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The Mekong Continental Shelf

The Primary Sink for Deltaic Sediment Particles and Their Passengers

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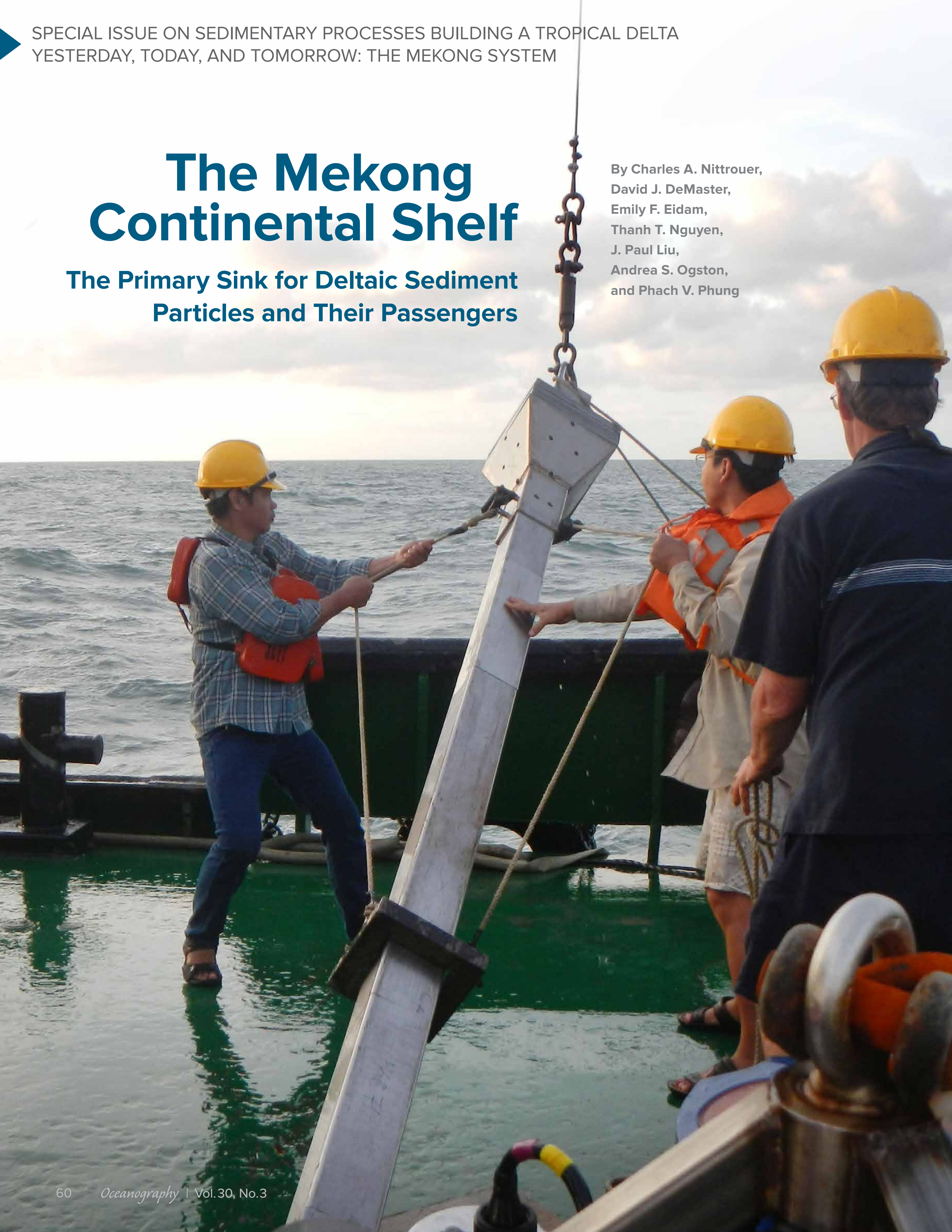


ABSTRACT. The Mekong River discharges into the Vietnamese East Sea and forms a subaqueous deposit known as a clinoform, the region of greatest sediment accumulation for the deltaic system. The peak discharge from the Mekong River is linked to seasonal monsoon conditions and occurs from August to November when ocean conditions are relatively quiescent. The river plume carries sediment to the clinoform where it is deposited. Subsequently (January to April), the coupling of energetic surface waves, tidal currents, and wind-driven currents resuspends much of the newly deposited shelf sediment and transports it landward and southwestward. This pathway displaces about two-thirds of the sediment to nourish distal coastal regions along the Ca Mau Peninsula. Throughout the year, the seaward flow of the Mekong surface plume causes estuarine circulation to draw much underlying ocean water landward onto the shelf (more than twice the volume of Mekong freshwater discharge). This process allows dissolved chemical components to become attached (i.e., adsorbed) to surfaces of suspended particles. The sediment accumulating on the seabed buries a broad array of these components from sources in the adjacent ocean water as well as the river drainage basin. The ocean portion of the Mekong River dispersal system involves an intricate coupling of temporally variable processes (e.g., river discharge, coastal winds, and along-shelf currents). Future alterations to the river source (e.g., due to damming) and to the ocean sink (e.g., due to climate change) will likely affect this coupling and modify the processes occurring on the Mekong continental shelf.

THE CONCERNS

The ultimate destination for most material produced on land (water, solutes, and particulates) is the shallow continental shelf, where river discharge enters the ocean. The sedimentary deposits formed there preserve a record of the good (e.g., seaward land growth), the bad (e.g., catastrophic floods), and the ugly (e.g., pollution from human activity) impacts on fluvial dispersal systems. Understanding mechanisms that control the fate and write the history of the accumulated sediment is critical to the lives and livelihoods of many millions of people inhabiting these coastal areas—especially during uncertain times as global and local conditions change at accelerating rates.

The particles produced on land flow down slope in rivers, until there is no slope at sea level. A wide range of chemical components are adsorbed onto the reactive surfaces of most particles in freshwater, and they are subsequently joined by others that are adsorbed in saltwater. These components include many materials created naturally, such as organic carbon and iron coatings, as well as products of human activities, including pesticides and heavy metals. The adsorbed chemical components make the journey to and through the ocean as passengers on sediment particles, with some adjustments for local environmental conditions (e.g., salinity, Eh) in the water column or seabed.

If a fluvial drainage basin supplies sediment more rapidly than coastal processes can remove it, a large deposit is created at the land-ocean interface in the form of a delta reaching to sea level. However, the dominant sediment flux to the bed, and consequently the bulk of deltaic mass, is found on the adjacent shallow continental shelf. This sediment flux forms the foundation on which the delta is built, filling the ocean space with subaqueous sedimentary deposits. This article describes the sedimentary mechanisms that operate on the shallow continental shelf at the mouth of the Mekong River and explains the relevance there and on other shelves. The lessons learned by investigating these sedimentary processes can help us mitigate the impacts of some natural and human actions, and also help us prepare for impacts over which we have no control.

