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Dynamic controls on shallow clinoform geometry: Mekong Delta, Vietnam

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ABSTRACT

Compound deltas, composed of a subaerial delta plain and subaqueous clinoform, are common termini of large rivers. The transition between clinoform topset and foreset, or subaqueous rollover point, is located at 25–40-m water depth for many large tide-dominated deltas; this depth is controlled by removal of sediment from the topset by waves, currents, and gravity flows. However, the Mekong Delta, which has been classified as a mixed-energy system, has a relatively shallow subaqueous rollover at 4–6-m depth. This study evaluates dynamical measurements and seabed cores collected in Sep 2014 and Mar 2015 to understand processes of sediment transfer across the subaqueous delta, and evaluate possible linkages to geometry. During the southwest rainy monsoon (Sep 2014), high river discharge, landward return flow under the river plume, and regional circulation patterns facilitated limited sediment flux to the topset and foreset, and promoted alongshore flux to the northeast. Net observed sediment fluxes in Sep 2014 were landward, however, consistent with hypotheses about seasonal storage on the topset. During the northeast rainy monsoon, low river discharge and wind-driven currents facilitated intense landward and southwestward fluxes of sediment. In both seasons, bed shear velocities frequently exceeded the 0.01–0.02 m/s threshold of motion for sand, even in the absence of strong wave energy. Most sediment transport occurred at water depths < 14 m, as expected from observed cross-shelf gradients of sedimentation. Sediment accumulation rates were greatest on the upper and lower foreset beds (> 4 cm/yr at < 10 m depth, and 3–8 cm/yr at ~10–20 m depth) and lowest on the bottomset beds. Physically laminated sediments transitioned into mottled sediments between the upper foreset and bottomset regions. Application of a simple wave-stress model to the Mekong and several other clinoforms illustrates that shallow systems are not necessarily energy-limited, and thus rollover depths cannot be predicted solely by bed-stress distributions. In systems like the subaqueous Mekong Delta, direction of transport may have a key impact on morphology.

1. Introduction

Large tropical rivers are major sources of sediment to global oceans (Milliman and Meade, 1983; Nittrouer and Kuehl, 1995; Milliman et al., 1999; Syvitski et al., 2003), and often form compound deltas composed of a subaerial deltaic plain and subaqueous deltaic clinoform (e.g., Nittrouer et al., 1986; Kuehl et al., 1989; Alexander et al., 1991; Nittrouer and DeMaster, 1996). Here we use the term “clinoform” to denote the total wedge-shaped package of sediments contained in the subaqueous-delta deposits. Subaqueous clinoforms contain large amounts of fluvially derived sediment, sequester diverse geochemical constituents and natural resources, and serve as the marine foundation for subaerial delta progradation (e.g., Coleman and Prior, 1982).

The Mekong River (Fig. 1) is one of the eleven largest rivers in terms of both water and sediment discharge (Milliman and Meade, 1983; Perry et al., 1996; Milliman and Farnsworth, 2011). In the past several thousand years, it has transported sediment from the Himalayas, Thailand, Laos, and Cambodia (Rubin et al., 2014) and formed a broad, asymmetric subaerial-delta plain bounded by a long, narrow subaqueous-delta clinoform. Mekong River sediment loads are expected to change, however, as a result of exacerbated human activities like dam construction and channel-bottom mining (e.g., Lu and Siew, 2006; Walling, 2008; Kummu et al., 2010; Kondolf et al., 2014; Brunier et al., 2014). These activities, combined with sea-level rise and land-surface subsidence, have prompted concerns about changes to Mekong Delta shorelines, including coastal erosion and increased flood risks (Takagi et al., 2014; Manh et al., 2015; Kondolf et al., 2015; Phan et al., 2015; Anthony et al., 2015).

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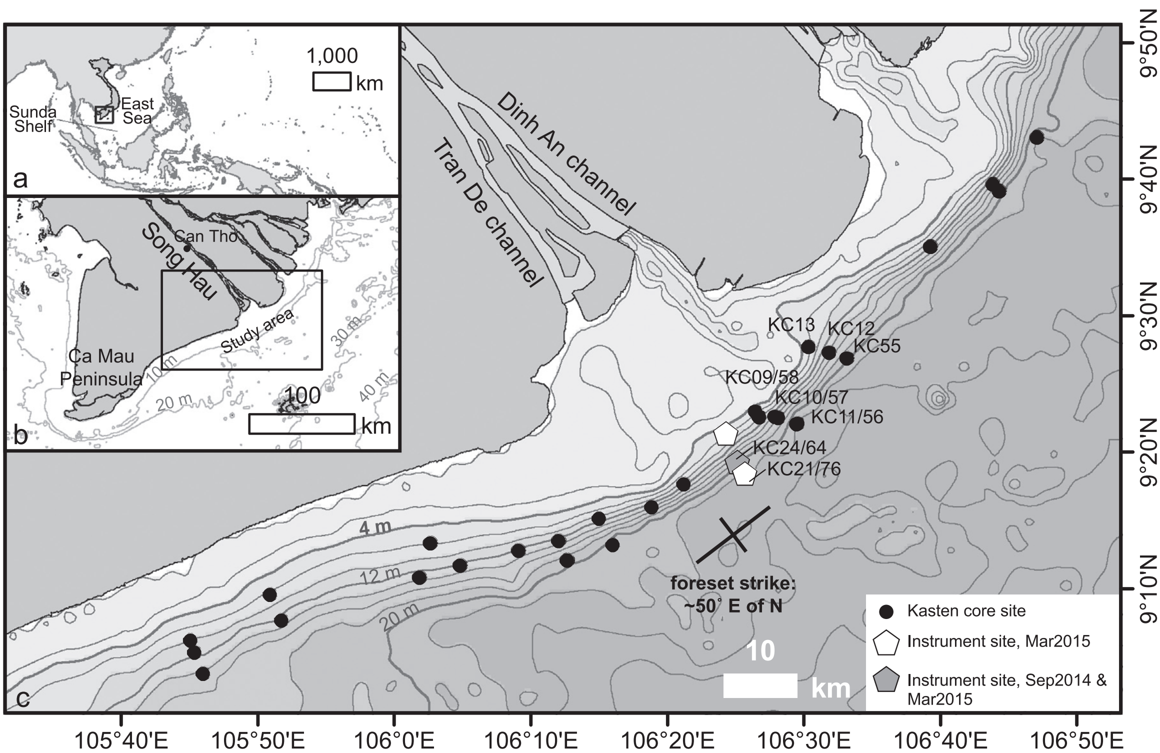

