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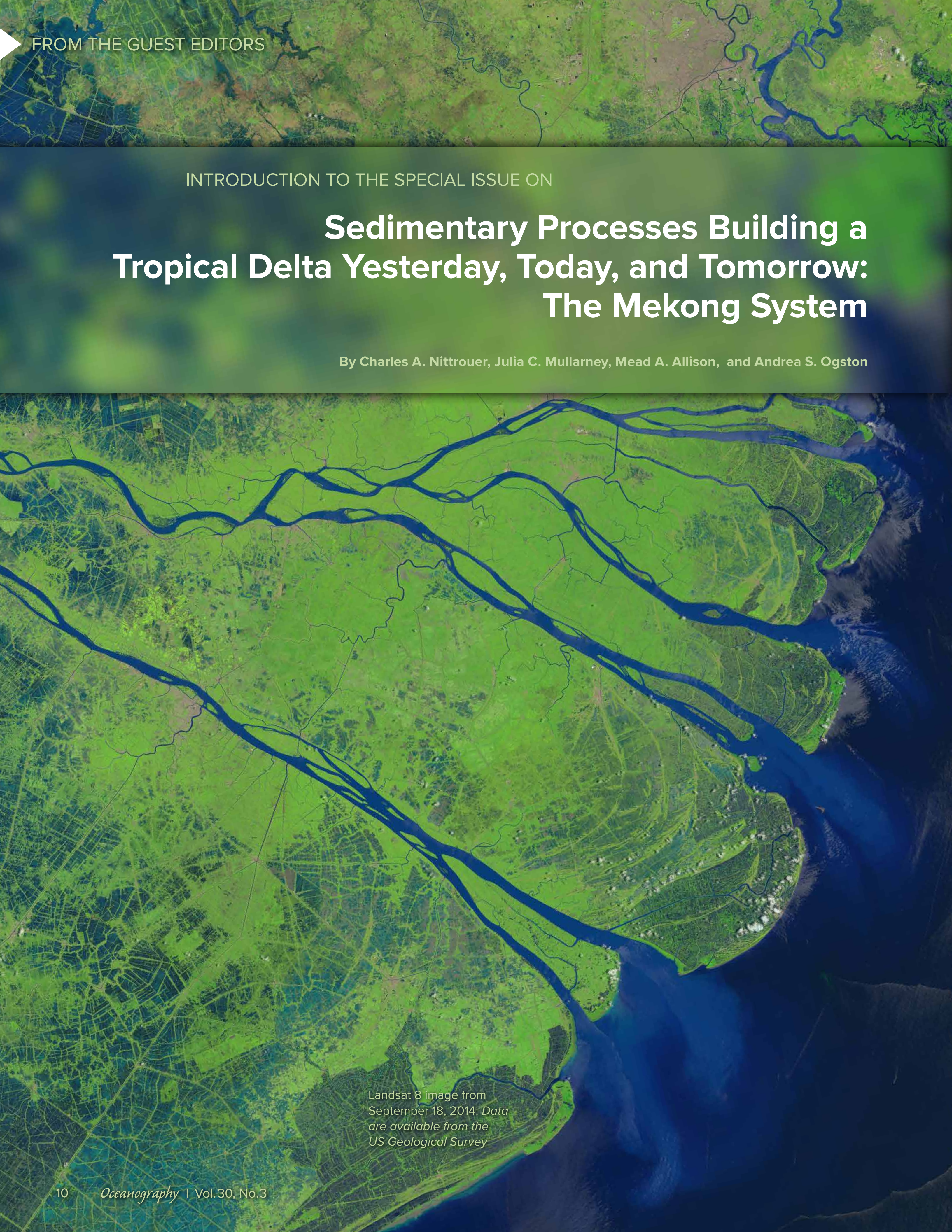
INTRODUCTION TO THE SPECIAL ISSUE ON

Sedimentary Processes Building a Tropical Delta Yesterday, Today, and Tomorrow: The Mekong System

By Charles A. Nittrouer, Julia C. Mullarney, Mead A. Allison, and Andrea S. Ogston



Landsat 8 image from September 18, 2014. *Data are available from the US Geological Survey*

ABSTRACT. River deltas are important for human habitation, commerce, food, and natural resources. Most terrestrial freshwater, dissolved substances, and suspended sediment supplied to the ocean pass through delta distributary channels. Transitions are complex as this river discharge moves through the serial environments of delta systems: tidal river, estuary, shoreline, continental shelf.

The bulk of Mekong sediment accumulates as a muddy clinoform deposit on the shallow continental shelf (<20–25 m water depth), which forms the foundation over which the subaerial delta surface has grown for the past ~8,000 years. The Song Hau distributary channel, the target of this investigation, receives ~40% of the Mekong discharge and transfers the majority of it to the adjacent shelf during high flow of the river (July–November). Some of the sediment is returned to the channel and to the mangrove shoreline during low flow of the river (December–April). The sediment reentering the channel is mostly mud, deposited by estuarine processes, that temporarily buries the channel bed and interrupts sand transfer to the coastal ocean.

Trapping of sediment supplied to the shoreline of the island, Cu Lao Dung, at the Song Hau mouth, is enhanced by the roughness from dense mangrove roots extending above the bed. Shoreline progradation is asymmetric with the most rapid sediment accumulation (~5 cm yr^{-1}) in the southwestern portion of the island, and the distribution of mangroves is linked to this sedimentation pattern. About one-third of Mekong sediment discharge accumulates in the shelf clinoform near the mouths of the distributary channels, with the greatest accumulation rates (>10 cm yr^{-1}) in the relatively steep foreset region. Intense landward and southwestward currents transport the other two-thirds of Mekong discharge during energetic shelf conditions (December–April). These sediments create a relatively shallow clinoform structure, cause the delta to grow asymmetrically toward the southwest, and form the Ca Mau Peninsula.

In the future, these same natural processes will operate under different conditions. Construction of many dams within the drainage basin (>200 constructed or approved) and the impacts of climate change (i.e., alterations in monsoonal conditions) will significantly decrease Mekong River discharge. In addition, the delta land surface will be flooded due to acceleration of eustatic sea level rise and local land subsidence. Together, loss of river discharge and rise of local sea level will cause many secondary impacts, including erosion of distributary channels, ocean shorelines, and the shelf seabed; saltwater intrusion farther into the channels, along with transfer of associated estuarine processes; and decreased supply of freshwater and solutes, including nutrients, to the coastal ocean. The collaborative research among international and Vietnamese scientists described in this special issue of *Oceanography* provides an integrated understanding of the Mekong Delta system, and could help formulate strategies to enhance the resiliency of the system and its ability to cope with future impacts.

