THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

CITATION

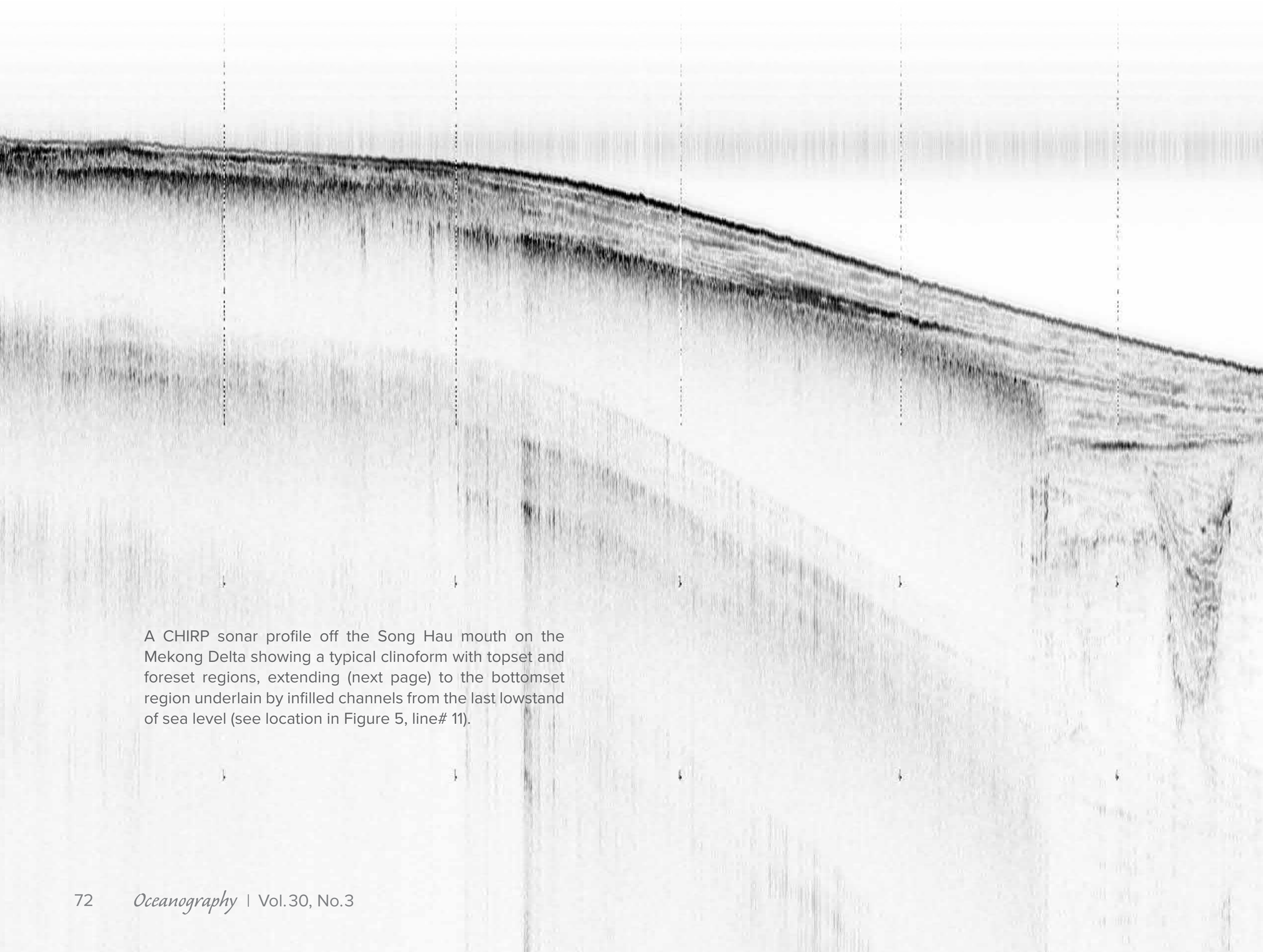
Liu, J.P., D.J. DeMaster, T.T. Nguyen, Y. Saito, V.L. Nguyen, T.K.O. Ta, and X. Li. 2017. Stratigraphic formation of the Mekong River Delta and its recent shoreline changes. *Oceanography* 30(3):72–83, https://doi.org/10.5670/oceanog.2017.316.

DOI

https://doi.org/10.5670/oceanog.2017.316

Stratigraphic Formation of the Mekong River Delta and Its Recent Shoreline Changes

By J. Paul Liu, David J. DeMaster, Thanh T. Nguyen, Yoshiki Saito, Van Lap Nguyen, Thi Kim Oanh Ta, and Xing Li



A CHIRP sonar profile off the Song Hau mouth on the Mekong Delta showing a typical clinoform with topset and foreset regions, extending (next page) to the bottomset region underlain by infilled channels from the last lowstand of sea level (see location in Figure 5, line# 11).

ABSTRACT. Where the Mekong River discharges into the East Sea (also known as the South China Sea), it has formed the world's third largest delta plain with an area of ~50,000 km^2. Numerous cores recovered from the subaerial delta reveal that it has prograded ~220 km southeastward within the past 7,500 years. Recent extensive seismic and geochemical surveys of the adjacent subaqueous delta indicate that the Mekong River forms a classic sigmoidal, cross-shelf clinoform immediately off its distributaries that is up to 15 m thick, with topset, foreset, and bottomset facies. These deposits are constrained within water depths of 20 m. Mekong-derived sediment packages extend ~300 km along shelf in the southwestward direction to the tip of the Ca Mau Peninsula, where they form a distal mud depocenter up to 22 m thick. These sediment packages can also be traced into the Gulf of Thailand to water depths of 25 m. The proximal and distal deposits cover ~11,000 km^2 of the shelf.

Historically, the Mekong Delta has prograded seaward at a mean rate of >30 m yr^{-1}, or 7 km^2 yr^{-1}; however, study of the past 43 years of Landsat images indicates that the mode of sedimentation in the delta shifted starting in 2005. From 1973 to 2005, the Mekong Delta's seaward shoreline growth decreased gradually from a mean of 7.8 m yr^{-1} to 2.8 m yr^{-1}, and after 2005 it became negative, with a retreat rate of −1.4 m yr^{-1}. The net deltaic land area gain has also been slowing, with the mean rate decreasing from 4.3 km^2 yr^{-1} (1973–1979) to 1.0 km^2 yr^{-1} (1995–2005), and then to −0.05 km^2 yr^{-1} (2005–2015). Thus, in about 2005, the subaerial Mekong Delta transitioned from a constructive mode to an erosional (or destructive) mode. Furthermore, not only is the subaerial Mekong Delta land area gradually diminishing, but high-resolution CHIRP sonar profiling surveys off the east-central Ca Mau Peninsula reveal that this portion of the subaqueous delta is also eroding. With the construction of more dams, sand mining, delta subsidence, increasing storms, and sea level rise, the Mekong Delta will likely face more destructive changes, with erosion both of coastlines and underwater deposits.