At the transition from river source to ocean sink, deltaic shelf environments are influenced by the full spectrum of processes operating on the land and in the sea. These include mixtures of seasonal and interannual fluctuations in precipitation that determine river flow and sediment transport, which can be modified by human manipulation (e.g., deforestation, agriculture, damming, water diversion, levee building, or channel dredging). The ocean side is equally capricious, as winds and waves, wind- and tide-driven currents, and river discharge change on hourly to seasonal time scales, and maybe with increasing energetics of a warming climate. These processes are superimposed on a background of regional ocean circulation, leading to complex coupling of the terrestrial and marine forces. To make matters more complicated, uncertainty is added by a changing coordinate system as shorelines move landward because rates of eustatic sea level rise and delta subsidence are accelerating (Syvitski et al., 2009).

Environmental settings on Earth are spatially variable. Terrestrial and marine processes can vary dramatically at different locations due to factors such as climatic and tectonic characteristics. For example, the mechanisms by which water, solutes, and sediment are discharged by high-latitude tidewater glaciers are much different than those at the Mekong's mouth. Similarly, small rivers draining coastal mountain ranges formed by subduction of oceanic plates have much different morphological frameworks than the Mekong mouth. Although the governing processes can change with location and time, the fundamental considerations remain universal, for example, the amount and type of sediment supplied, the relative timing of water/sediment discharge and of coastal conditions, and the dominant physical forces, including their strengths and coupling. The continental shelf beyond the Mekong mouth can provide many lessons for other large river deltas that occur in wet tropical settings and/or have been manipulated by diverse human activities.

THE LOCATION

The setting for the Mekong River system shares source and/or sink characteristics with many of the largest and most important river systems on Earth—a source in the Himalayan highlands and a sink in the wet tropics. Its source is the same as six of the ten top rivers that historically have supplied sediment to the ocean: Huang He (Yellow), Changjiang (Yangtze), Ayeyarwady (Irrawaddy), Brahmaputra, Ganges, and Indus (Milliman and Farnsworth, 2011). Most Mekong sediment originates from the Himalayan highlands, and the river supplies ~10^8 Mt yr^{-1} to its delta (presently ranking eleventh worldwide). The ocean sink for this sediment is located in the wet tropics, a geographic area of the world within 15° of the equator, where temperature and precipitation are constantly high. Rivers entering these areas supply to the world ocean >60% of the fluvial sediment and >50% of the fluvial freshwater (Nittrouer et al., 1995) it receives. The Mekong River delivers ~5.5×10^3 km^3 yr^{-1} of water to its delta (presently ranking seventh worldwide; Milliman and Farnsworth, 2011).

Where a large river reaches the ocean and builds a delta, sediment accumulation at sea level blocks flow, causing the channel to bifurcate. The main channel of the river breaks into distributary channels that share the discharge to the marine environment. The Mekong has multiple distributaries (Figure 1). The largest is the Song Hau, which is the southernmost channel and carries ~40% of the Mekong water and sediment discharge (A.D. Nguyen et al., 2008). Sediment accumulation in the mouth of the Song Hau has formed an island, Cu Lao Dung, which splits the channel. The island continues to grow seaward with an advancing mangrove forest on its ocean shoreline (Fricke et al., in press).

The Mekong Delta has been growing seaward into the East Sea (also known as the South China Sea; Figure 1) for ~8,000 years (Tamura et al., 2009). At this location, the continental shelf is wide (~250 km) and has a gentle gradient to its shelf break (~130 m deep). The delta has grown onto the shelf asymmetrically, with a southwestward extension, creating the Ca Mau Peninsula (V.L. Nguyen et al., 2000). Although seaward progradation has characterized the Mekong Delta, there have been times and places of erosion, including some areas along the modern delta shoreline and Ca Mau Peninsula (Anthony et al., 2015).

After transport down long river systems, most of the sediment reaching the ocean is fine silt and clay (i.e., muddy sediment finer than 64 μm), with some sand trapped in shallow coastal settings. For the Song Hau distributary channel, >70% of the sediment mass in transit is the muddy material (Wolanski et al., 1996). The sediment reaching the shallow continental shelf has even higher mud concentrations, which dominate the modern deposit there (Unverricht et al., 2013). The settling of this mud has led to formation of a classic clinoform structure that extends >300 km along the inner shelf adjacent to the Mekong Delta (Figure 2a; Liu et al., in press and 2017, in this issue) and clearly demonstrates a shallow topset region (<5 m deep), an inclined foreset region (~5–20 m), and a bottomset region (>20 m deep). This modern feature

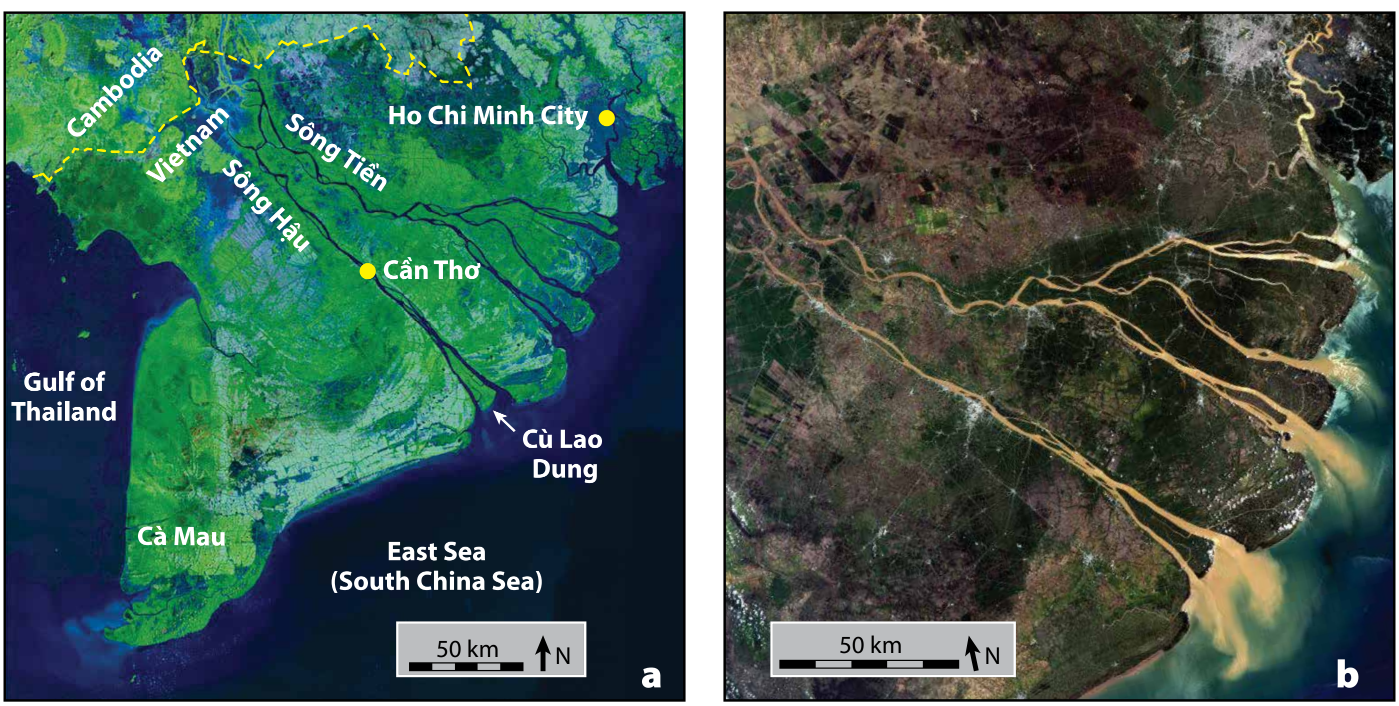


FIGURE 1. (a) The Mekong Delta in Vietnam, showing multiple distributary channels, including the focus of this study: Song Hau. The Ca Mau Peninsula is the asymmetric southwestern extension of the delta. *From Fricke et al. (in press)* (b) Discharge of the Mekong distributaries forming plumes on the inner shelf during quiescent high flow conditions of September 18, 2014. *From Wackerman et al. (in press)*