INTRODUCTION

Rivers are Earth's dominant circulatory system. They are responsible for transferring water, solute, and particulate material from high land elevations to deep ocean depths, largely in a serial path. Numerous environments along the way have uniquely defined characteristics (e.g., water-surface gradients, flow mechanisms, substrate, vegetation, geochemistry), and there are an equal number of transitions between these environments. A series of especially important transitions occurs as a fluvial system reaches sea level. The scientific relevance of the processes active through this region is that they define the change from primarily transporting material to primarily depositing it, and do so in especially complex settings (e.g., deltas) where both terrestrial and marine mechanisms operate. The human relevance is that much of the world population lives in these regions and depends on food, natural resources, and commerce located there.

Of the 30 largest river systems delivering water to the ocean, eight originate on the Himalayan Plateau and transport ~55% of the fluvial sediment reaching the world ocean (Allison et al., 2017, in this issue). Of these eight rivers, the one extending to the lowest latitude is the Mekong, which enters the ocean in the wet tropics. This geographic area has relatively constant heat and humidity, and worldwide it receives >50% of the fluvial freshwater and >60% of the associated sediment entering the ocean (Nittrouer et al., 1995). The Mekong system presents a special opportunity to understand the processes that deliver fluvial material from an important source and disperse that material into an important sink. The Mekong Tropical Delta Study focused on the transitions that occur as the river load reaches the influence of sea level and extends into the coastal ocean.

MEKONG TROPICAL DELTA STUDY

For the reasons described above, the lower portion of the Mekong system has been investigated by a number of previous studies that focused on a wide range of topics: water dynamics (Wolanski et al., 1996, 1998; A.D. Nguyen et al., 2008; Noh et al., 2013; Takagi et al., 2014);

groundwater extraction (Erban et al., 2014; Minderhoud et al., 2017); sediment dynamics (Lu and Siew, 2006; Kummu and Varis, 2007; Xue et al., 2011; Wang et al., 2011; C. Liu et al., 2013; Bravard et al., 2014; Brunier et al., 2014; Kondolf et al., 2014; Lu et al., 2014; Manh et al., 2015; Darby et al., 2016; R.J.P. Schmitt et al., in press); sea level change (Wassman et al., 2004; Smajgl et al., 2015; T.T.X. Nguyen and Woodroffe, 2016); shoreline change (Thu and Populus, 2007; Tamura et al., 2010, 2012a; K. Schmitt et al., 2013; Albers and Schmitt, 2015; Anthony et al., 2015; Phan et al., 2015; Besset et al., 2016); ocean processes (Schimanski and Stattegger, 2005; Tjallingii et al., 2010; Xue et al., 2010, 2012; Szczucinski et al., 2013; Unverricht et al., 2013, 2014; Loisel et al., 2014; Vinh et al., 2016); and delta evolution (V.L. Nguyen et al., 2000, 2005; Ta et al., 2002, 2005; Tamura et al., 2009, 2012b; Hanebuth et al., 2012; Li et al., in press). The Mekong Tropical Delta Study, in contrast, examined the linkages among environments in the continuum extending from the tidal river (freshwater with tidal modulation) to the estuarine reaches of delta distributary channels (with some salinity), and beyond to the shorelines dominated by mangrove forests and to the major sediment sink on the continental shelf (Figure 1). This coordinated study required the participation of many scientists and students from Vietnam, the United States, New Zealand, and the Netherlands. The results are briefly introduced in this article, and more fully presented in the following articles in this special issue.

The goals of the Mekong Tropical Delta Study are to understand the mechanisms and the deposits associated with sedimentary processes that have created the Mekong Delta over the past ~8,000 years (Tamura et al., 2009) and that will continue to modify the delta into the future. Addressing these goals required: investigation of the historical record preserved by delta stratigraphy, observation of modern processes impacting hydrodynamics and sediment dynamics, and forward extrapolation of past and present processes based on anticipated future environmental conditions. The Mekong Delta contains numerous distributary channels that share the load discharged to the ocean (Figure 1). In order to have a manageable study domain, the target of this investigation was the largest distributary channel, Song Hau, which carries ~40% of Mekong water and sediment discharge (A.D. Nguyen et al., 2008). The major coordinated study was preceded by preliminary measurements during 2012–2013 (Nowacki et al., 2015), which provided knowledge of environmental and logistical concerns regarding the Song Hau and allowed design of the more intense study in 2014–2015.

The numerous environmental factors that impact the Mekong Delta vary on time scales intrinsic to those factors. For hydrodynamics and sediment dynamics, the most important temporal variabilities occur with seasonal and tidal periodicities. The discharge of the river reaches a peak that propagates downstream between July and November (Figure 1). Because of its location in the wet tropics, the Mekong Delta and the adjacent ocean are impacted by monsoonal variations: weak winds, waves, and currents toward the northeast prevail during the period of peak river discharge, and conditions switch to energetic winds, waves, and currents toward the southwest during the period of low discharge from December to April (Figure 1). Tidal forcing with semidiurnal and fortnightly periods is superimposed on these seasonal fluctuations. The Mekong Delta is mesotidal, with a range of 3–4 m during spring tides, and these fluctuations cause strong tidal currents that are coupled with other ambient forces (e.g., river flow, ocean waves, and shelf circulation).

In order to resolve seasonal and tidal variations in hydrodynamics and sediment dynamics, two intense field campaigns were undertaken with two-week durations during September–October 2014 and March–April 2015. The fieldwork areas (Figure 1) included: ~90 km of the lower Song Hau below the city of Can Tho (Figure 2); the mangrove forest on the ocean shoreline of Cu Lao Dung, an island that causes the Song Hau to bifurcate at its mouth (Figure 3); and the continental shelf seaward of the Song Hau mouth (Figure 4). In addition, these same regions were examined during the same periods by collaborative efforts using remote sensing and numerical modeling. Together, these research programs shed new light on sedimentary processes building the Mekong Delta in the past, present, and future. For each of these three time frames, the contributions from the Mekong Tropical Delta Study are highlighted below.