INTRODUCTION

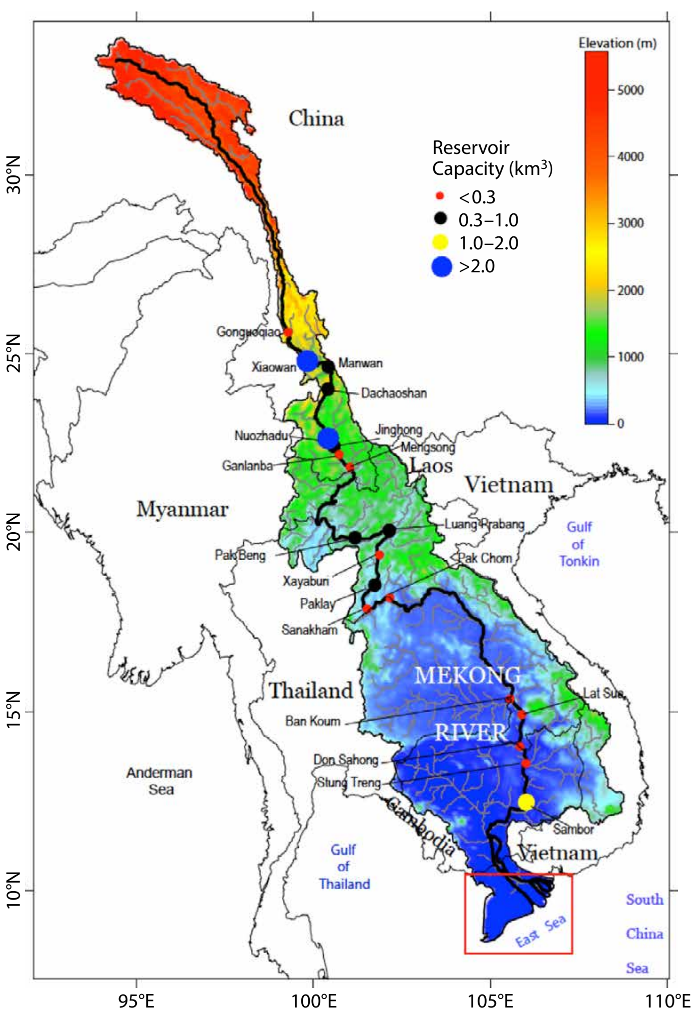
The Mekong River (Figure 1) runs ~4,700 km from the Himalayas, through China, Myanmar, Thailand, Laos, Cambodia, and Vietnam, to the East Sea (also known as the South China Sea). Its annual freshwater discharge is ~470 × 10^9 m^3, and the estimated annual sediment flux was ~130–160 million tons in the 1960s and 110 million tons in the 1990s (Milliman and Farnsworth, 2011). In southern Vietnam, the Mekong River has accumulated a massive subaerial delta of 50,000 km^2 (Figure 1), the third largest tide-dominated delta in the world after the Amazon and Ganges-Brahmaputra Deltas (Coleman et al., 2003). The Mekong Delta is home to 20% of Vietnam's population and currently produces >20 million tons of rice annually; it is therefore often called Vietnam's "Rice Bowl" (Cosslett and Cosslett, 2014). In a recent World Wildlife Fund report (WWF, 2016), the Mekong was labeled a "biological treasure trove" because of the >2,400 new species discovered in the Greater Mekong Basin between 1997 and 2015.

With 30 large dams already constructed (Figure 1), the fluvial sediment flux to the sea has been decreasing (Lu et al., 2014; Wang et al., 2011)—and ~200 new dams have been authorized. In addition, there has been a significant increase in coastal sand mining activities (Brunier et al., 2014). Together, decreasing sediment flux and increasing sand mining threaten the future of the deltaic shoreline and adjacent continental shelf. Currently, the distributary channel floors, the river banks, and the adjacent deltaic shoreline of the Mekong River delta are all eroding (Xue et al., 2011; Noh et al., 2013; Anthony et al., 2015; Smajgl, et al., 2015; Allison et al., in press). Given that the Mekong Delta average elevation is <2 m above sea level, many delta provinces have already been subject to deleterious effects from subsidence and saltwater intrusion (Allison et al., 2017, in this issue; Minderhound et al., 2017). Significant future changes can be expected in delta progradation, coastal circulation, and patterns of sediment delivery, transport, and accumulation (Xue et al., 2010; Darby et al., 2016; Li et al., 2017; Schmitt et al., in press).

In this article, we look at the historical evolution of the modern Mekong Delta: its progradation from the land to the sea, its across-shelf and along-shelf sediment transport regime, and the resultant proximal (including shoreline) and distal accumulation. The goal is to use the long-term (decadal to millennial) geological depositional records to help us understand (1) the Mekong Delta's recent geologic evolution, and (2) the rapid alterations that are beginning along its coasts and marine depositional environments in response to relative sea level rise, land use change, and alterations to the sediment supply.

LATE HOLOCENE SUBAERIAL DELTA EVOLUTION

Most of the world's large rivers began to form their Holocene marine deltas as a result of deceleration in the postglacial rate of sea level rise (Stanley and Warne, 1994). The modern Mekong Delta was initiated during the local sea level still-stand about 7,500 years ago (Bird et al., 2010; Hanebuth et al., 2012). Extensive stratigraphic studies have been conducted based on more than 20 deep boreholes drilled in the Mekong Delta plain (Figure 2; e.g., Nguyen et al., 2000; Ta et al., 2002; Hanebuth et al., 2012; Tamura et al., 2012a, 2012b). These studies indicate that sea level regression began along the delta front about 4,800 years ago, coincident with the slowdown in sea level rise that allowed buildup of a subaerial delta. This led to the delta depocenter shifting farther seaward and



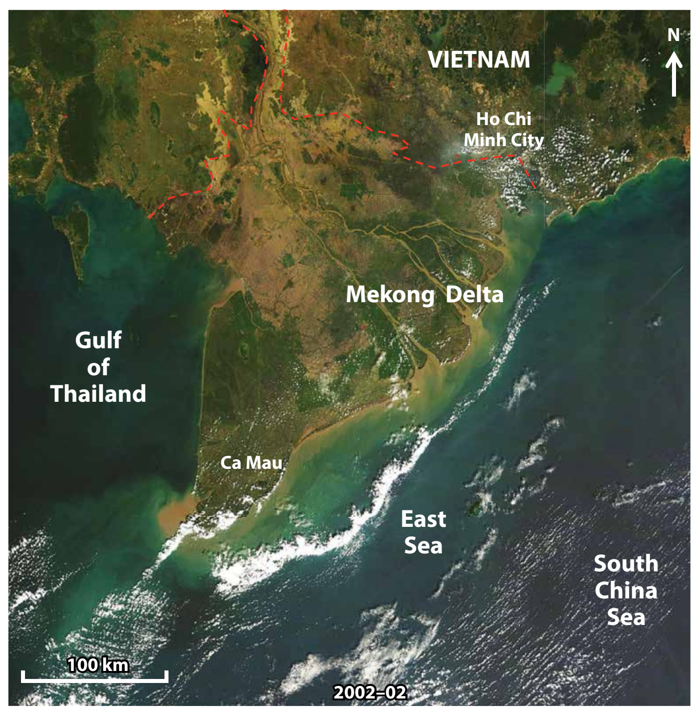


FIGURE 1. (left) Topographic relief map of the Mekong River Basin with constructed and planned large capacity reservoirs/dams (the Shuttle Radar Topography Mission data are available at http://dds.cr.usgs.gov/srtm; dam information is from Wang et al., 2011, and Xue et al., 2011). The red box denotes the area of the Mekong River delta shown in the figure at right. (right) MODIS-Terra satellite image (January 8, 2002; the white features are clouds) showing the Mekong Delta's distributary channels, suspended sediments emanating from the river mouths into the East Sea, and coastal turbidity extending to the Gulf of Thailand.

the onset of subaqueous delta progradation at that time (Hanebuth et al., 2012). About 3,000 years ago, the Mekong Delta depositional package shifted from being "tide-dominated" to "tide-and-wave-dominated" (Ta et al., 2002), marked by the development of sandy chenier ridges in its lower delta plain (Tamura 2012a, 2012b; Figure 2).