Fig. 1. Location of study area and sample sites. a) The Mekong River discharges onto the Sunda Shelf in the East Sea. b) The study area was a ~160-km-long section of the subaqueous delta (or clinoform) offshore of the two branches of the Song Hau, the southernmost Mekong distributary c) Kasten cores and instrument sites were located on the foreset and bottomset. Cores presented in this paper are labeled, and are located near the Song Hau. Cores KC09 through KC24 were collected in Sep14; cores KC55 through KC76 were collected in Mar15. Data from the unlabeled cores are presented in DeMaster et al. (in this issue). (Contours are 2 m; bathymetry is courtesy of the Vietnam Institute of Marine Geology and Geophysics.).

Subaerial and subaqueous deltas are dynamically linked, because a finite amount of sediment is distributed between these two sinks (e.g., Swenson et al., 2005). The fraction of total fluvial sediment sequestered in each sink depends on multiple factors including time since initiation of the delta, floodplain deposition, sea-level change, change in accommodation space, subaqueous delta progradation rate, and wave and current transport (e.g., Goodbred and Kuehl, 1999; Swenson et al., 2005). This dynamic link has also been recognized for the Mekong Delta (Ta et al., 2002), and the fate of its shoreline is dependent on the mechanics of subaqueous clinoform growth. Previous work has suggested a seasonal connection in sediment transport and storage between the southernmost distributary (Song Hau; Fig. 1b) and the subaqueous delta (e.g., Gagliano and McIntire, 1968; Wolanski et al., 1998; Tamura et al., 2010; Nowacki et al., 2015). However, the timing and processes of sediment transfer seaward of the river mouth remain poorly understood (Anthony et al., 2015).

The Mekong clinoform is distinguished among large-river deltas in that the transition (or subaqueous "rollover point") between the broad, flat topset and steeper foreset lies at a depth of only 4–6 m (see Xue et al., 2010; Unverricht et al., 2013; Liu et al., in this issue). For many large-river deltas, the subaqueous rollover depth is considered the fairweather "wave-current base" (Walsh et al., 2004; Fig. 2), and is commonly located at 25–40 m depth (e.g., Amazon River, ~40 m, Nittrouer et al., 1986; Ganges-Brahmaputra River, ~30 m, Kuehl et al., 1997; Indus River, ~30 m, Giosan et al., 2006; Ayeyarwady River, ~30 m, Rodolfo, 1969; and Gulf of Papua, 25–40 m, Walsh et al., 2004). Above this depth, waves and currents provide the energy needed for a majority of sediment to bypass the topset. Below this depth is a "stress refuge," or zone of reduced bed stress, where sediment rapidly accumulates after delivery by advection, diffusion, and/or gravity-flow processes (e.g., Kuehl et al., 1986; Kineke et al., 1996; Pirmez et al., 1998; Traykovski et al., 2007; Walsh and Nittrouer, 2009).

The mechanics that produce shallow rollovers like that of the

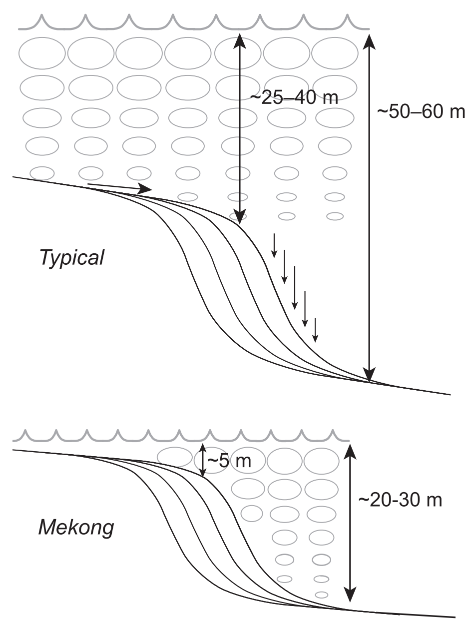

Fig. 2. Conceptual diagram contrasting typical large-river clinoforms with the Mekong clinoform. Gray ellipses represent potential wave-orbital velocities. Note the different rollover and bottomset depths, and similar clinoform thickness.

Mekong (4–6 m), Atchafalaya (~5 m; Neill and Allison, 2005), and Yangtze (~12–15 m, Hori et al., 2002; Liu et al., 2007) are poorly constrained, but important to understand because changes in transport energy and/or sediment supply (as expected for the Mekong) can alter the extent or depth of the subaqueous topset, and consequently the