THE MEKONG DELTA DURING THE PAST 8,000 YEARS

Starting ~20,000 years ago, global (i.e., eustatic) sea level began to rise rapidly and continued until ~8,000 years ago, when rates of rise slowed to ~2 mm yr^{-1}, allowing many rivers to begin building their deltas (Stanley and Warne, 1994). This Holocene sea level rise caused transgression of the shoreline (landward movement). As the shoreline migrated landward, the sandy deposits (particle size >63 μm) of beach and nearshore environments created relatively coarse surfaces on newly formed continental shelves. When deltas began to form, shoreline regression (seaward movement) resulted as river sediment accumulated over the transgressive sand surface. Fluvial sediment discharged to the ocean is predominantly muddy (particle size <63 μm); the sediments moving through the Song Hau are >70% mud (Wolanksi et al., 1996). So, delta sedimentation accumulates mostly mud above the basal sand layer. Delta growth also creates a surface veneer of shoreline and channel sands atop the muddy deposits.

Studies of these strata within the Mekong Delta (e.g., V.L. Nguyen et al., 2000; Ta et al., 2002; Hanebuth et al., 2012; Tamura et al., 2012a, 2012b) demonstrate that regression intensified ~5,000 years ago and that the control of sedimentation changed ~3,000 years ago from tidal processes alone to mixed tides and surface waves. The ancient rate of sediment discharge by the Mekong River is difficult to evaluate, but estimates made before dam construction indicated a discharge of ~160 Mt yr^{-1} (Milliman and Meade, 1983). Sediment accumulation has built the Mekong Delta ~220 km seaward and formed ~50,000 km^2 of subaerial surface (Liu et al., 2017, in this issue). The shoreline extends for >300 km along the front of the delta, which has grown asymmetrically southward and created the Ca Mau Peninsula (Figure 1).

The Mekong Tropical Delta Study's primary contribution to the understanding of delta stratigraphy and history concerns the formation of interior mud deposits on time scales of centuries and millennia (DeMaster et al., in press; Eidam et al., in press; J.P. Liu et al., 2017, in this issue; J.P. Liu et al., in press). These deposits comprise the dominant mass of the delta structure, the foundation on which its subaerial surface is built. Most sediment accumulation occurs below sea level and creates a feature known as a clinoform (Figure 4), a deposit with a sigmoidal shape in the across-shelf direction. Ocean waves and currents intensely rework a shallow topset region, inhibiting sediment accumulation. The dominant flux of sediment into the seabed occurs farther seaward in the foreset region, where relatively steeply dipping strata build rapidly upward and seaward. The boundary between the topset and foreset regions is known as the rollover point (Figure 4). At the base of the foreset, clinoforms commonly have thin bottomset deposits overlying the basal sand layer that predates delta growth. The topset also can be sandy, but otherwise the Mekong clinoform is dominantly composed of mud (Eidam et al., in press).

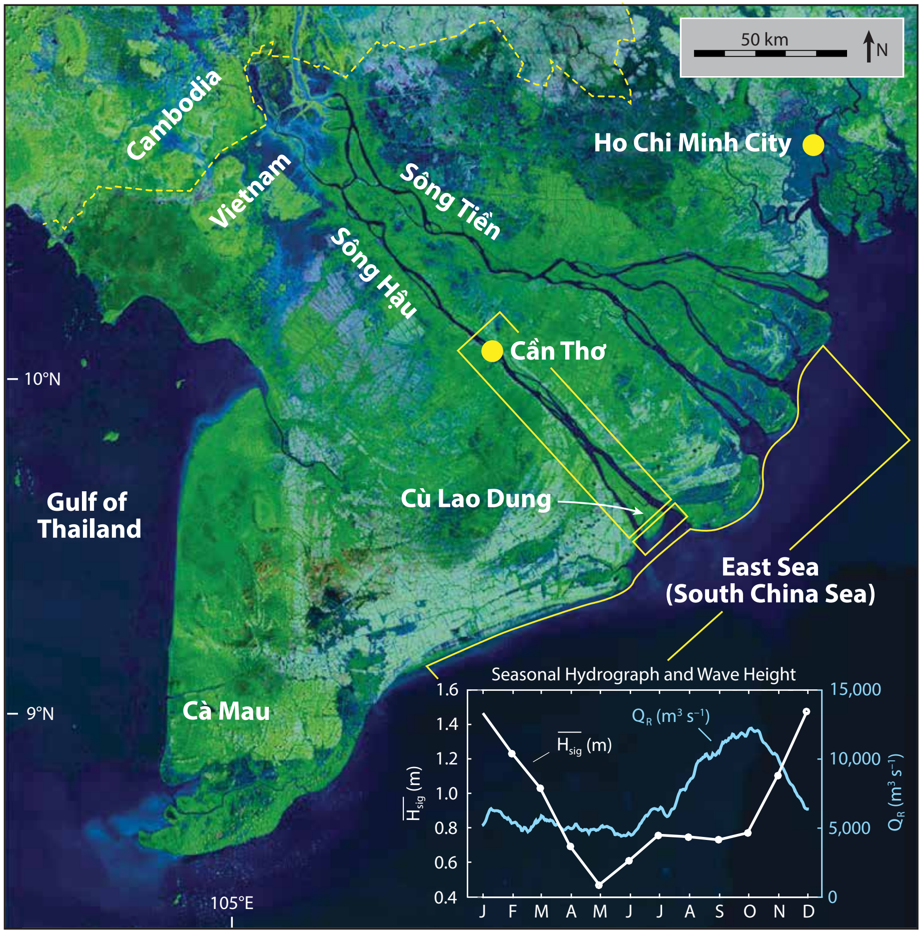


FIGURE 1. The Mekong Delta and its distributary channels. The Song Hau was the focus of the Mekong Tropical Delta Study. The long yellow box from Can Tho to the coast was investigated for channel processes. The small box at the seaward end of Cu Lao Dung contains tidal flats and a mangrove forest, which were also studied. The seaward portion of the study area was conducted in the yellow box on the inner continental shelf. Many fluvial and marine processes varied on a seasonal monsoon time scale (lower right inset), driven by river discharge (Q_R) with a peak in July–November and by winds demonstrated by peak wave height (H_{sig}) in December–April. *From Eidam et al. (in press)*