Since the middle Holocene (~7,500 years ago), the delta has prograded more than 220 km from Cambodia eastward into the East Sea at a long-term mean rate of ~30 m yr^{-1}. This progradation has buried earlier phases of the subaqueous delta beneath later subaerial deltaic deposits, thus becoming the foundation for delta development (i.e., as a part of the Holocene delta). Transects A-B and X-Y in Figure 3, including 12 boreholes across the lower delta plain, clearly show the depositional sequences and time lines (Ta et al., 2002, 2005) associated with this growth. These results and other studies (Ta et al., 2002; J.P. Liu et al., in press) also indicate that the current coastal zone and subaqueous delta on the shelf were formed only in the past 1,000 years (Figures 2 and 3). Cores VC-1, CM, and 5-1, drilled on the Ca Mau Peninsula, also verified that most distal accumulation has occurred within the past 1,000 years (unpublished data of authors Nguyen and Ta). This delta evolution model is different from those of other large river delta systems on East Asian margins such as the Yangtze (J.P. Liu et al., 2006, 2007), the Pearl (Ge et al., 2014), and the Red (van Maren, 2004; Tanabe et al., 2006; Ross, 2011) Rivers. The paths of along-shelf transport and locations of distal accumulations for these deltas have been relatively unchanged for the past 7,000 years (J.P. Liu et al., 2009, in press). However, the rapidly growing Mekong Delta has kept creating new shoreline and moving seaward (~30 m yr^{-1}). Therefore, the modern subaqueous deposit we observed on the shelf represents a relatively young deltaic clinoform.

PREVIOUS STUDIES OF THE SUBAQUEOUS DELTA

The offshore portion of the Mekong Delta rests on a very shallow and gently sloping (1:15,000) continental shelf. Two different tidal systems surrounding the Mekong Delta distribute sediments discharged from the river channels: to the east in the East Sea, tides are semidiurnal with an average range of 2.5 m; to the west in the Gulf of Thailand, tides are diurnal and microtidal with mean ranges of only 0.8–1.0 m. Seasonal monsoonal wind patterns exert primary control on coastal water circulation around the delta; the dominant current moves northeastward under the wet monsoon (May to October) and shifts southwestward under the dry monsoon (Xue et al., 2010). About 85% of the Mekong River's discharge is delivered during the wet monsoon season, with only ~15% discharged between November and April during the dry monsoon (Mekong River Commission, 2005). Numerical simulations using the Delft3D model and direct observations indicate that suspended sediment is advected out of the lower Song Hau channel to the sea during the high flow season, whereas net sediment transport is back into the channel during the low flow season (Nowacki et al., 2015; McLachlan et al., in press; Xing et al., in press; Ogston et al., 2017, in this issue). Outside the distributary channels, the nearshore tidal currents and wind-driven surface currents play a major role in controlling suspended particle transport throughout the topset region. For example, observed net sediment fluxes near the Song Hau distributary mouth were predominantly seaward/

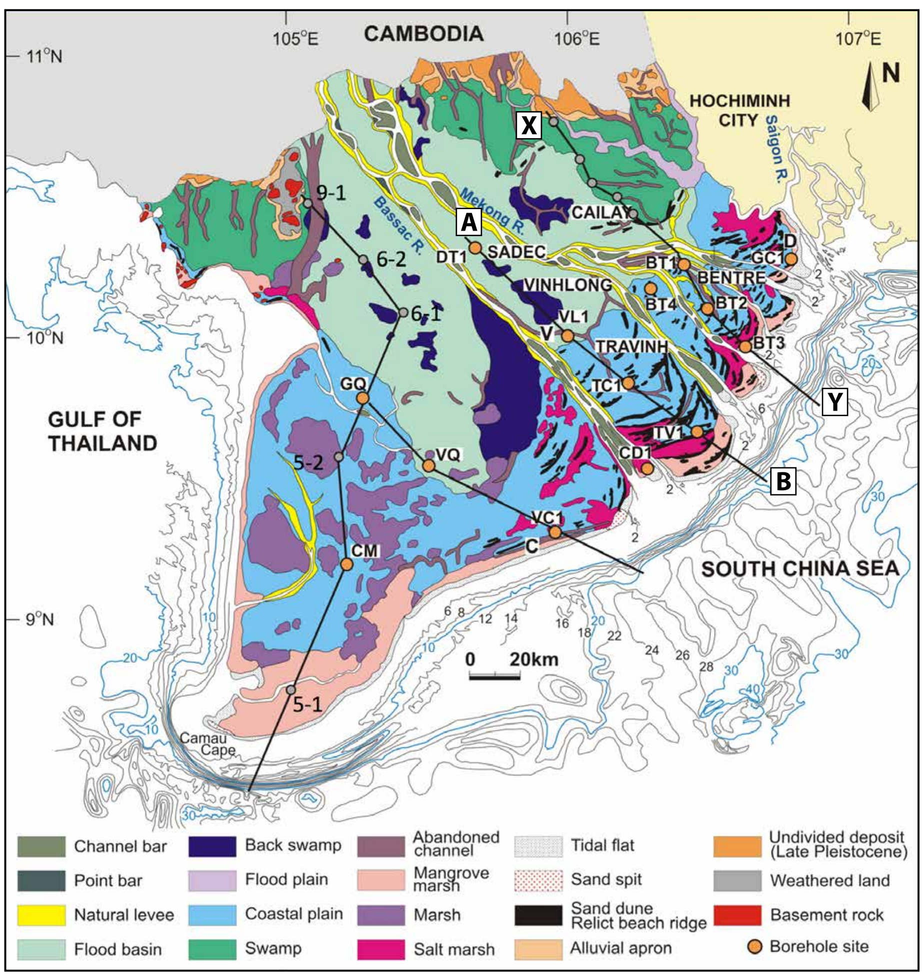


FIGURE 2. Geomorphological features of the Mekong Delta and the distribution of the deep boreholes drilled over the entire delta plain (from Ta et al., 2002, 2005; Nguyen et al., 2005). The selected cross sections X-Y and A-B are shown in Figure 3.

northeastward during the wet season and predominantly landward/southwestward during the dry season (Eidam et al., in press; Nittrouer et al., 2017, in this issue). Numerical simulations using the ROMS (Regional Ocean Modeling System) model also indicate that during the wet monsoon, extensive volumes of fluvial sediment are delivered and deposited near Mekong River distributary mouths (Xue et al., 2012). The model simulation shows that during the dry monsoon, a portion of sediment previously stored on the inner shelf is resuspended and transported away from the proximal delta area. A more recent Delft-3D model simulation of sediment transport (Thanh et al., in press) verifies the dominance of along-shelf transport toward the southwest during the dry monsoon. Near the southern end of the Ca Mau Peninsula, Unverricht et al. (2013) report that tidal processes in the subaqueous Mekong Delta can also have a significant influence on sediment resuspension and transport direction. The ebb-tidal currents, with their relatively high velocities, also act to transport suspended sediment over longer distances southwestward.