is building seaward onto old sedimentary deposits that were formed as sea level rose after the last glacial low stand.

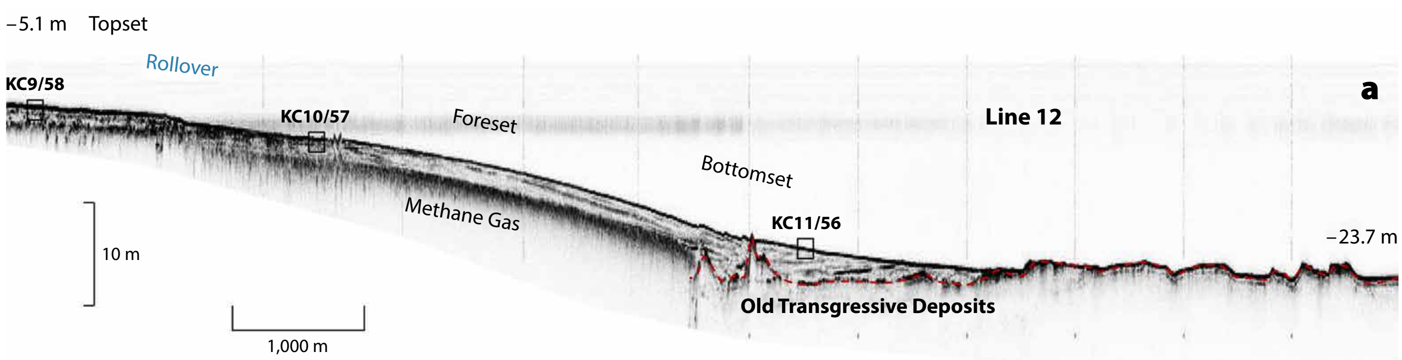
THE GOALS

During 2014 and 2015, an international group of scientists investigated the sedimentary processes operating on the seaward side of the Mekong Delta (as highlighted in this special issue of *Oceanography*). The general objective was to document the processes controlling the fate of sediment where the river meets the ocean. The study could only focus on a region of manageable size within the >300 km Mekong shoreline, and the largest distributary, the Song Hau, became the target region of the Mekong Tropical Delta Study. Simultaneous investigations were undertaken along sequential deltaic sub-environments, from the tidal river (freshwater with tidal fluctuations), through the estuarine reach of the distributary channel, to the mangrove forests at the seaward end of Cu Lao Dung, and onto the shallow continental shelf.

The observations were designed to unravel the linkages between the various sub-environments and to determine how exchanges of sediment affect its ultimate fate. Although much of the effort focused on lateral movement of sediment on time scales ranging from tidal to seasonal, the vertical accumulation of sediment was also investigated on time scales of decades to millennia. Other articles in this special issue address the short-term processes operating in Song Hau channel (Ogston et al. and Meselhe et al.) and in the mangrove forest (Mullarney et al. and Fagherazzi et al.), as well as those recorded over longer time scales throughout the delta system (Allison et al. and Liu et al.). The focus of this article is understanding the processes controlling the fate of sediment (and its adsorbed passengers) on the inner shelf over time scales of active processes (tidal and seasonal), and understanding the integrated sedimentary record over decades.

THE TOOLS

The sedimentary processes active in the water column were investigated in time and space (Eidam et al., in press). During two cruises, September 2014 and March 2015, seasonal variability (see next section) was investigated. On each of these cruises, semidiurnal anchor stations allowed measurement of current velocities throughout the water column using an acoustic Doppler current profiler (ADCP) mounted on the ship. At the anchor stations, a small profiling instrument was lowered through the water column every 30 minutes, with sensors to measure variations in salinity, temperature, and turbidity. The bottom boundary layer (lowermost ~1 m) was simultaneously investigated with sensors mounted on a fixed tripod frame (Figure 3a) to measure water properties: salinity, temperature, turbidity, velocity profiles, and pressure fluctuations (surface waves, tidal elevation). These stations were located on topset, foreset, and bottomset regions of



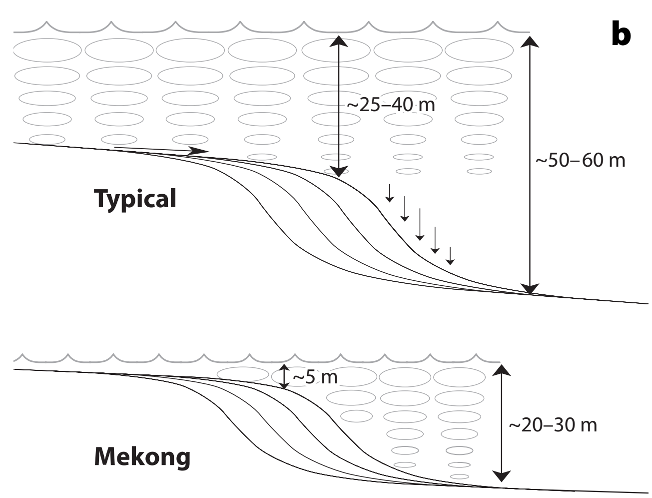


FIGURE 2. (a) Seismic profile seaward of the Song Hau distributary channel (see Figure 4 for location of cores along seismic line), demonstrating clinoform morphology that characterizes the Mekong inner shelf (topset, foreset, and bottomset regions; "rollover" is the boundary between topset and foreset). Methane gas within parts of the clinoform structure prevents deep penetration of the seismic signal. The basal reflector (red dashed line) to the right (southeast) is from old transgressive deposits formed as sea level rose after the last glacial low stand. Seaward progradation of the modern clinoform buries these deposits. *From Liu et al. (in press)* (b) Cartoon contrasting typical shelf clinoforms off large river deltas (deep rollover) with the Mekong clinoform (shallow rollover). *From Eidam et al. (in press)*

the clinoform structure (Figure 4).

