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Dynamic particle segregation and accumulation processes in time and space revealed in a modern river-dominated delta: A spatiotemporal record of the Kiso River delta, central Japan

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ABSTRACT

The Holocene succession of the Kiso River delta — a sand-rich, river-dominated delta in central Japan — was analyzed at high temporal and spatial resolution. The results demonstrate how the spatiotemporal distribution of sedimentary facies, gross sediment accumulation rates, and accumulation rates of mud versus sand relate to the geomorphic development of the delta and the post-glacial, sea-level history. The centers of peak mud and sand accumulation have migrated seaward in parallel during a regressive stage from 6.5 ka to the present at the rate of 3–9 m/y. The mud and sand accumulation centers mark the bottom and top, respectively, of the delta-front slope. The sediments of the prograding delta show strong sorting and clear upward coarsening because of the steep slope of the delta front. Such internal topographic control redistributes and separates the coarse and fine fractions of the fluvial input during regression. The topographic-controlled sedimentary segregation constructs delta-front topography, in reverse. Therefore, the proportion of sand to mud in the fluvial input controls the stability of the delta-front morphology. Our modeling of the Kiso River delta may have implications for prediction of coastal flooding adjacent to deltas in other parts of the world.

1. Introduction

Deltas have been important areas for the development of early and modern civilizations (Stanley and Warne, 1993; Stanley and Chen, 1996), but many deltas are now at risk of inundation because of human activities and natural processes (Syvitski et al., 2009). Understanding the dynamics of modern deltas is important for predicting the growth and decay of coastal areas and for using the subareal and subsurface of deltas. To this end, past studies reconstructed the migration of paleocoastlines and the accumulation rates of deltaic sediments (e.g., Scruton, 1960). Many studies of the morphology, history, and internal structures of modern and ancient deltas have developed models and concepts to represent the dynamic evolution of deltas in response to sea-level changes (Vail et al., 1977; van Wagner et al., 1988; Neal and Abreu, 2009). Models based on sequence stratigraphy have been supported and improved by recent drill core data and by radiocarbon dating of Holocene shallow marine sediments (Stanley and Warne, 1993; Saito, 1995; Amorosi et al., 1999; Hori et al., 2001; Ta et al., 2002; Tanabe et al., 2006; Vis and Kasse, 2009; Sato and Masuda, 2010; Hijma and Cohen, 2011). Although it is more difficult to determine the detailed sedimentary structure of modern deltas from drill cores than it is for ancient deltaic outcrops, a major benefit is that modern deltas can be radiocarbon-dated; consequently, studies of their sedimentation and progradation rates at thousand-year time scales have contributed to our understanding of the dynamic development of modern deltas (Masuda, 1998; Berendsen and Stouthamer, 2000; Amorosi and Milli, 2001; Storms et al., 2005).

In recent years, many case studies of modern deltas have reported changes in their growth rates during the Holocene and have discussed the relation between those changes and local sea-level changes, as well as the onset of large-scale cultivation and land modification in the catchment (Sato and Masuda, 2010; Vis et al., 2010; Giosan et al., 2013). However, to clarify changes in sedimentation and progradation rates in time and space and to evaluate how humans have influenced these rates, more detailed studies are necessary. Even though several remarkable case studies of Asian mega deltas have been reported (Hori et al., 2001; Tanabe et al., 2003; Storms et al., 2005; Tamura et al., 2009) and because of the immense size of these deltas, the spatial resolution of the studies has often been too low to adequately resolve depositional processes. High-resolution case studies are essential for understanding relationships and feedback mechanisms between process and form, which are the basis of landform change predictions.

On the other hand, the morphology and facies of the prodelta and delta front of many modern, ancient, and laboratory- and computer-simulated deltas have been described (Gani and Bhattacharya, 2005).

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A typical river-dominated delta is characterized by remarkable clinoforms, which consist of a relatively flat prodelta and a steeply dipping delta front. The transition from the mud-dominant prodelta to the sand-rich delta front is characterized by an upward-coarsening succession that is the hallmark of a prograding delta. The development of such a distinctive deltaic morphology requires the following conditions: (i) a receiving basin with a minimum depth greater than the depth of the channel of the feeding river is required to develop the steep delta-front slope, (ii) a feeding river that supplies mixed-load sediment is required to develop the sand-to-mud transition from delta front to prodelta, and (iii) the tidal environment of the receiving basin must not be overly dominant.

Nonetheless, the relationship between the morphology and facies of river-dominated deltas suggests that the geometry of the prodelta and delta front is strongly related to the segregation of particles at the river mouth. In addition to tidal range and wave strength, sediment properties such as cohesion control the morphology and development of deltas (Galloway, 1975). Recently, a numeric geomorphic analysis by Edmonds and Slingerland (2010) clearly demonstrated the important influence of sediment cohesion on delta morphology. Therefore, changes in the volume and particle size distribution of sediment discharge should also affect sedimentary processes and morphology at the delta front. It follows, therefore, that changes in sediment composition should be described quantitatively and compared with changes of facies and accumulation rates during delta formation.

In this study, we carried out a high-resolution spatial and temporal analysis of the Kiso River delta, Japan — a medium-sized, sand-rich delta for which unprecedentedly densely-measured radiocarbon ages are available. The Kiso River delta is well suited for examination of the internal structure and dynamic evolution of a river-dominated delta because of its regional setting, as described in the next section.