GEOPHYSICAL AND GEOCHEMICAL STUDIES OF MEKONG-DERIVED SEDIMENTATION: PROXIMAL VERSUS DISTAL ACCUMULATION

To further study the processes controlling proximal and distal sediment distribution, transport, accumulation, and formation of the Mekong clinoform, two research

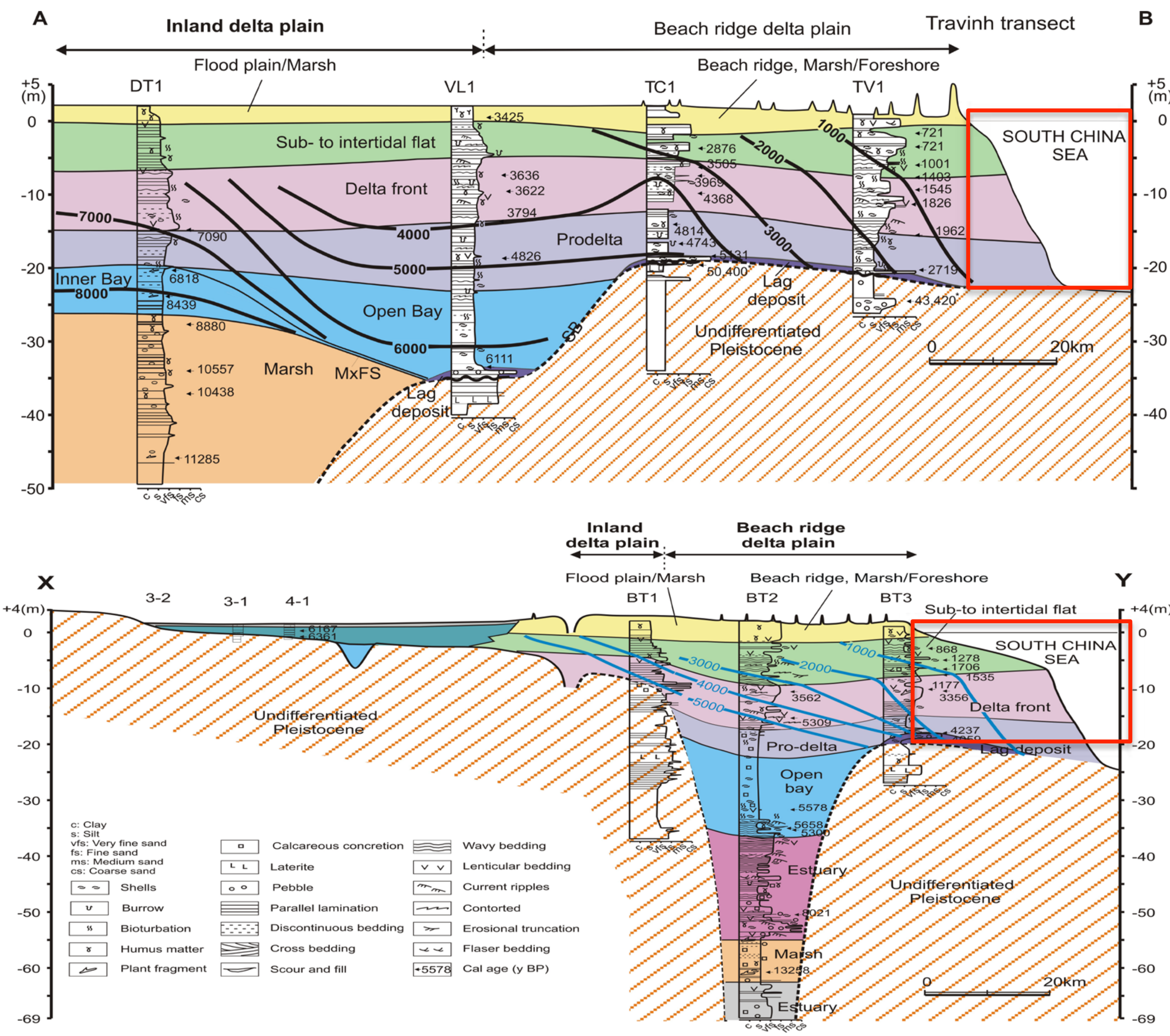


FIGURE 3. Selected cross-sections X-Y and A-B (see Figure 2) show Mekong Delta depositional facies with time lines from the middle to the late Holocene. The time line contours are from Ta et al. (2002, 2005) and Nguyen et al. (2005), using calibrated ^{14}C and optically stimulated luminescence ages. The red boxes highlight the subaqueous deltaic deposits on the shelf.

cruises were jointly conducted by a team of scientists from the Institute of Marine Geology and Geophysics, Vietnam; North Carolina State University, USA; and University of Washington, USA, in September 2014 and March 2015. Using an EdgeTech 0512i CHIRP subbottom profiler (frequency range: 0.5–12 kHz), a total of 62 high-resolution seismic profiles were acquired, spanning more than 1,000 km on the inner shelf adjacent to the modern Mekong River delta. Most profiles were collected seaward of four distributary channels: My Tho, Ham Luong, Co Chien, and Song Hau (Figures 4 and 5). Besides the CHIRP sonar profiles, 32 kasten cores, 19 Shipek surface grab samples, and numerous water samples were obtained during the two research cruises (see DeMaster et al., in press; Eidam et al., in press; J.P. Liu et al., in press).

Analysis of seismic profiles from the Mekong inner shelf reveals a typical clinoform structure with topset, foreset, and bottomset beds (Figure 5c). The Holocene subaqueous delta is ~15–20 m thick nearshore on the topset, which extends ~8–10 km seaward. The topset rolls over into the foreset at a water depth of ~4-6 m; the foreset then extends another 5–6 km and gradually transitions into the bottomset at ~20 m water depth (Figure 5).

In the northern and southern proximal portions of the continental shelf seaward of the Mekong's distributary mouths, J.P. Liu et al. (in press) observed, based on the 2014–2015 study, that the clinoform extends <15 km seaward between the 4.5 m and 20.5 m isobaths (Figures 4 and 5). In the central transition area, adjacent to the eastern side of the Ca Mau Peninsula, clinoform sediments become thinner (<10 m) but extend much farther (~20–35 km) from shore. No obvious topset facies have developed in this area, and seabed erosional features (e.g., truncated beds) are present. The area around the southern Ca Mau Peninsula has accumulated a very thick clinoform (up to 22 m), with steep foreset and bottomset beds in relatively deep water (up to 25 m). In the Gulf of Thailand, Mekong sediment extends 20–30 km farther seaward (to 26 m water depth). The amount of Holocene sediment associated with Mekong accumulation gradually diminishes in the northwestern part of the delta, where no major distributary channels connect the Mekong River to the Gulf of Thailand.

Based on CHIRP sonar profiles from the 2014–2015 and earlier studies, J.P. Liu et al. (in press) created an isopach map of Mekong-derived, late-Holocene sediment accumulation on the shelf (Figure 6a). Beyond the 15 m-thick proximal subaqueous delta that has formed adjacent to the distributary channel mouths (Figures 5 and 6a), a distal depocenter (up to 22 m thick) is growing ~300 km southwestward along the shelf, surrounding the Ca Mau Peninsula. J.P. Liu et al. (in press) calculated the area of the Mekong subaqueous delta and estimated the total volume of the deltaic sediment on the shelf. The results show that Mekong sediment covers more than 11,000 km^2 on the inner shelf, with a calculated total volume of ~120 km^3. Based on a dry bulk density of 1.0–1.2 g cm^{-3} in this area (Szczuciński et al., 2013; DeMaster et al., in press), the Mekong subaqueous delta has accumulated a total of 120–140 × 10^9 tons of sediment on the shelf in the past 1,000 years. More specifically, the Mekong proximal subaqueous delta has accumulated ~48 × 10^9 tons of sediment immediately off its distributary channels and ~36 × 10^9 tons in the central transition area. In the distal area, ~60 × 10^9 tons of sediment have accumulated around the Ca Mau Peninsula and in the Gulf of Thailand (Figure 6a).