Seabed sampling (DeMaster et al., in press; Eidam et al., in press) was accomplished with two primary instruments. A Shipek grab sampler was used for sandy bottoms. However, most sites studied were muddy, and a kasten-type gravity corer was able to collect cores up to 300 cm in length (Figure 5). Sedimentary structures in cores were examined by x-radiography, and then the sediment was carefully dissected to obtain samples for measurements of grain size, porosity, and radiochemistry (^{210}Pb). Cores were collected across the clinoform structure from shore-perpendicular transects in a shelf region ~100 km both north and south of the Song Hau mouth (Figure 4). At most of these stations, the profiling instrument was used to measure salinity, temperature, and turbidity in the water column.

THE OCEAN AND THE DISCHARGE

At the shoreline of the Mekong subaerial delta, the tidal range is 3–4 m during spring tides, providing significant semidiurnal and fortnightly current fluctuations that are superimposed on the seasonally variable wave and current regimes. In this wet tropical location, the seasonal wind patterns are related to monsoonal conditions. Unlike at higher latitudes, where moving cyclonic storm systems cause severe fluctuations in wind speed and direction on time scales of several days to a week, tropical trade winds are relatively continuous for months at a time. On the Mekong coast, they blow energetically from the northeast between December and April, and more weakly from the southwest between May and November. These two wind conditions, respectively, drive energetic surface waves and barotropic currents toward the southwest, and then weaker waves and currents toward the northeast (Liu et al., 2001). The Mekong shelf is on the southern boundary of the Pacific tropical storm belt where it is infrequently buffeted by the distal effects of typhoon winds and waves.

A significant factor affecting the fate of Mekong sediment is the relative timing of river discharge and oceanographic conditions. The Mekong hydrograph indicates greatest discharge of water and sediment (August–November) during the period of weak southwest monsoon winds (Nowacki et al., 2015). Therefore, most of the fluvial sediment is discharged to the ocean during relatively quiescent conditions on the shelf, with weak waves and currents moving northeastward. These

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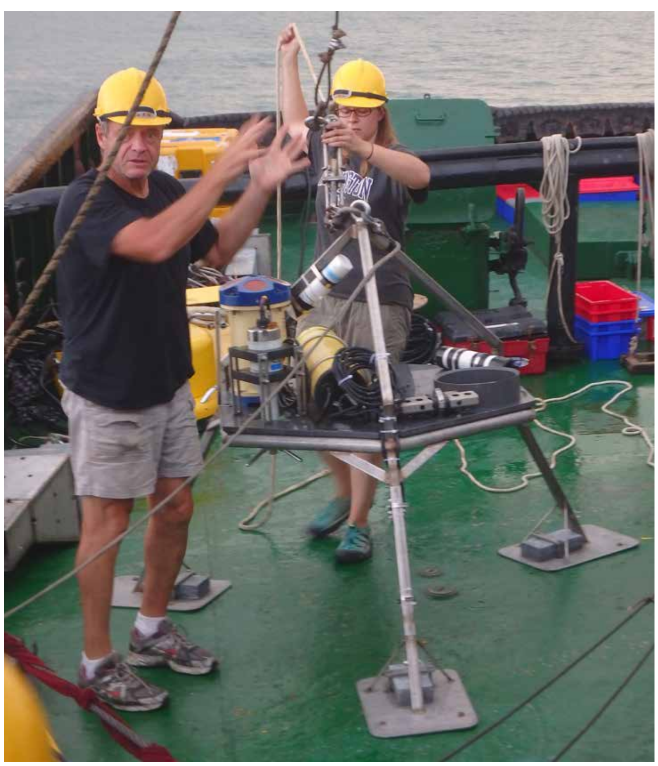

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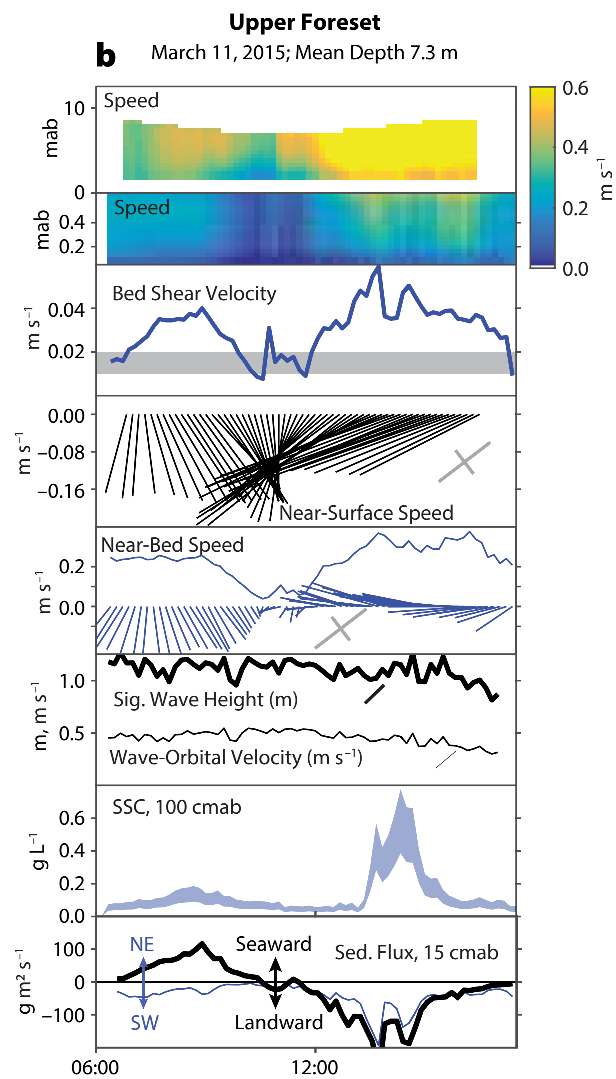


FIGURE 3. (a) Benthic tripod with various sensors being prepared for deployment on the upper foreset near the mouth of the Song Hau distributary channel (see Figure 4 for location). (b) Semidiurnal time series of measurements in the bottom boundary layer. Note the intensified flood tides (~14:00–15:00), when current speed was >0.4 m s^{-1} at 0.2 m above the bed (mab), suspended sediment concentration was >0.6 g L^{-1} at 100 cm above the bed (SSC, 100 cmab), and sediment flux was strongly landward. *From Eidam et al. (in press)*

conditions should cause suspended sediment flux in the same direction, and also allow it to settle to the seafloor. The minimum discharge from the Mekong (January–April) coincides with energetic northeast monsoon winds, causing larger waves and stronger currents directed toward the southwest. The lack of coherence between peak sediment discharge to the shelf and peak energetics of physical oceanographic processes is an interesting phenomenon that influences the pathways of sediment transport.