Detailed seismic surveys of the Mekong subaqueous delta (J.P. Liu et al., 2017, in this issue; J.P. Liu et al., in press) reveal a clinoform with a rollover depth of 4–6 m and bottomset deposits ~20 m deep; therefore, many of the foreset deposits are ~15 m thick. Coring into the foreset region indicates that the grain size is >75% mud with porosity ~0.6 (DeMaster et al., in press; Eidam et al., in press; Nittrouer et al., 2017, in this issue). The character of the clinoform changes along the delta and around the Ca Mau Peninsula, with the base of the foreset deepening to ~25 m southward and into the Gulf of Thailand, and thicknesses increasing to >20 m. An inventory of clinoform sediment indicates that about one-third has accumulated off the mouths of Mekong distributary channels, and the other two-thirds have accumulated southward toward the Ca Mau Peninsula and around it into the Gulf of Thailand (J.P. Liu et al., 2017, in this issue; J.P. Liu et al., in press). Assuming an age at the base of the clinoform deposits of ~1,000 years (Ta et al., 2002) allows estimation of a sediment budget that indicates a mean accumulation of ~120–140 Mt yr^{-1} for this time scale (J.P. Liu et al., 2017, in this issue; J.P. Liu et al., in press). Sediment accumulation rates for the past century have been directly measured from sediment cores and are commonly 1–10 cm yr^{-1} (DeMaster et al., in press; Eidam et al., in press; Nittrouer et al., 2017, in this issue). Observations from these measurements indicate patterns of sediment flux and mass budgets similar to the seismic observations. On both millennial and centennial time scales, total sedimentation in the clinoform approximates the pre-dam discharge estimate of ~160 Mt yr^{-1} (Milliman and Meade, 1983). These fluxes have created the foundation of the Mekong Delta, which is composed of rapidly accumulating, soft muddy deposits.

THE MEKONG DELTA TODAY

Song Hau Distributary Channel

As the Mekong River approaches sea level, marine processes become superimposed on purely fluvial conditions, affecting its flow (Ogston et al., 2017, in this issue; Xing et al., in press). The seaward serial transitions (Figure 2) are: (1) freshwater river with unidirectional flow downstream, (2) freshwater tidal river with unsteady and then reversing flow, (3) interface zone with flow convergence as estuarine conditions are approached, (4) estuary where freshwater and saltwater meet and bottom flows can be upstream, and (5) marine conditions. In the Mekong system, tidal fluctuations propagate several hundred kilometers upstream, and estuarine circulation can extend ~50 km upstream. The locations of the transitions change with seasonal flow conditions, and to a lesser degree with tidal fluctuations. Despite the inherent complexities, defining the spatial and temporal variabilities of processes is critical for understanding how muddy and sandy sediment are transported and exported, and, during some conditions, why significant amounts of sediment are imported into the Song Hau from the ocean.

Although the same hydrodynamic transitions described above apply, transfers of mud and sand fractions from the Song Hau to the ocean are generally disconnected. This is due to differences in transport mechanisms (Ogston et al., 2017, in this issue). Flocculation (particle aggregation), settling, and bed stresses all affect muddy particles. In the Song Hau, the fine particles reaching the tidal river below Can Tho are significantly flocculated before coming into contact with saline conditions (McLachlan et al., in press). However, these particles and aggregates stay in suspension until they reach the interface zone, where near-bed flow slows and bed stresses decrease. These conditions allow settling and deposition within both the interface and the estuarine turbidity maximum at the base of the salt wedge, whose locations change seasonally. During high flow of the river, ebb-tidal flows become dominant, and the salt wedge is generally displaced onto the shelf, where most muddy sediment is deposited (Nowacki et al., 2015; McLachlan et al., in press). However, during low flow of the river, fluvial advection has minimal importance to net sediment flux, flood-tidal flows dominate, and estuarine processes are displaced 40–50 km into the Song Hau. Muddy downstream discharge can be trapped in the channel, and muddy sediment resuspended on the continental shelf can be imported by landward estuarine bottom flows. During low flow, the estuarine channel bed is covered with a mud layer 25–100 cm thick (Allison et al., in press).

In the Song Hau, sandy sediment can be transported as bedload, but most moves in suspension (Stephens et al., in press). Sand can represent as much as 5%–20% of the mass in the suspended load, but it generally settles during slack tidal currents and is eliminated during seasonal low flow where mud covers the channel bed (lower 40–50 km). In contrast, during seasonal high flow of the river, bedload transport creates fields of sand dunes on ~20% of the channel bed, and relict bottom strata are eroded into furrows on ~80% of the bed (Allison et al., in press). Additionally, this high-flow condition is the time when suspended sand can be exported from the Song Hau mouth to shallow coastal areas (Stephens et al., in press).

Growth of Cu Lao Dung has created two subchannels at the mouth of the Song Hau: Dinh An on the northeast side and Tran De on the southwest side (Figure 2). Water flow and sediment transport conspire to maintain greater fluxes through Dinh An than through Tran De. Dinh An dominates sand transport (Stephens et al., in press). Tran De, in contrast, exhibits a better mixed estuarine regime, has a greater fraction of flocculated silt and clay, and consequently has more muddy sediment deposition (McLachlan et al., in press). The ultimate fate of Tran De could be infilling and closure, as observed for another Mekong distributary farther north, Ba Lai (Tamura et al., 2012b).

Cu Lao Dung Mangrove Shoreline

Beyond the environments of the Song Hau distributary channel are the tidal flat and mangrove coast of Cu Lao Dung, whose seaward growth represents regression of the shoreline over top of the clinoform deposit on the adjacent continental shelf. This growth also has helped create the island that splits the Song Hau into the two smaller distributary channels, Dinh An and Tran De, with differing hydrodynamics and sediment dynamics. Mangroves dominate intertidal vegetation in most tropical settings, and several species are found on Cu Lao Dung: *Sonneratia* spp., *Aegiceras corniculatum*, and *Avicennia marina* (Bullock et al., in press; Fagherazzi et al., 2017, in this issue). Their presence and associated vegetation (e.g., *Nypa fruticans*) create complex interactions with water flow and sediment transport (Bryan et al., in press), a situation that is typical of tropical shorelines.