Based on the maximum thickness (15–22 m) and the estimated age of the subaqueous deltaic deposits, the shelf-wide averaged sediment accumulation rate (SAR) on a time scale of ~1,000 years is up to 2 cm yr^{-1}, which agrees with ^{210}Pb-derived SARs (100-year time scale; DeMaster et al., in press) from cores collected during the 2014–2015 studies. The ^{210}Pb-based SARs are typically high (1 to >10 cm yr^{-1}) immediately off the distributary mouths on the northeastern side

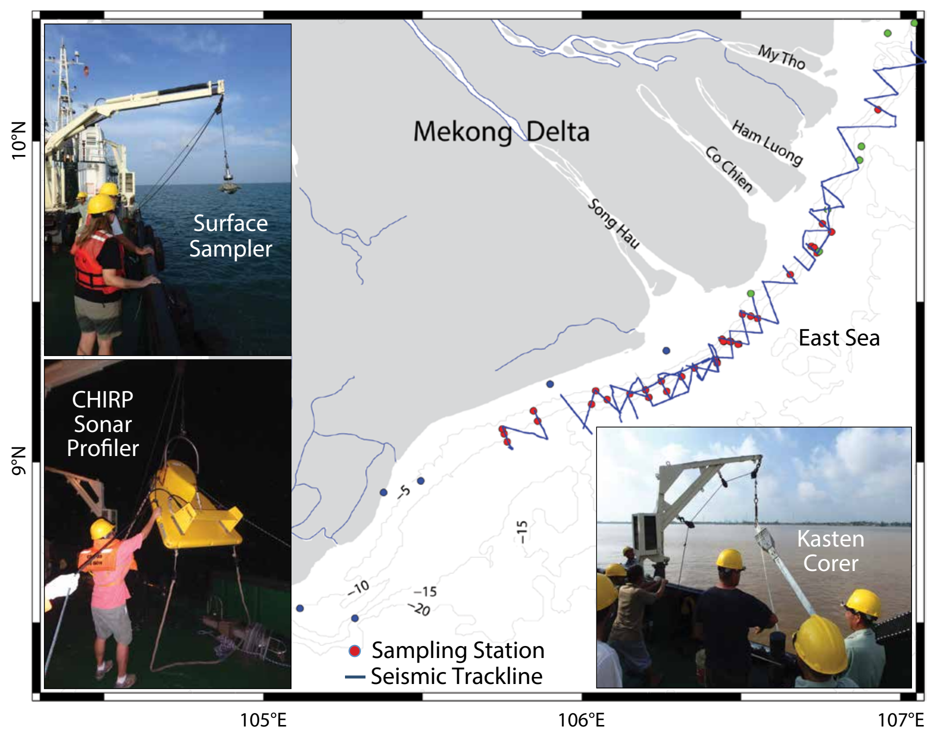


FIGURE 4. 2014–2015 ship track lines for the CHIRP subbottom seismic profiler survey and sediment sampling stations off the Mekong distributary channels in the eastern side of the delta. Photos show deployments of the surface grab sampler, CHIRP profiler, and kasten corer. (The blue and green stations are from other related cruises.)

of the delta (the proximal depocenter) as well as in the areas south and west of the Ca Mau Peninsula (Figure 6b). Most foreset locations have ^{210}Pb SARs between 1 cm yr^{-1} and 3 cm yr^{-1}, and the bottomset locations have slower rates of ~0.5 cm yr^{-1} (DeMaster et al., in press). On a 100-year time scale, regions offshore of the distributary mouths and south of the Ca Mau Peninsula are the two main depocenters, with sediment accumulation rates greater than those in the central transition area and the offshore Gulf of Thailand area. This pattern agrees well with the isopach map derived from CHIRP sonar data (Figure 6b). The geochemical, geological, and hydrodynamic characteristics of the sediments offshore of the Mekong distributaries are further discussed by other papers in this issue (i.e., Nittrouer et al., 2017, in this issue).

SHORELINE RETREAT AND SUBAQUEOUS DELTA EROSION

As outlined above, in the past 7,500 years, the Mekong River mouth has prograded 220 km seaward, built a 50,000 km^2 subaerial delta over the foundation of the former subaqueous delta, and built a 11,000 km^2 modern subaqueous delta. Based on the size and age of the Mekong Delta, the long-term average shoreline growth rate has been ~30 m yr^{-1}, and the net land gain rate has been 7 km^2 yr^{-1}. However, the modern Mekong Delta has been experiencing large-scale shoreline erosion and land loss in the past decade (Syvitski et al., 2009; Anthony et al., 2015). In addition, its river channels and the banks of the delta have also eroded strongly (Noh et al., 2013). Due to gradually increasing groundwater extraction over the past 25 years, on average the Mekong Delta has subsided by ~18 cm, with some areas sinking >30 cm (Erban et al., 2014; Minderhoud et al., 2017). The total coverage of mangrove forests on the Mekong Delta coastal zone decreased by 50% between 1965 and 2001, with most of these forests destroyed after 1995 (Thu and Populus, 2007). This resulted both