THE SEDIMENT TRANSPORT

Past observations of the Mekong shelf have examined suspended sediment and its distribution. These measurements have included satellite images of the surface waters (Figure 1b; Loisel et al., 2014; Wackerman et al., in press), which demonstrate that turbid river plumes generally disappear from surface water (upper ~2 m) within 20–30 km from the coast (i.e., topset region). Some direct observations extend down near the seabed (Unverricht et al., 2014), and suspended sediment concentrations have been documented in quantities of tens of mg L^{-1}. However, our tripod measurements (Figure 3b; Eidam et al., in press) recorded values of hundreds of mg L^{-1} for energetic seasonal conditions (March 2015) in ~7 m water depth (upper foreset) during peak tidal currents. It is important to recognize that concentrations >10 g L^{-1} (known as fluid muds) have never been measured. This observation is crucial, because such values are needed for gravity flows. These very high suspended sediment concentrations make seawater dense enough to flow downhill under its own weight. Such flows have been observed for clinoforms off other large delta systems (e.g., Amazon River, Kineke et al., 1996; Fly River, Martin et al., 2008), and represent an important mechanism for moving sediment to the steeper foreset region of the clinoform structure. Without these gravity flows, movement of sediment is dependent on physical stresses exerted by waves and currents to erode and transport sediment. A caveat is that our water column observations were limited in time and space. Extensive measurements have not yet been made on the Mekong shelf, and infrequent and localized conditions may initiate fluid muds and gravity flows (see The Accumulation section below).

Our measurements on the inner shelf (Eidam et al., in press) demonstrate the importance of the temporally variable and coupled flows associated with riverine, tidal, and monsoon conditions. During September when discharge of water and sediment are at their peak, the large freshwater flow results in ebb-dominant currents in the distributary channels and enhanced offshore migration of the plume. This enhanced discharge is important for delivering sediment to the foreset region. Superimposed on this freshwater river discharge are along-shelf flows to the northeast, consistent with the seasonal shelf circulation. During March, the freshwater discharge is dramatically reduced and flood-dominant tidal currents are observed in the distributary channels (Nowacki et al., 2015), with residual shelf currents directed southwestward and onshore (Eidam et al., in press; Thanh et al., in press). The combined peak bottom stresses from waves and currents during this energetic period are sufficient to erode most of the clinoform surface and put sediment in motion. As indicated, the direction for that motion is landward and southwestward, with two important consequences (Eidam et al., in press). The first is that landward transport constrains sediment to shallow shelf areas and impacts the morphology of the clinoform (Figure 2b): the boundary between the topset and foreset (i.e., the rollover) is shallow (~5 m) relative to clinoforms off other large delta systems (e.g., Amazon River ~30–40 m, Nittrouer et al., 1986; Fly River ~25-40 m; Walsh et al., 2004). The second result is that southwestward transport of remobilized sediment during the energetic monsoon conditions (December–April) causes net annual sediment flux in this direction, and has extended the clinoform asymmetrically on the shallow shelf (Liu et al., in press). Over time scales of centuries and millennia, the subaerial surface (i.e., mangrove shoreline) has prograded seaward over

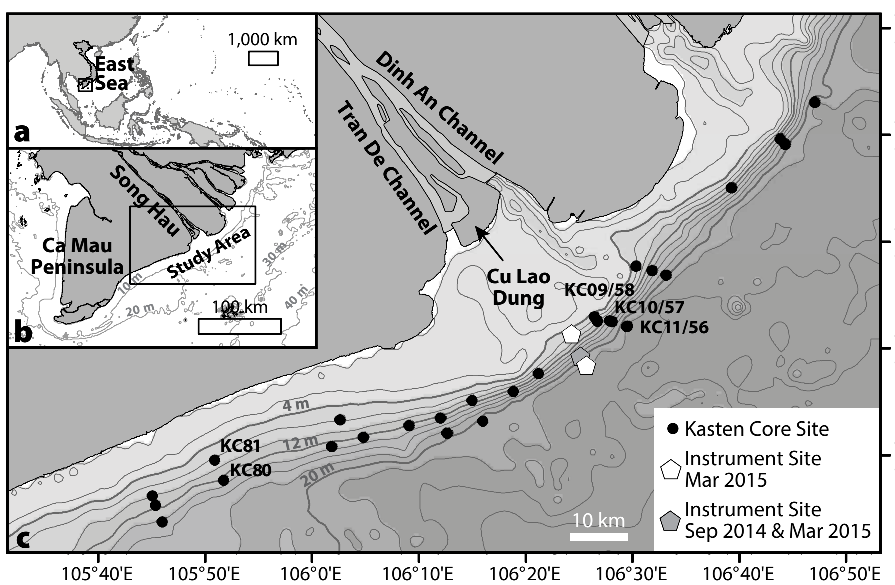


FIGURE 4. Station locations for this study, including kasten core sites (KC) and anchor stations (tripod deployments). Note that close spacing of isobaths indicates the location of the inclined foreset region, with topset and bottomset found landward and seaward, respectively. The transect with KC stations near the Song Hau mouth shows locations of cores for Figure 7a, and this is also the transect for the seismic profile in Figure 2a. X-radiographs in Figure 6 are located farther southwestward (KC80 and KC81). *Modified from Eidam et al. (in press)*