Mangroves have developed root systems with various structures above bed level to address important biotic functions, such as oxygen exchange and salt filtration. These roots, called pneumatophores, have different shapes commonly described as stilt, knee, or pencil depending on the mangrove species (Mullarney et al., 2017, in this issue). The roots radiate away from the base of the tree trunk and extend a few tens of centimeters above the bed. Individual pneumatophores have diameters of a centimeter to a few centimeters. The pencil-shaped pneumatophores that dominate the Cu Lao Dung forest typically exhibit surface roughness in the way their bark is formed and especially from growth of barnacles

(Mullarney et al., 2017, in this issue). The pneumatophores are found in dense concentrations known as "canopies" that are sufficient to impact flow from surface waves and tidal currents.

Water flow through pneumatophore canopies generates frictional drag forces, creating turbulent eddies, slowing flow, and rotating its direction (Henderson et al., in press; Mullarney et al., in press; Norris et al., in press). Depending on the exact pneumatophore concentration and the tidal water level, the drag forces respond differently (Figure 3). Very dense concentrations and high water levels can cause enough drag high in the canopy that hydrodynamic stresses may not reach the bed. In contrast, sparser distribution of pneumatophores and lower water levels may entrain turbulence downward, accentuating bed stress and causing erosion. When mangroves are located at the mouth of a turbid river, sediment becomes an added factor that can variously be deposited or eroded by the processes described above, and can be sorted by grain size. Each of these sedimentary processes has feedback to the health of the pneumatophores and consequently the mangroves (Fagherazzi et al., 2017, in this issue; Mullarney et al., 2017, in this issue).

Sedimentary processes impact mangroves from birth to death. In the Cu Lao Dung forest, mangrove seedlings are common in stable sand substrates, and are uncommon where easily erodible mud substrates are found (Bullock et al., in press; Fagherazzi et al., 2017, in this issue). The dominant mangrove, *Sonneratia* spp., and its pneumatophore canopy are very effective at trapping sediment, thereby raising bed level and smothering the mangrove's roots, ultimately leading to their demise. However, *Sonneratia* mangroves continue to thrive, as new trees grow farther seaward in more suitable conditions. The old locations have higher elevations with decreased water immersion times, creating conditions ideal for the other types of mangroves and leading to species succession and zonation (Figure 3; Nardin et al., 2016; Fagherazzi et al., 2017, in this issue). Consistent with these observations, sedimentary characteristics demonstrate landward trends. The frictional drag beginning at the mangrove fringe causes bottom stresses to decrease progressively into the forest, bed grain sizes to become finer (from sand dominant to mud dominant), and accumulation rates to increase (from ~3 cm yr^{-1} to

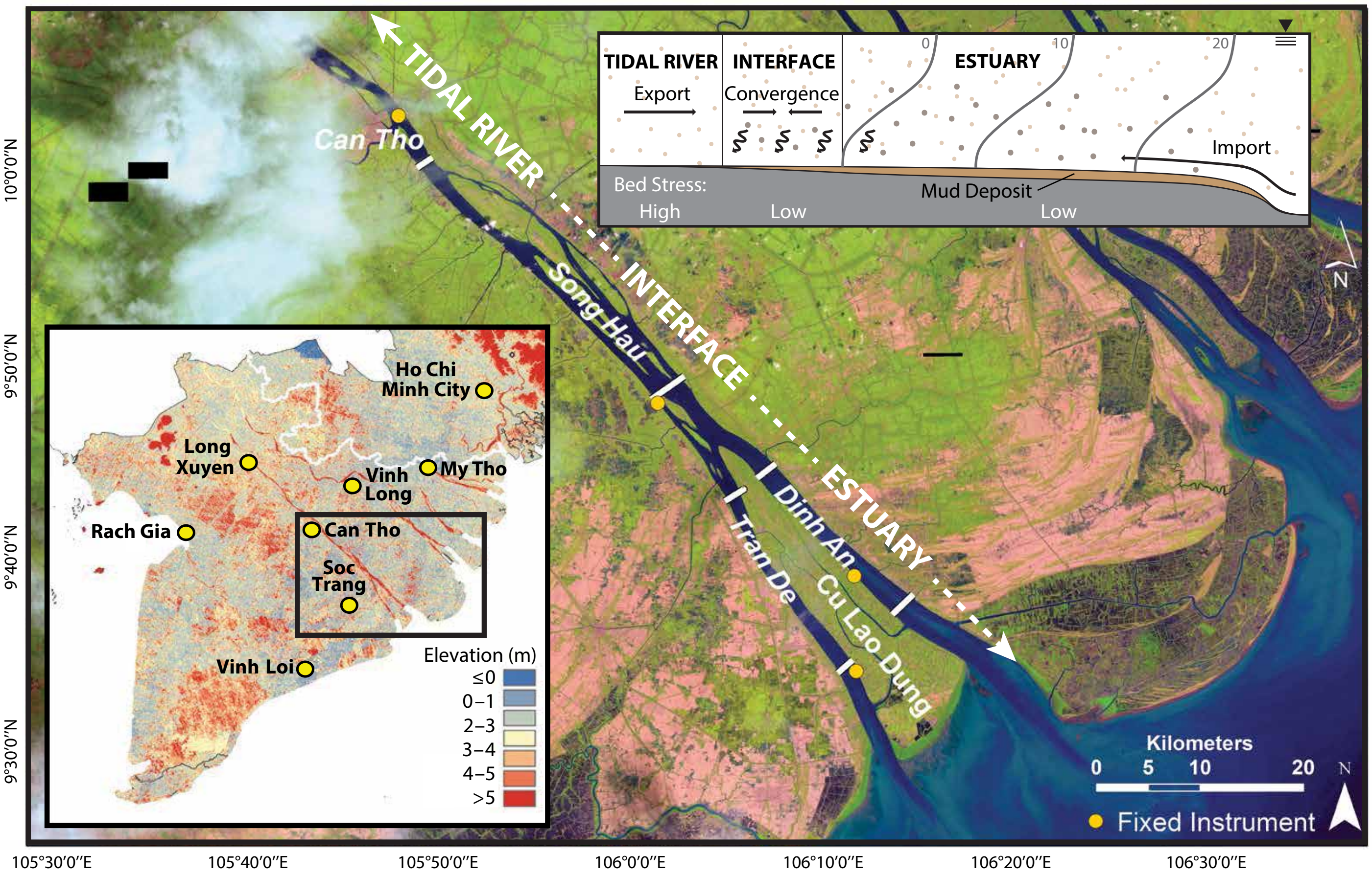


FIGURE 2. Channel studies deployed fixed instruments and examined numerous transects from Can Tho to the coast, as shown on the base map. These were located to allow detailed investigation of the transitions from the tidal river through the interface zone into the estuarine regime. The inset at upper right shows the condition during low flow of the river, December–April. *From Ogston et al. (2017, in this issue)* The land surfaces surrounding the channels have a mean elevation of just 2 m, as shown in the lower left inset, a digital elevation model of the Mekong Delta. *From Allison et al. (2017, in this issue)*

~5 cm yr^{-1}; Mullarney et al., 2017, in this issue; Fricke et al., in press).