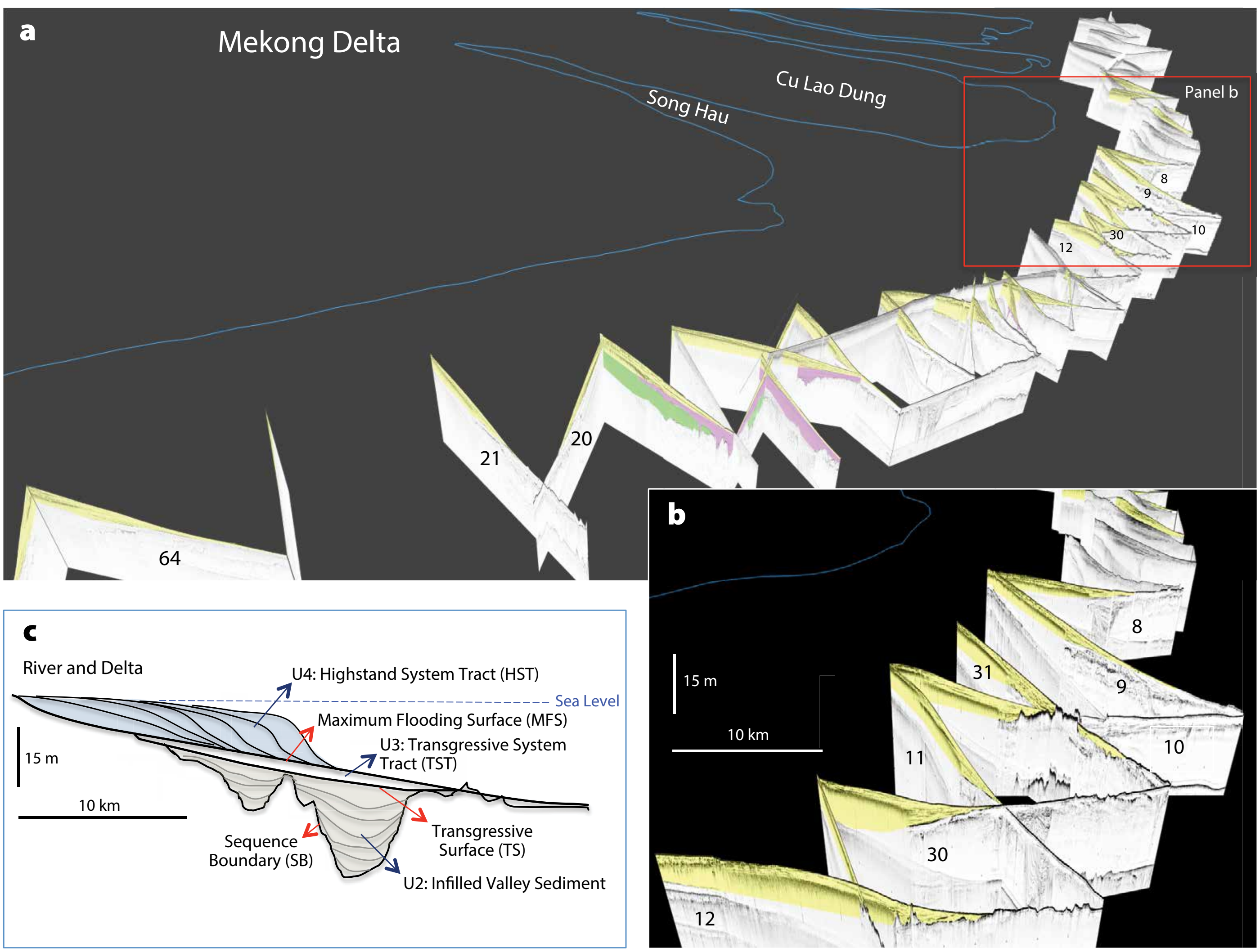


FIGURE 5. (a) Three-dimensional fence diagrams of CHIRP sonar profile results off the Mekong River mouth in 2014–2015, and (b) selected profiles 8-12 and 29-31 off the Mekong's main distributary channel, Song Hau. Yellow represents the Mekong subaqueous delta on the shelf, pink indicates infilled valley or channel sediment, and green areas are deposits from before the last glacial low stand. (c) Explanation of the seismic stratigraphic sequences in which the Highstand System Tract (HST) is the same as the yellow strata shown in (a) and (b).

from fragmentation (Seto and Fragkias, 2007) and from replacement by aquaculture operations and shoreline stabilization (Gupta, 2009). The exposure of the coast to waves and currents not only impacts the conditions for accumulation of sediment and progradation of mangroves but also complicates natural shoreline evolution (Phan et al., 2015; Fagherazzi, et al., 2017, in this issue).

During the pre-dam era, Mekong River sediment discharge was 160 million tons per year (Milliman and Syvitski, 1992). Milliman and Farnsworth (2011) reported the sediment discharge decreased to 110 million tons per year as a result of dam construction in the basin. More recent estimates for post-dam sediment discharge vary from less than 67 million tons per year to 145 million tons per year (C. Liu et al., 2013; Koehnken, 2014; Lu et al., 2014; Darby et al., 2016). Sediment transport in the Mekong Basin, especially downstream of Kratie, is still poorly understood. Currently, the serious lack of long-term and accurate sediment data for the Mekong River makes the sediment flux into the delta, and hence its potential impact on delta front evolution, difficult to assess (Walling, 2008; Wang et al., 2011; Wild and Loucks, 2014; Darby et al., 2016). In fact, not only dam construction but also land use change, climate variations, and hydrological cycles critically affect the sediment load in the Mekong Basin (Wang et al., 2011; Allison et al., 2017, in this issue). In addition, the estimated amount of annual sediment dredged from the lower Mekong River channels as a result of sand and gravel mining is ~56 Mt yr^{-1} (Bravard et al., 2013). Manh et al. (2015) reported that there might be as much as a 95% reduction in Mekong-derived sediment reaching the sea in the future.

Anthropogenic changes in the Mekong Delta, such as those mentioned above, are often difficult to observe in seismic profiles of the subaqueous deltaic clinoform. A more sensitive indicator of net deltaic growth on a time scale of decades is change in the shoreline as it responds to temporal variations in sediment supply, deposition and erosion, and sea level rise. Consequently, we have examined satellite images of the shoreline along the southern Vietnam coast over the past 43 years to document the transition in delta dynamics from a mode of constructive progradation to a mode of destruction and erosion (Li

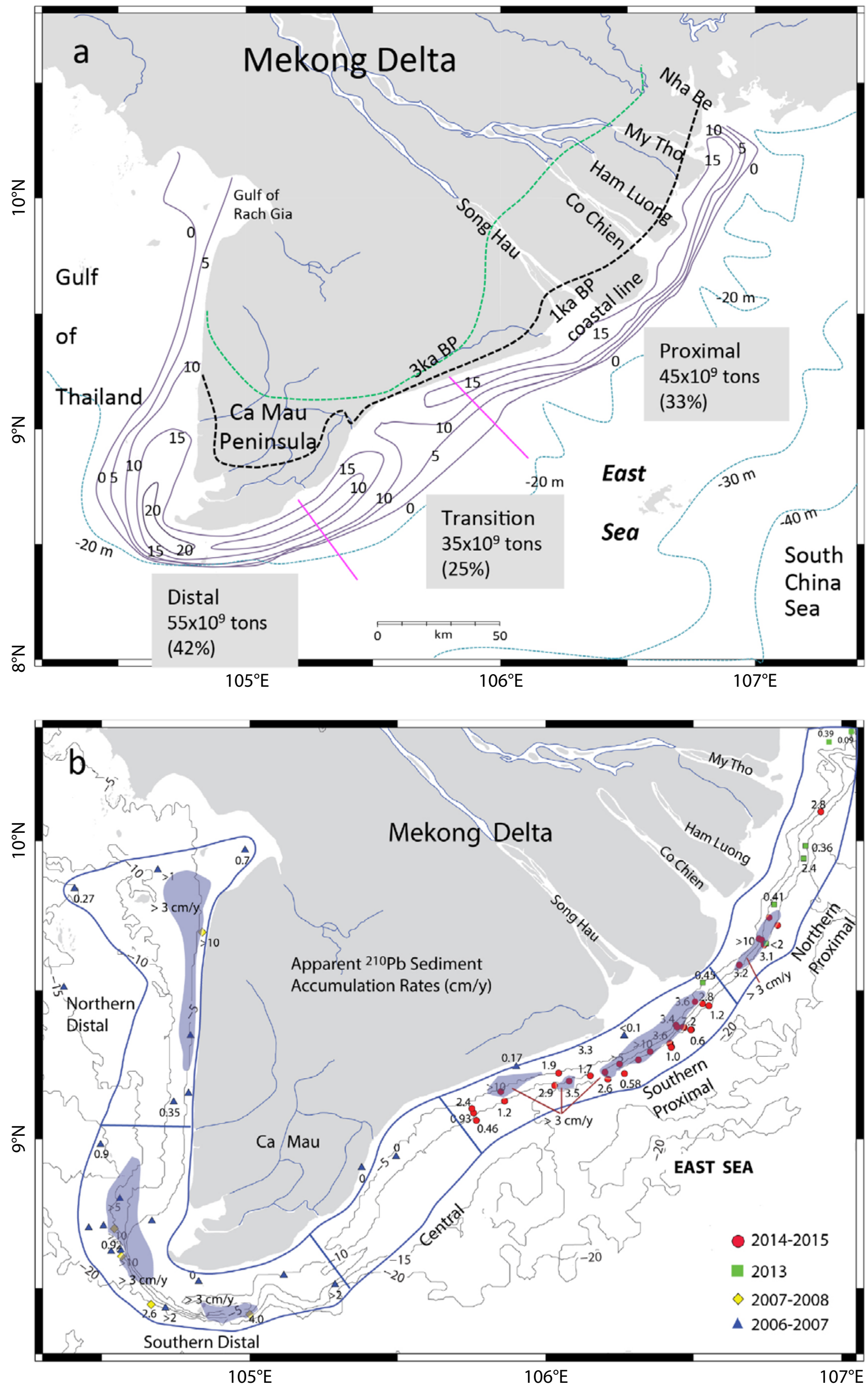


FIGURE 6. (a) Seismic-derived isopach map and budget estimates of the Mekong's late Holocene sediment accumulation on the shelves of the East Sea and the Gulf of Thailand (J.P. Liu et al., in press). Thickness is shown in meters. (b) Distributions of ^{210}Pb-derived sediment accumulation rates and mud depocenters over the proximal and distal deltaic deposits (DeMaster et al., in press).

et al., 2017). To compare our newly digitized shorelines to the shorelines widely used in GIS applications, we employed the Global Self-consistent, Hierarchical, High-resolution Shoreline Database (GSHHS; Wessel and Smith, 1996) as a reference base map, and then overlaid our new shorelines.