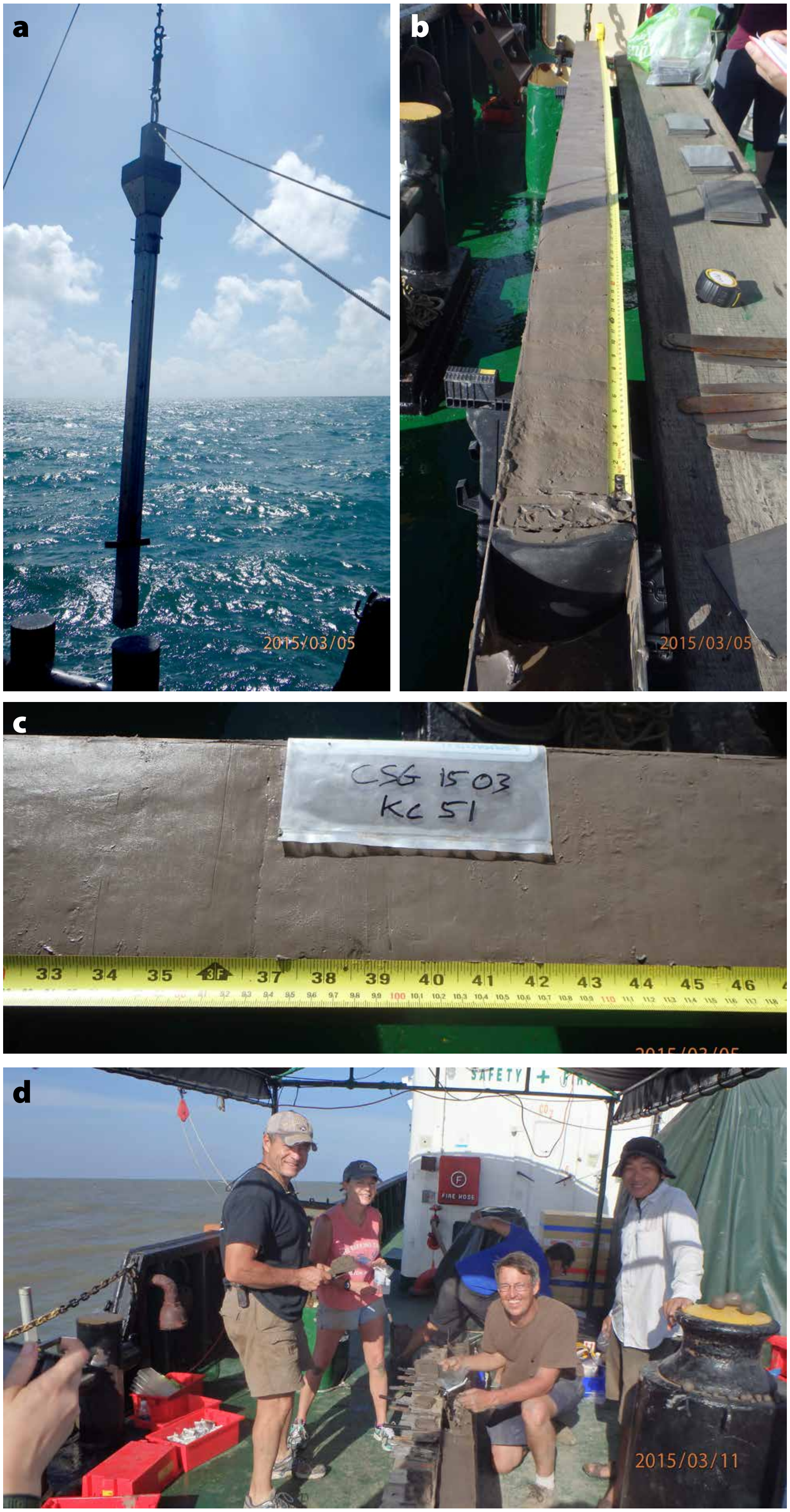


FIGURE 5. Kasten coring process. (a) Deployment of kasten corer. (b) Core opened for subsampling. (c) Detailed view before x-radiograph subsamples are extracted. (d) Smiling faces dissecting core on the deck of tugboat CSG-99.

the clinoform, and the result is asymmetric growth of the Mekong Delta toward the Ca Mau Peninsula.

The relative timing of the Mekong seasonal hydrograph and the offshore seasonal energetics causes an interesting linkage between the shallow shelf and the landward environments of the delta. During September, observations in the Song Hau channel (Nowacki et al., 2015; McLachlan et al., in press; Ogston et al., 2017, in this issue) and in the Cu Lao Dung mangrove forest (Fricke et al., in press; Mullarney et al., 2017, in this issue) confirm export of muddy sediment, when the supply from upstream is at a seasonal peak. In contrast, during March, similar observations demonstrate an import of sediment from the shelf. Flood-dominant tidal currents during this period move water and sediment landward, and estuarine circulation (i.e., landward bottom current) then transports the turbid shelf water far into Song Hau channel (upstream beyond Cu Lao Dung). There, it is trapped and stored on the channel bed (Allison et al., in press; McLachlan et al., in press). These flows and the intensified wave climate also nourish the mangrove forest with net onshore sediment flux. The seasonal variation in sediment transport is an important observation and is not intuitive; for example, the mangrove forest receives most of its sediment for seaward growth when the Mekong River and Song Hau channel are carrying a minimal sediment supply from upstream (Fricke et al., in press). This observation demonstrates the importance of the sedimentary deposits on the shallow continental shelf as temporary repositories of sediment needed for delta progradation, and highlights the extended impact of estuarine circulation beyond the confines of the Song Hau channel.

THE WATER

Numerous dissolved chemical components ("passengers") can be adsorbed onto sediment surfaces. Silt- and clay-sized particles are particularly reactive due to their mineral structure, and, collectively, their enormous surface area for adsorption. Some of these passengers originate from terrestrial weathering (e.g., Fe, Mn, P). Others have a marine source and are adsorbed when suspended particles discharged from a river meet ocean water. One of the dissolved components with a dominant marine source is the natural radioisotope ^{210}Pb, which is produced from the ^{238}U decay series (with an effective parent ^{226}Ra in offshore waters). Dissolved ^{210}Pb has an affinity for the surfaces of sediment particles and is irreversibly adsorbed when the two meet. From that point, the ^{210}Pb becomes a passenger on the sediment particles and rides with them during transport around the shelf, including settling to and accumulation in the seabed. Throughout the process, the ^{210}Pb radioactivity is decaying with its characteristic half-life of 22.3 years. In the seabed, the burial and decay can be used to calculate sediment accumulation rates, as described in the next section.

If the dissolved ^{210}Pb concentration in offshore waters and the sum of adsorbed ^{210}Pb radioactivity buried in shelf sediment (corrected for decay) are known, then the amount of landward flux by offshore ocean water can be calculated (DeMaster and Pope, 1996). The kasten cores were investigated for their integrated inventories of ^{210}Pb, and these were compared to the known ^{210}Pb concentration in East Sea waters (DeMaster et al., in press). The conclusion is that ~13 × 10^3 km^3 yr^{-1} of ocean water are brought to the inner continental shelf. This is distant ocean water drawn landward by estuarine circulation, while the freshwater of the Mekong is discharged seaward as a buoyant surface plume. The amount of landward flux is more than twice the freshwater discharge of the Mekong (~5.5 × 10^3 km^3 yr^{-1}). Although impressive, it is substantially less than the relative fraction of ocean water drawn landward by discharge of the Amazon River (10 times its freshwater discharge; DeMaster and Pope, 1996). These differences likely result from local circulation on the respective inner shelves (e.g., the Amazon plume is much larger and extends into deeper water). However, the Mekong River discharge causes substantial delivery and burial on the inner shelf (within the clinoform deposit) of more chemical components than are brought from terrestrial weathering alone. It also causes dissolved components from offshore ocean water to be drawn landward and subjected to a range of fates—for example, dissolved nutrients (N and P) are upwelled and help river-borne nutrients stimulate primary production that delivers organic C to the seabed sediment (DeMaster and Pope, 1996), and dissolved metals are adsorbed on suspended particles and buried in the seabed, allowing ^{210}Pb to be used to calculate sediment accumulation rates.

THE ACCUMULATION

Grab samples and kasten cores demonstrate that mud (silt and clay) dominates sediment within the modern deposits of the shelf clinoform, although some fine sand is also observed (Eidam et al., in press). The shallow deposits (e.g., upper foreset) commonly reveal laminations (Figure 6) produced during transport and deposition by physical processes (waves and currents). In greater water depth (>10 m), the laminations are destroyed by mixing of the seabed sediment through the activities of benthic animals living there (Figure 6), a process known as bioturbation. The flux into the seabed of these sedimentary particles can be measured using radioisotopes to evaluate time scales extending back ~4–5 times the half-life of the radioisotope. Hence, ^{210}Pb works well in marine sediment for a time scale of about a century (Koide et al., 1972; Nittrouer et al., 1979).