The driving forces for hydrodynamics and sediment dynamics are not equally distributed in space and time along the Cu Lao Dung shoreline. The two ends of the shoreline border Dinh An and Tran De subchannels, with differing flow and sediment characteristics. In addition, the ocean waves and currents approach from different directions, with different intensities, during different seasonal conditions. Consequently, sedimentation is neither uniform nor steady (Fricke et al., in press). The southwest end of the Cu Lao Dung shoreline receives the greatest wave energy, creating a sandy substrate on the tidal flat. However, muddy sediment transport converges in this area and causes the greatest sediment accumulation rates, >5 cm yr^{-1} within the forest (Fricke et al., in press). The northeast end of the shoreline is more quiescent and sediment fluxes into the mangrove forest are weak, so accumulation rates are <3 cm yr^{-1}. The result is asymmetric growth of the tidal flat and shoreline, as the southwest end progrades more rapidly, at mean rates ~80 m yr^{-1} for the past 35 years, as indicated by satellite observations (Fricke et al., in press; Wackerman et al., in press). Contrary to expectations, the primary supply of sediment to the tidal flats and mangrove shoreline is not during high flow of the Mekong River (July–November). Most sediment flux to the Cu Lao Dung coast occurs during the period of river low flow (December–April), and the supply comes from the adjacent continental shelf (Fricke et al., in press).

Mekong Inner Continental Shelf

The dominant sink for Mekong sediment is the clinoform structure found in water depths of <20–25 m on the adjacent continental shelf. This observation is also typical of other large river systems (e.g., Amazon, Changjiang, Ganges-Brahmaputra), where the greatest rates of sediment accumulation within the clinoform are found on the foreset region (Nittrouer et al., 2017, in this issue). Extensive studies of the Mekong clinoform find such an across-shelf trend (DeMaster et al., in press; Eidam et al., in press). Accumulation rates reach values

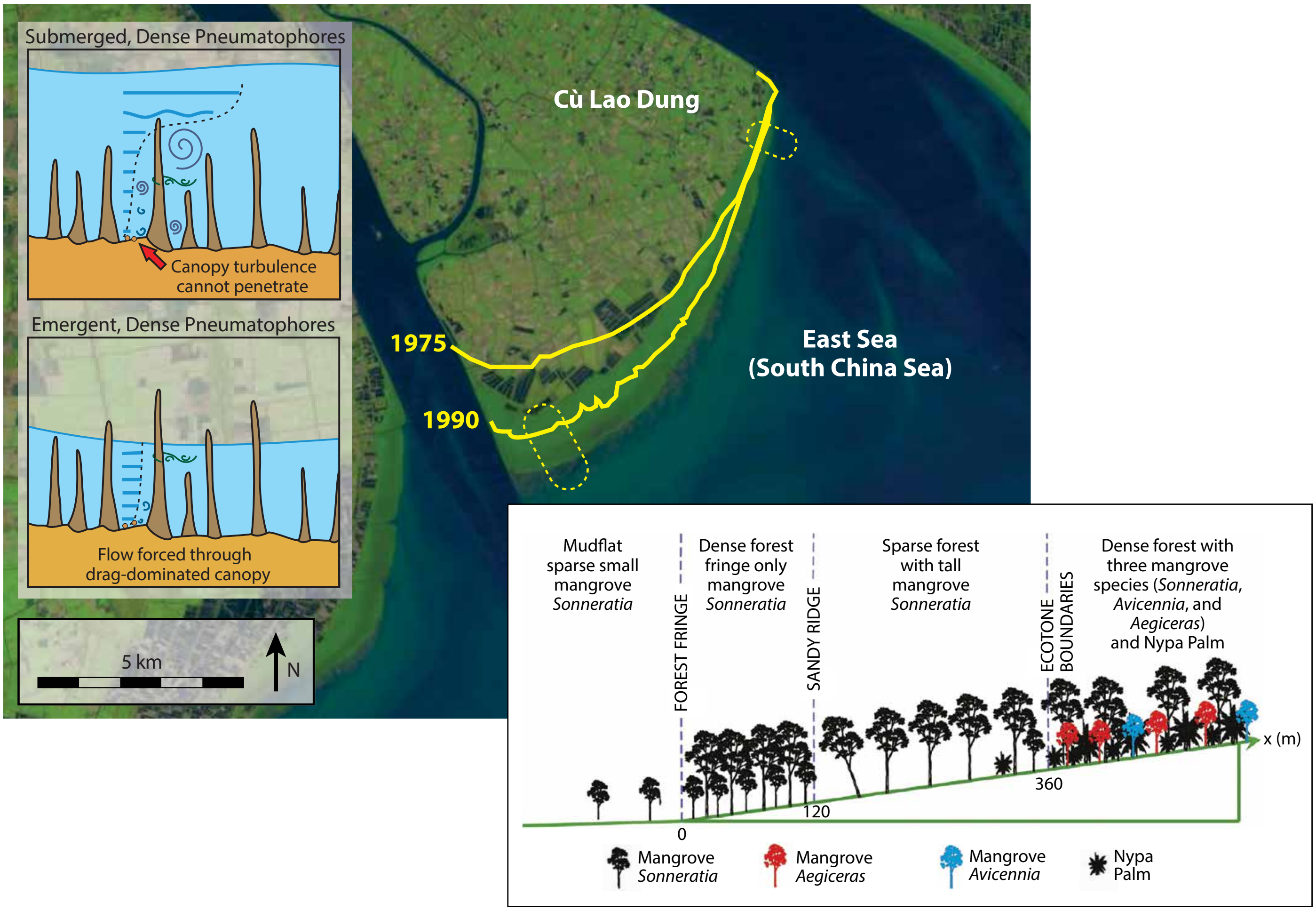


FIGURE 3. The shoreline of Cu Lao Dung has been prograding seaward asymmetrically, as shown by the base map. *From Fricke et al. (in press)* Two areas of the tidal flat and mangrove forest were studied in detail (dashed yellow ovals) at the southwest and northeast ends of the shoreline. The left inset demonstrates that turbulent flows within mangrove root (pneumatophore) canopies vary depending on water levels. *From Mullarney et al. (2017, in this issue)* The resulting processes of sedimentation cause succession of mangrove species as shown for southwest study area. *Lower right inset from Nardin et al. (2016); Fagherazzi et al. (2017, in this issue)*