The Mekong deltaic coast was divided into four segments based on the shoreline change rate: proximal (river mouth) coast (Segment 1), Ca Mau east coast (Segment 2), Ca Mau west coast (Segment 3), and Gulf of Thailand coast (Segment 4). The results show almost 50% of the Mekong's shoreline is currently eroding (see Figure 7a). Segments 1 and 3 are the main accretionary segments, and Segments 2 and 4 are predominantly erosional (see Figures 7a and 8a,c). Furthermore, based on the trends and rate changes of accretion or erosion, Li et al. (in press) catalogued the coastal zone into four ranks: (1) increasing accretion, (2) decreasing accretion, (3) increasing erosion, and (4) decreasing erosion (Figure 7a). For example, the eastern shore of Cu Lao Dung and western side of Ca Mau are still growing (Figure 8a,c), but the southeastern side of Ca Mau is severely retreating (Figure 8b, Zone 2 in Table 1). In addition, the annual shoreline change rate has significantly decreased over the past four decades from 7.84 m yr^{-1} to −1.42 m yr^{-1} (Table 1). The land area gain of the entire delta decreased from 4.32 km^2 yr^{-1} in the 1970s to 1.0 km^2 yr^{-1} from 1995 to 2005, and the shoreline receded by −0.05 km^2 yr^{-1} from 2005 to 2015 (Table 1). There is a notable shift around 2005, coincident with the onset of river damming, when the Mekong Delta is characterized by both shoreline accretion/erosion and geomorphological changes. In addition, beginning in 2006, Mekong Delta subsidence rates have increased from 0.4–0.6 cm yr^{-1} to 0.9–1.1cm yr^{-1} (Minderhoud et al., 2017). Thus, we infer that dam construction and land subsidence might be major contributors to delta erosion. Other factors that contribute to these shoreline trends, such as sea level rise and sand mining, are further discussed by Allison et al. (2017, in this issue).

Not only are the modern Mekong Delta shorelines extensively retreating but our nearshore high-resolution subbottom profiling surveys reveal that the east-central portion of the subaqueous deltaic seabed is also strongly eroding (e.g., Line 07-9 and 07-11 in Figure 7b,c). Sediment cores, coupled with analyses of

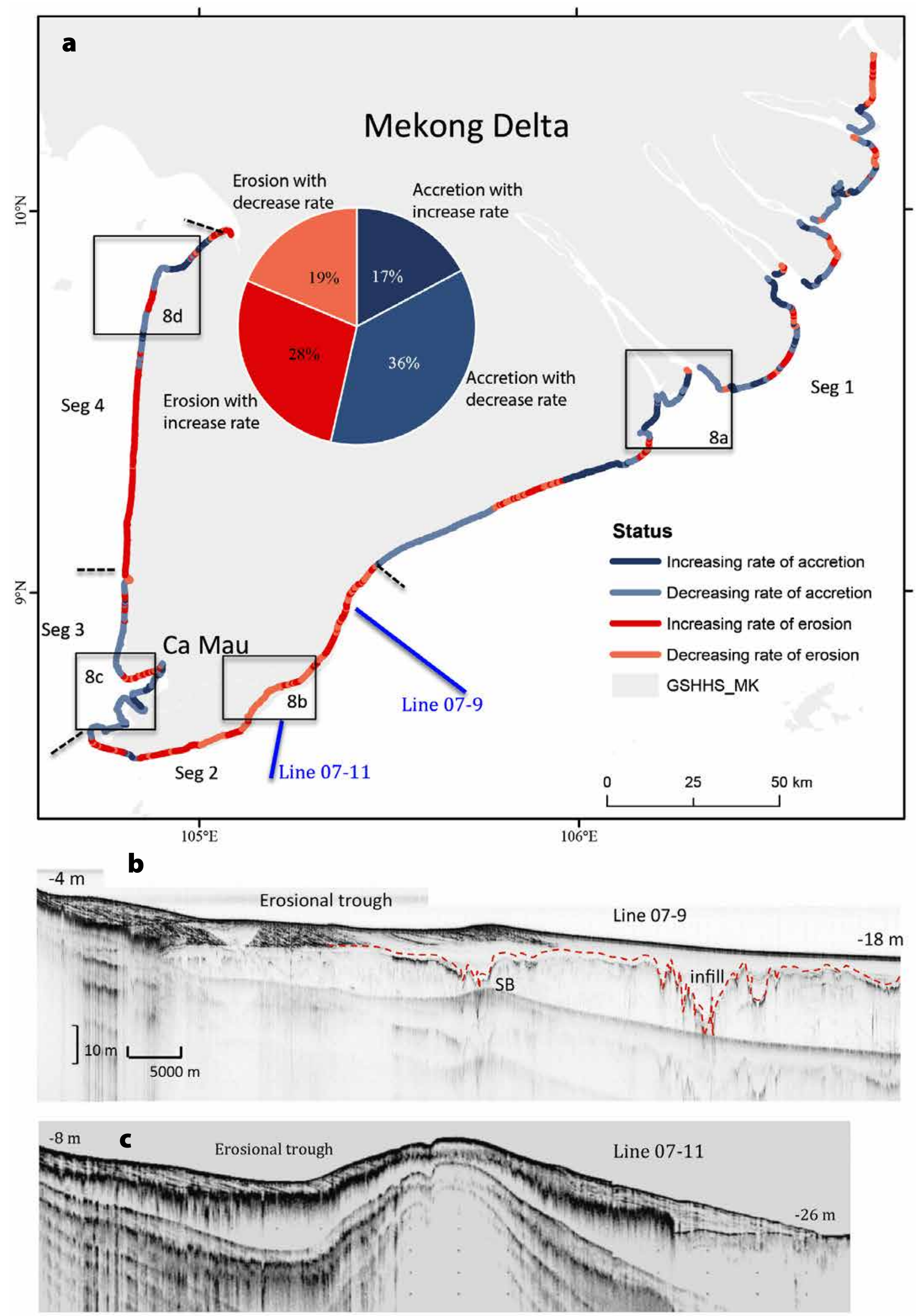


FIGURE 7. Mekong Delta shoreline changes between 1973 and 2015. (a) Spatial variations of coastal erosion versus accretion from Li et al. (2017). The pie chart shows the percentages of the coastline undergoing increased or decreased accretion and erosion. (b) and (c) CHIRP sonar profiles (Lines 07-9 and 07-11, respectively) showing a distinct erosional feature on the seafloor surface off the eastern Ca Mau Peninsula, where the shoreline has been retreating in recent decades (see Figure 8b).