In this paper we describe spatiotemporal variations in sedimentary facies, grain size, and sediment accumulation rates in the coastal area of the Kiso River delta in response to relative sea-level changes during the last 10 ky and develop a model for the processes by which muddy and sandy deposits are separated during delta development.

2. Study area

The Kiso River delta (Fig. 1) occupies the central part of the Tokaido megalopolis and includes the Chukyo metropolitan area, which has a population of nearly 9 million. In 1959, Typhoon Vera (Isewan Typhoon) struck Chukyo and more than 5000 lives were lost, mostly because of heavy storm surges and flooding. Since the 1920s, numerous dams have been built for flood control and electricity generation in the Kiso River catchment. Declining sediment fluxes and changes in the grain size of sediments delivered to the river mouth as a consequence of entrapment by the dams can affect sedimentary conditions along the lower reaches of the river and in the delta.

The Holocene Kiso River delta (ca. 1600 km^2) is fed mainly by the Kiso, Nagara, and Ibi rivers. The Kiso River (229 km long) is the largest of these and has its headwaters at 2446 m elevation. The total catchment area is 9100 km^2, and the average discharge at the mouths of the three rivers is 370 m^3 s^{-1}. The sediment discharges at the river mouths were estimated using a three-dimensional depositional structure constructed from a database of hundreds of borehole logs (Yamaguchi et al., 2006). The volume of Holocene deltaic deposits recognized in borehole logs (formed during the last ~6.0 ky) was calculated by Yamaguchi et al. (2006) to be 13 km^3; this volume, together with the bulk densities of 1.5–2.0 g cm^{-3}, indicates an average sediment discharge at the river mouths of 3.3–4.3 × 10^6 t y^{-1} since the middle Holocene. The delta is at the head of Ise Bay, an enclosed bay facing the Pacific Ocean. The depth of the bay beyond the delta front is 35–40 m. The amplitude of the spring tide at the river mouth is 2.0 m, and mean and maximum wave heights are 0.3 and 3.1 m, respectively (Kawai et al., 2009). Because of the low energy level of the tidal and wave

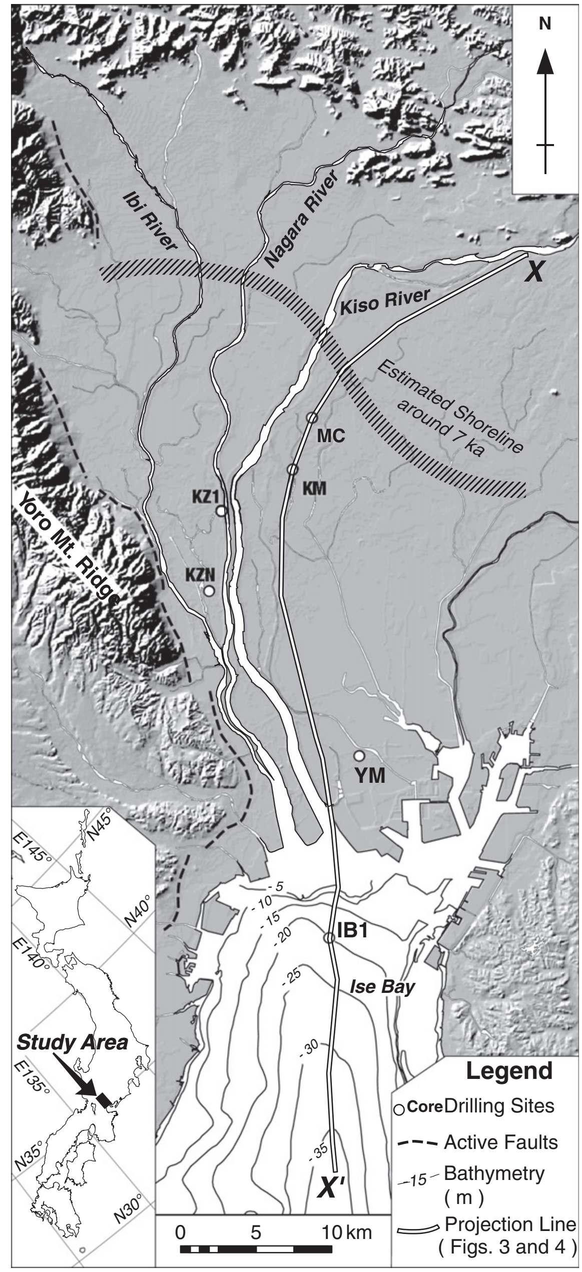

Fig. 1. Locations of the Kiso River delta and drill sites. Five cores from onshore sites (MC, KM, KZ1, KZN, and YM) and two cores from offshore sites (IB1) were used in this study. The drill cores were projected onto line X–X' to create the geological cross section shown in Fig. 2 and the spatiotemporal diagrams shown in Fig. 4.
The estimated shoreline around 7 ka is traced after Umitsu (1979) and Ono (2004).

activity at the river mouth, the delta is sand rich and river dominated. The Kiso River delta is characterized geomorphologically by the following fluvial to shallow-marine landforms, from upstream to downstream: (i) a braided river on an alluvial fan, (ii) a fluvial plain with a meandering river channel and back swamps, (iii) a flat deltaic plain below mean sea level, (iv) a delta front with sand bars at the river mouth and a steep delta-front slope, and (v) a prodelta that slopes gently to the muddy bay floor (Fig. 2).

3. Materials and methods

Our investigation of the Holocene Kiso River delta is based on analyses of five onshore and one offshore sediment cores (Table 1) for which