approaching and exceeding 10 cm yr⁻¹ on the foreset region, and decrease both landward and seaward (Figure 4). This pattern leads to the sigmoidal shape of the clinoform surface, which builds upward and seaward. However, there is a significant inconsistency regarding the Mekong clinoform, because the rollover depth is significantly shallower (4–6 m depth) than those of other large river systems (20–40 m depth; Nittrouer et al., 2017, in this issue; Eidam et al., in press). The cause of the shallow rollover is linked to the hydrodynamic and sediment dynamic processes operating on the Mekong shelf.

A distinct characteristic of the Mekong River and shelf is the lack of coherence in timing for the peak river discharge (July–November) and peak ocean energetics (December–April). Most Mekong sediment is discharged to the ocean when surface waves are small and ocean currents are weakly directed toward the northeast. Sediment is deposited on the shelf near the mouth of the Song Hau and at the mouths of other Mekong distributary channels (Nittrouer et al., 2017, in this issue). Some of the sediment remains to accumulate and create the northern portion of the clinoform, with about one-third of the discharged sediment (DeMaster et al., in press; Liu et al., in press). The rest is resuspended by the more energetic waves and currents during December–April, and transported landward and southwestward (Eidam et al., in press; Thanh et al., in press). The intense landward transport constrains Mekong sediment near the coast, keeping rollover depths shallow (Eidam et al., in press) and providing suspended sediment to mangrove forests and distributary channel mouths (Fricke et al., in press; McLachlan et al., in press). In the latter case, low-flow conditions in channels are periods of flood-dominant tidal currents and landward estuarine bottom currents. Together, these flows can transport the resuspended shelf sediment far into the channels, 40–50 km for the Song Hau (Nowacki et al., 2015; McLachlan et al., in press). The intense southwestward shelf transport moves the remaining two-thirds of the discharged sediment and has caused the delta to grow in that direction, forming the Ca Mau Peninsula (Liu et al., 2017, in this issue; DeMaster et al., in press; Liu et al., in press).

Many chemical components are released by land-surface weathering and erosion, and are carried by river water to the ocean. Some remain dissolved in freshwater while others (e.g., Fe, organic C) can be adsorbed to the surfaces of sediment particles and follow the