The ^{210}Pb that sinks to the seabed adsorbed on suspended particles is buried as subsequent particles arrive. With continual sediment burial and radioactive decay, a profile of radioactivity is created in the seabed, whose gradient of downward decrease can be used to calculate the sediment accumulation rate at each core site (Figure 7a). On the Mekong shelf, there is a recognizable trend in accumulation rate with increasing water depth (Figure 7b; DeMaster et al., in press; Eidam et al., in press): topset regions 1 cm yr^{-1} to 3 cm yr^{-1}, foreset regions 1 cm yr^{-1} to >10 cm yr^{-1}, and bottomset regions <2 cm yr^{-1}. In areas with significant bioturbation (e.g., Mekong lower foreset), vertical mixing of ^{210}Pb can artificially enhance the sediment accumulation rates calculated. The rates given above should be used cautiously, although

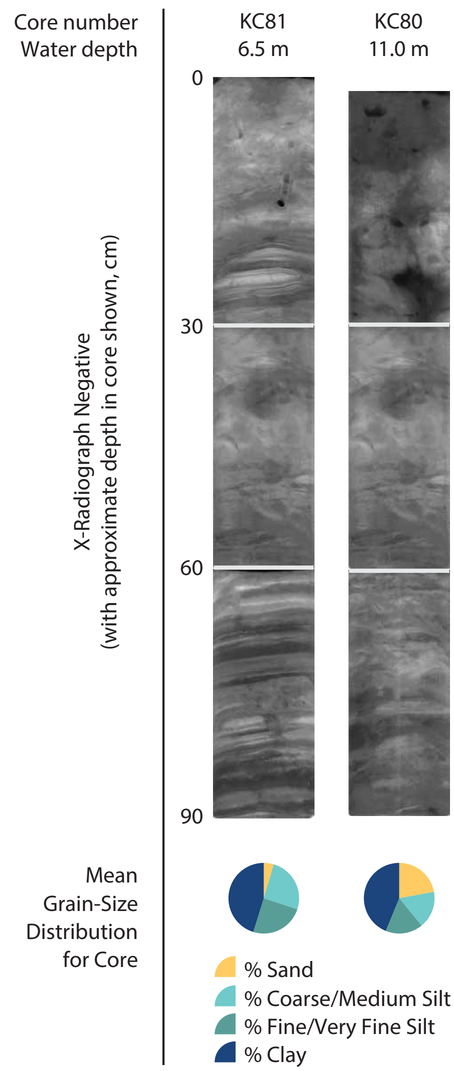


FIGURE 6. X-radiographs from upper foreset region (KC81 in 6.5 m water depth) and lower foreset region (KC80 in 11 m water depth). Both cores are predominantly silt and clay, as shown in pie charts. KC81 is dominated by laminations created by current and wave stresses. These laminations are absent in KC80, having been largely destroyed by benthic infauna bioturbation.

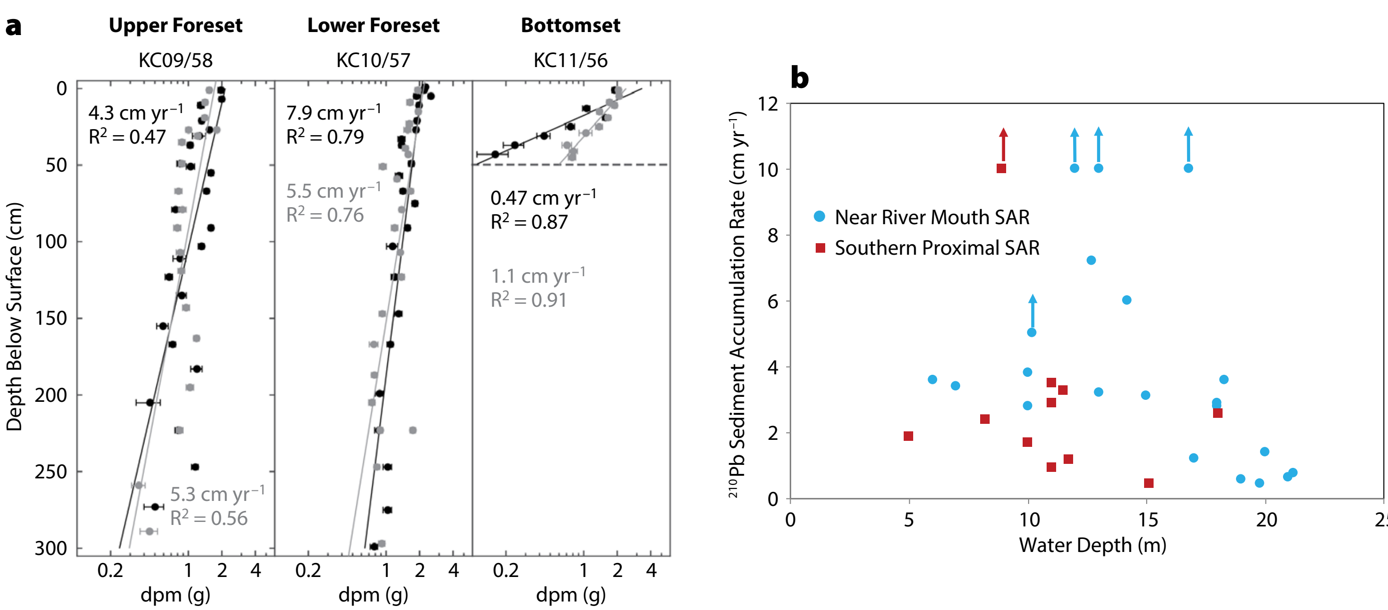
bioturbation usually does not significantly impact rates this large (Nittrouer et al., 1984). The trend toward greater accumulation rates on the foreset is typically observed for clinoform structures (e.g., Amazon River shelf, Kuehl et al., 1986; Fly River shelf, Walsh et al., 2004), and the foreset region represents the zone of most rapid upward and seaward growth in a delta system. Sedimentary structures observed in some x-radiographs of foreset sediment cores may demonstrate evidence for gravity flow emplacement (Eidam et al., in press).

Values measured for porosity in the seabed allow transformation of sediment accumulation rates to mass fluxes. These can be used to characterize various regions across and along shelf, and to calculate a budget of sediment buried in the seabed (Figure 7c). For the Mekong shelf, important observations emerge from the ^{210}Pb rates that represent a century of sediment accumulation (DeMaster et al., in press). Approximately one-third of the Mekong sediment is sequestered in proximal shelf locations near the mouths of distributary channels, and the other two-thirds is found in distal areas extending to the Ca Mau Peninsula and beyond. This highlights the along-shelf expanse of the Mekong sediment dispersal system.

THE FUTURE

For millennia, direct (e.g., levee building) and indirect (e.g., agriculture) human activities have impacted the Mekong River and its sediment dispersal system. Now, however, the impacts are accelerating and intensifying. Increased damming of the drainage basin will dramatically reduce water and sediment discharge. Climate change could affect precipitation patterns over land and wind patterns over the adjacent ocean (see Allison et al., 2017, in this issue). Although the magnitudes of these changes are not easy to predict, we can consider an extreme impact of dam construction and water diversion—nearly complete loss of water and sediment discharge. This scenario is possible, and has already occurred with the Huang He River in China, the Ebro River in Spain, and the Colorado River in the United States and Mexico.

