers longer than 100 km whereas the others are shorter (Table 1). The total drainage basin area of the eight SMRs is 6953 km^2. The SWTD consists of a subaerial portion with an area of about 5000 km^2 and a subaqueous portion amounting to 2000 km^2 (Fig. 1).

The SWTD owes its elongated form partly to its multiple sediment supplies and partly to the tectonic and structural restrictions posed by the Chukou and Chelungpu thrust faults to the east, the Changhua-Pakuashan anticline to the north and the Laonung fault to the south (Shyu et al., 2005). To the west, the Taiwan Strait is a seaway about 140 km wide with a mean water depth around 60 m, connecting the East China Sea and the South China Sea (Fig. 2). Features on the floor of the Taiwan Strait, including the west and east Changyun sand ridges, Penghu Channel and Taiwan Bank, are products of the modern tidal current system (Chern and Wang, 2000; Yu and Huang, 2003; Liao and Yu, 2005). The south part of the Taiwan Strait is relatively shallow by the Taiwan Bank and Penghu Islands. The east Changyun sand ridge lies directly off the northern part of the subaqueous delta. To its south, the funnel-shaped Penghu Channel runs N–S between the Penghu Islands and southwestern Taiwan (Liao and Yu, 2005). The northern part of the subaqueous delta extends to about 40 m depth in front of the east Changyun sand ridge, and the southern part extends down to about 100 m east of the Penghu Channel (Fig. 2). The southwestern part of the delta near Tainan includes a series of lagoons and lakes along the current shoreline (Yang and Su, 2001). The average tidal current in the Taiwan Strait is 0.46 m/s with a range of 0.2–0.8 m/s, and the average mean current is about 0.40 m/s (Wang et al., 2003).

The sea level in the Taiwan Strait west of Taiwan has been relatively stable since 7 cal ka BP (Chen and Liu, 1996, 2000). In southwestern Taiwan, the first major transgression began prior to ~8.5 cal ka BP (7.68 ^{14}C ka BP) and the maximum transgression occurred about ~6.8 cal ka BP (6.0 ^{14}C ka BP) (Taira, 1975). For example, Fig. 3 shows that the chronology in core TN-SF was determined from six ^{14}C ages. The interval from 20 to 85 m core depth was characterized by marine facies, and the maximum flooding surface was identified at 46.3 m with an age of 7 cal ka BP. The Holocene sediments of the SWTD consist mainly of sand, gravel, and some clay plus substantial soil carbonate (Lin, 1969; Ho, 1988; Dadson et al., 2003). The Holocene and late Pleistocene stratigraphy of the Choshui and Tsengwen river deltas has been derived from core drilling in the Choshui Delta, which yielded numerous ^{14}C dates (Chen and Liu, 2003; Chen et al., 2010) that are listed in Table 2.

3. Data and methods

3.1. Paleo-bathymetry evaluation on a decadal timescale

We compiled historical charts made by organizations in Taiwan and Japan to map the shorelines and bathymetry off western Taiwan in 1930 (Fig. 4a) and 2002 (Fig. 4b). We also used the present-day bathymetry (about 2010) to evaluate bathymetric changes. Decadal-scale coastal changes can be discerned during the intervals 1930–2002 and 2002–present (Fig. 4c). We calculated sediment volume changes from these charts with respect to the modern shoreline, using MATLAB functions in the Statistical toolbox and Mapping toolbox. We digitized each water depth of the