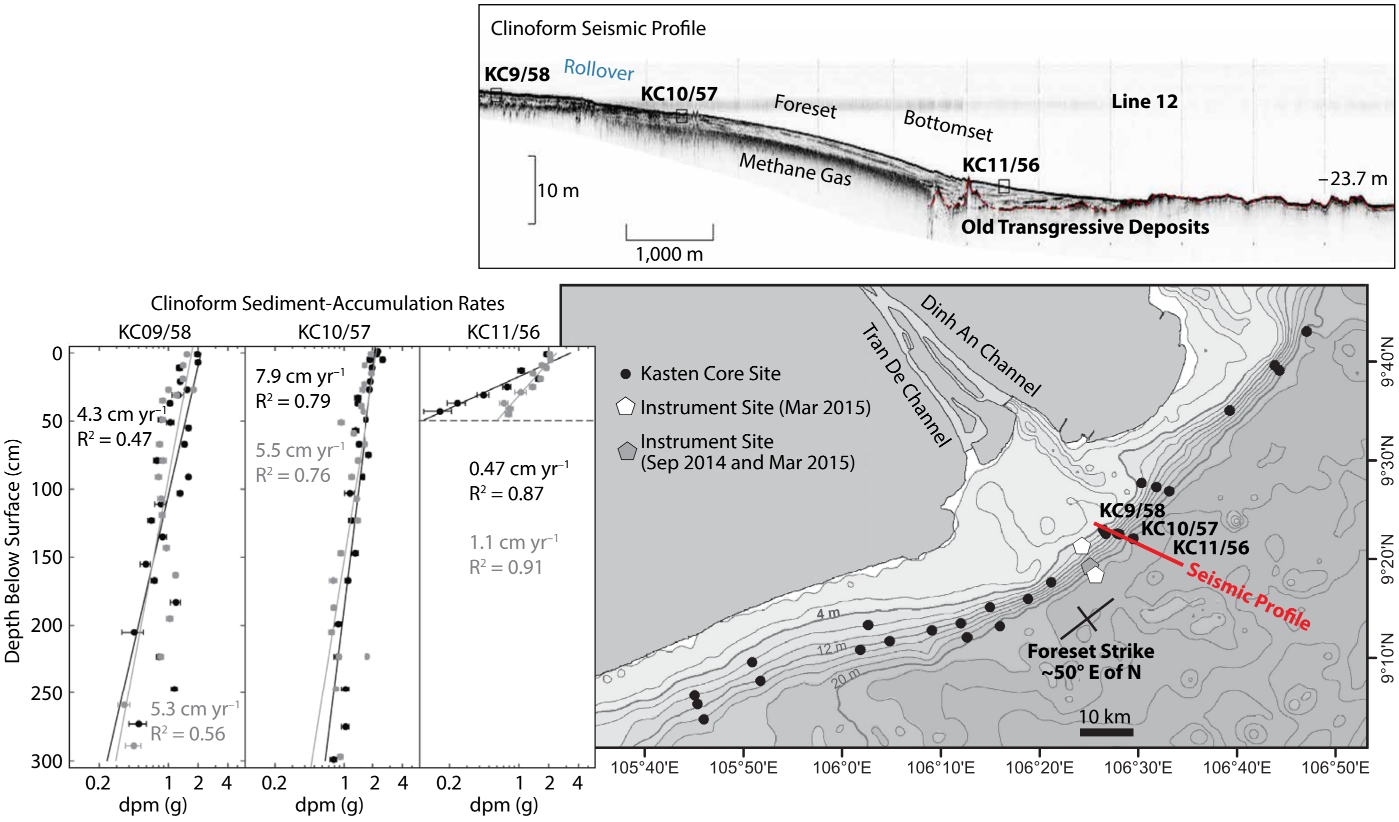


FIGURE 4. The seaward portion of the study area is the inner continental shelf, which was examined by dynamical measurements, seabed coring, and seismic profiling. The shelf is characterized as a clinoform surface shown by the seismic profile at the top. *From Liu et al. (in press); Nittrouer et al. (2017, in this issue)* Sediment accumulation is inhibited on the topset region by intense wave and current stresses. Greatest accumulation rates are on the foreset region. The bottomset beds are burying the relict transgressive sand surface. The distribution of accumulation rates (lower inset) is documented by vertical profiles of ^{210}Pb radioactivity collected from kasten cores, that demonstrate rates (cm yr⁻¹) for the past century at the station sites shown on the seismic profile. *From Eidam et al. (in press); Nittrouer et al. (2017, in this issue)*

paths of those particles to and through the ocean. Additional dissolved chemical components are found in ocean water, which is drawn to the mouths of distributary channels by estuarine circulation (DeMaster et al., in press). If these components are capable of particle adsorption, they will be scavenged by the turbid coastal waters and follow the paths of the particles. The Mekong freshwater discharge causes a landward flow of ocean water that is twice the volume of that freshwater (DeMaster et al., in press). Many oceanic chemical solutes are adsorbed and buried with the sediments in the clinoform deposit; others (e.g., N, P) can help stimulate the intense productivity of deltaic waters, and the resulting organic matter is buried. The large flux of fluvial effluent can have complex interactions with the adjacent ocean.

THE MEKONG DELTA IN THE FUTURE

Natural processes will determine the future of the Mekong Delta system, but those processes will be operating under conditions altered by human actions. The source area of the Mekong in the Himalayan Plateau and its sink in the wet tropics add some special impacts to the system, but much of the description below is similar to the fate of other major delta systems around the world. It is important to recognize that preservation of a delta system is much less difficult (and much less expensive) than its restoration (Allison et al., 2017, in this issue).

The human actions that will impact the future of the Mekong Delta are wide ranging, but there are two broad causes of change, one that originates from the land (i.e., river discharge) and the other from the ocean (i.e., sea level rise). Climate change will affect monsoonal conditions within the Mekong drainage basin, likely reducing precipitation and runoff, thus reducing water, solute, and particulate supply to the delta system (Darby et al., 2016). However, the greatest reduction is likely to come from construction of dams within the drainage basin that began in the early 1990s, with 35 dams completed by 2015, and 226 more dams approved for construction (Allison et al., 2017, in this issue). Dams reduce discharge and alter the timing and character (highs and lows) of the hydrograph, and these impacts are propagated to the delta and ocean beyond. Local sea level rise that affects a delta is a combination of eustatic rise and land subsidence, both of which are accelerating for the Mekong Delta. By 2050, eustatic sea level is expected to rise by ~30 cm and the land surface is expected to sink by ~90 cm (Erban et al., 2014; Meselhe et al., 2017, this issue). The sinking is due to natural compaction of the muddy clinoform deposits underlying the subaerial delta surface and to the human extraction of fluids. This ~120 cm of local sea level rise is significant, because the average elevation of the delta surface is only ~200 cm (Figure 2).

The impacts of discharge reduction could be dramatic, and, for sediment, estimates of reduction approach 96% if all dams are constructed (Kondolf et al., 2014). Obviously, the sediment supply to the delta and its ocean sink would be devastated. Without deposition on the continental shelf during high flow of the river, the subsequent sediment supply to the mangrove shoreline would be

minimized. Tidal currents, ocean waves, and coastal currents would continue to operate, and climate change might even energize the latter two. Without sufficient sediment supply, the distributary channels, shorelines, and seabed would eventually erode. Dam operations that alter the timing and character of discharge would disrupt the natural balance of sediment transfer between channel, shelf, and back to shoreline. Reduction in water discharge would be similarly devastating, as saltwater intrusion would penetrate farther upstream and with it the interface and estuarine processes that trap sediment discharge. Reduction in water discharge would mean less solute transfer from land, including important nutrients for primary productivity. Without the freshwater, ocean water and its constituents would not be drawn landward by estuarine circulation.

The impacts of sea level rise are obvious. The Mekong Delta is home to millions of people, and the delta surface will become progressively more prone to flooding by spring tides and high flow of the river, and by shoreline migration landward. The sediment accumulation rates documented for the present mangrove forest (reaching ~5 cm yr^{-1}) and for the shelf clinoform (reaching and exceeding 10 cm yr^{-1}) are sufficient to maintain subaerial and submarine surfaces, but these values will be severely reduced with loss of sediment supply. The expected reduction in bed growth demonstrates the dangerous coupling of damming effects and local sea level rise.

Some impacts are already being felt. Recent estimates of Mekong sediment discharge (e.g., Nowacki et al., 2015; Darby et al., 2016) are half or less than the early estimates (160 Mt yr^{-1}; Milliman and Meade, 1983). Sedimentation distribution along delta shorelines is naturally heterogeneous, but recent observations show a distinct shift toward slower seaward progradation in some areas and retreat in other areas (Liu et al., 2017, in this issue). According to these observations, the delta shoreline's historical progradation (~30 m yr^{-1}) slowed during 1973–2005, and it became net erosional after that.

What could be done to minimize future impacts on the Mekong Delta? Some actions are obvious but difficult to implement: minimize dams and their hydrograph modification, reduce sand dredging in distributary channels, limit fluid extraction from the delta subsurface, and promote mangrove growth on shorelines (Allison et al., 2017, in this issue). Other actions are scientifically based and result from the studies described in this article: develop numerical models that can help mitigate future impacts; document changes by remote sensing; enhance fixed-station monitoring in channels, shorelines, and coastal ocean waters; obtain ground truth through repetitive field observations (Allison et al., 2017, in this issue; Meselhe et al., 2017, in this issue).

The future of sedimentary processes on the Mekong Delta is uncertain—but seems ominous. The research described in this article and in this special issue provides an integrated view of those processes operating in distributary channels, mangrove shorelines, and shelf clinoform deposits. Altogether, this research promotes development of insights to the future of the Mekong and other deltas worldwide that will experience similar fates.

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