The landward deltaic sub-environments



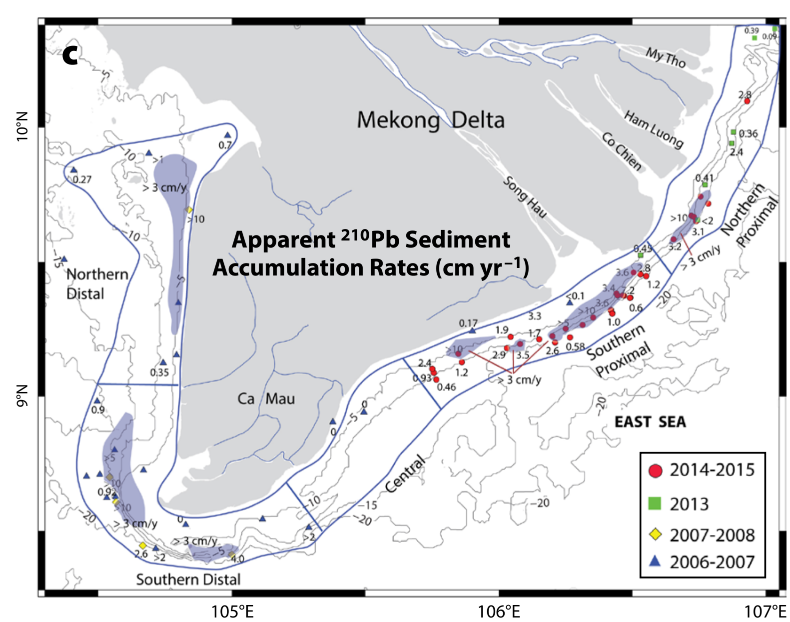


FIGURE 7. Observations from ^{210}Pb geochronology. (a) Profiles of ^{210}Pb (excess activity) from upper foreset (KC09 and KC58), lower foreset (KC10 and KC 57), and bottomset (KC11 and KC56) regions. Kasten core sites (see Figures 2 and 4) were reoccupied in September 2014 (black points and lines) and March 2015 (gray points and lines) as closely as possible with a tugboat. Positioning difficulties could explain some differences in sediment accumulation rates for repeat cores. The rates are greatest on foreset and less on the bottomset. *From Eidam et al. (in press)* (b) Relationship of sediment accumulation rates (SAR) to water depth for all kasten core sites investigated by this study (see Figure 4). The greatest accumulation rates are found on the foreset region (5–20 m depth). (c) Distribution of accumulation rates used to calculate sediment budget. Data points are from this study (red circles and green squares), Xue et al. (2010) (blue triangles), and Unverricht et al. (2013) (yellow diamonds). About one-third of Mekong sediment accumulates in proximal areas near mouths of distributary channels, and two-thirds accumulates in the more distal region of the Ca Mau Peninsula. *From DeMaster et al. (in press)*

would be dramatically impacted by changes such as salt intrusion, which would move the estuarine turbidity maximum and sediment entrapment far upstream in the distributary channels (Allison et al., 2017, and Ogston et al., 2017, both in this issue). The small amount of sediment that reached the delta would likely be trapped before entering the ocean. The sediment discharge to the shelf during the usual high-flow period would be dramatically reduced as the sediment and freshwater fluxes were both minimized. Therefore, less sediment would be available for landward supply to shorelines during the seasonal low flow period. Consequently, the delta and distal shorelines would become undernourished, and likely mangrove forests, such as Cu Lao Dung, would be eroded and destroyed if coastal processes (e.g., waves and currents) remained similar or became more energetic. Even if water and sediment discharges were not eliminated, intense regulation of discharges could impact the seasonal balance of coastal sediment export and import related to ocean processes (winds, waves, currents), which would affect sediment accumulation on the shelf and shoreline. With accelerated sea level rise and delta subsidence (e.g., Minderhoud et al., 2017), shorelines will migrate landward, making former land surfaces into shallow continental shelf seabeds, further complicating the sediment-exchange processes. Some shorelines (Anthony et al., 2015; Schmitt et al., in press) and inner shelves (Liu et al., 2017, in this issue) already show erosional features that may reflect the beginning of this process.

Minimized water discharge would cause the Mekong plume to be substantially reduced and the processes drawing ocean water landward would be similarly diminished. Nutrient supply to the shelf from both land and ocean water would be smaller. With suspended sediment discharge depleted, the adsorbed chemical components from land weathering and ocean sources would have reduced particle surfaces to adsorb them, and their removal to the seabed would be diminished. This could impact transport of organic carbon, which is associated with muddy sediment and used as a food source by benthic organisms. Reduction in the quantity and quality of sediment accumulation (inorganic and organic) could impact the dynamics and the life on the seabed of the inner shelf.

Climate change could modify monsoonal conditions (e.g., Darby et al., 2016) and ocean hydrodynamics, causing similarly great impact. Differing intensity, timing, and/or direction of wind patterns would affect surface waves and wind-driven currents. Intensification of these processes could further enhance shelf and shoreline erosion. Changes in the seasonal monsoon conditions could also upset the natural balance of coastal sediment export and import. The concerns described for changes to both the terrestrial and marine environments are similar in other river-delta-ocean systems, and many of these already exhibit the impacts mentioned above. For the Mekong system, the bulk of change is yet to come, and will influence the millions of people living on the delta and relying on the deltaic environment (e.g., for rice production).

SUMMARY

The predominant sink for fluvial sediment within deltaic systems is the shallow continental shelf. Many chemical components adsorbed to particle surfaces accumulate with this sediment. The locus of most sediment accumulation is a subaqueous structure on the shelf known as a clinoform. The sedimentary processes impacting this accumulation were investigated in the Mekong Delta system, as an example of an Asian fluvial source (draining the Himalayan highlands) and of a wet tropical sink (impacted by monsoonal conditions).

Most Mekong sediment is discharged with peak flow to the East Sea during quiescent oceanic conditions (August–November), with the sediment bypassing coastal environments (e.g., mangrove forests). Subsequently, energetic ocean conditions resuspend shelf sediment and transport it back to the coast to nourish shorelines with mangrove forests and to be carried into deltaic distributary channels. Most of the sediment remaining in the ocean accumulates on the inclined region of the clinoform known as the foreset at local rates of >10 cm yr^{-1}. About two-thirds of Mekong sediment accumulates in distal portions of the dispersal system (i.e., the Ca Mau Peninsula and beyond).

The surface plume from the Mekong moves offshore and causes underlying ocean water to flow landward. Many dissolved chemical components (e.g., dissolved nutrients and radioisotopes) are imported from the open ocean and meet the turbid Mekong water. Some of these components have a natural affinity for suspended sediment, are adsorbed to particle surfaces, and accumulate with the sediment. The clinoform structure is the sink for particle-reactive chemical components both weathered on land and formed in the open ocean.

These processes are likely to change in the future as many dams are built, causing sediment entrapment and water reduction. The shelf seabed could be starved, and denied many chemical components that arrive with new water and sediment. Climate change is likely to cause differences in the physical processes on the shelf, with additional ramifications for the sediment dispersal system.

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