^{210}Pb geochronology, indicate that there is little to no modern fluvial sediment accumulation on the seafloor off the central transition area (DeMaster et al., in press), which parallels the rapid shoreline retreat. Extensive seismic data analyses by J.P. Liu et al. (in press) indicate that an erosional trough also extends offshore of the southern Ca Mau Peninsula (see Figures 5 and 7). Numerical modeling of offshore areas using ROMS reveals that strong bed erosional stress is affecting the portion of the modern Mekong subaqueous delta east of the Ca Mau Peninsula, particularly during intense dry monsoon seasons (Xue et al., 2012). With an increase in the number of dams, ongoing sand mining, delta subsidence, and sea level rise, the Mekong Delta will likely continue to transition from a constructive to a destructive phase, with erosion of both continental shelf deposits and shorelines.

SUMMARY

Beginning in the early middle Holocene ~7,500 years ago, the Mekong River has prograded seaward >220 km and formed one of the largest delta plains in the world. Sediment cores and sequence stratigraphic studies show that the coastal zone and adjacent subaqueous delta on the shelf were mainly formed in the past ~1,000 years, and thus the Mekong subaqueous delta is young compared to the other Asian deltas. CHIRP sonar surveys off the Mekong subaerial delta reveal a subaqueous delta 10–20 m thick on the inner shelf (20–25 m water depths), hugging the modern shoreline and shoreface. This is a relatively small and young clinoform. The modern Mekong subaqueous delta extends only 15–30 km across the shelf; however, the clinoform extends >300 km southwestward along the shelf.

Based on seismic-derived sediment thicknesses and approximate age, the calculated thousand-year-time scale accumulation rate for the coast of southern Vietnam is ≤2 cm yr^{-1}, which is comparable to many of the ^{210}Pb-derived SAR values for the area (i.e., 1–10 cm yr^{-1} on the topset and foreset beds; DeMaster et al., in press; Eidam et al., in press). The

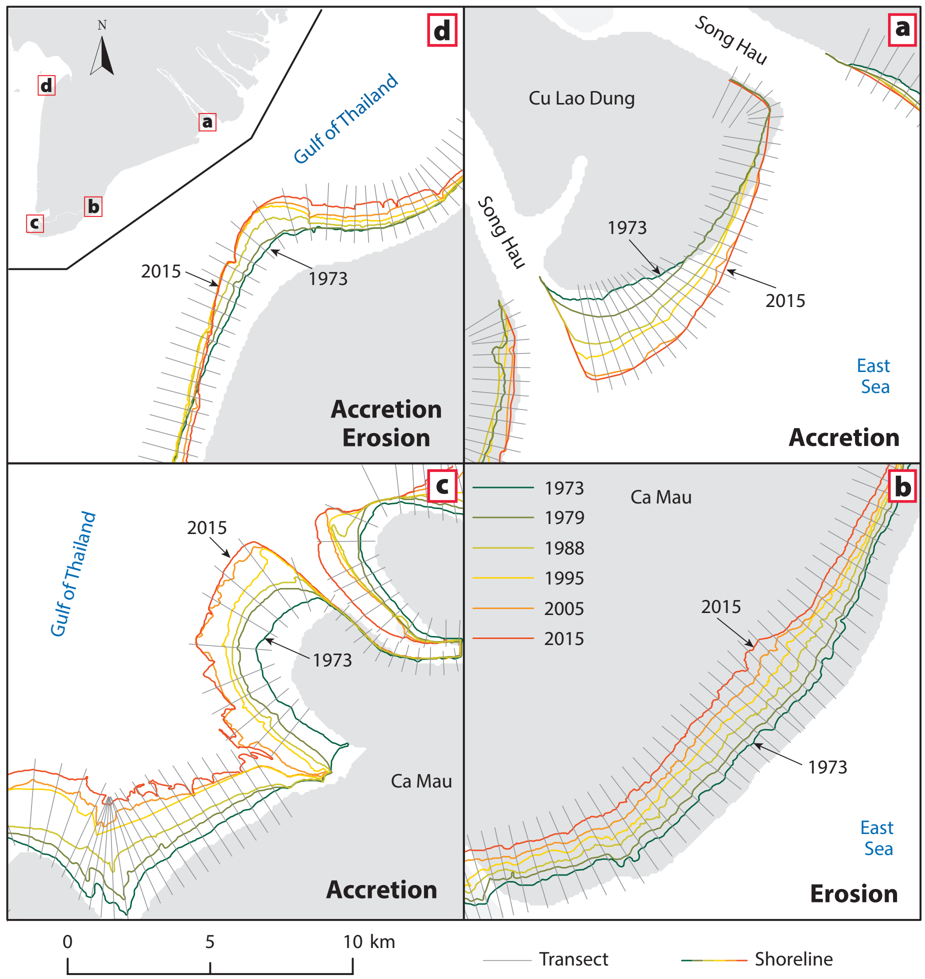


FIGURE 8. Selected locations showing detailed shoreline changes digitized from Landsat images collected between 1973 and 2015 (see locations in (a) and upper left in (d)). The shaded areas represent the land, and the coastline is based on the Global Self-consistent, Hierarchical, High-resolution Shoreline Database (GSHHS; Wessel and Smith, 1996).

TABLE 1. Mekong Delta's historical shoreline growth rates and land-area-gain rates, based on Landsat images from 1973 to 2015.

Shoreline Change (m yr^{-1})						
Zones	1973 – 1979	1979 – 1987	1987 – 1995	1995 – 2005	2005 – 2015	43 yr Average
1	8.66	8.07	12.07	9.68	4.52	**8.87**
2	−10.32	−8.00	−12.22	−13.15	−20.90	**−12.79**
3	28.15	23.33	27.55	19.48	11.83	**21.53**
4	8.43	2.48	3.57	−10.03	−4.53	**−1.66**
All Areas	**7.77**	**6.11**	**7.84**	**2.75**	**−1.42**	**4.36**

Area Change (km^2 yr^{-1})						
Zones	1973 – 1979	1979 – 1987	1987 – 1995	1995 – 2005	2005 – 2015	43 yr Average
1	1.94	2.01	2.96	2.25	1.15	**2.12**
2	−1.39	−1.87	−2.23	−1.75	−1.71	**−1.71**
3	2.82	2.16	1.71	1.09	1.64	**1.99**
4	0.95	0.35	−0.53	−0.56	−1.13	**−0.18**
All Areas	**4.32**	**2.64**	**1.91**	**1.03**	**−0.05**	**2.23**

total sediment volume of the subaqueous delta is estimated to be ~120 km^3, equivalent to 120–140 billion tons of sediment. Based on this estimate, the annual average accumulation of Mekong River sediment for the past 1,000 years has been ~120–140 million tons per year, which is within the estimated range of the historical annual sediment load (110–160 million tons).

Analysis of Landsat images from the past 43 years shows a significant decrease in the rate of shoreline accretion for the Mekong Delta. The rate of shoreline progradation has steadily decreased from 7.2 m yr^{-1} between 1973 and 1995 to 2.8 m yr^{-1} between 1995 and 2005 to −1.4 m yr^{-1} between 2005 and 2015. Shoreline migration rate is a sensitive indicator of change in delta growth mode, as this Mekong deltaic system appears to be transitioning in recent decades from a constructive (accretionary) mode to a destructive (erosional) mode. In the near future, the realization of planned dams, expansion of water withdrawal, uncontrolled riverbed mining, climate change, and other factors threaten to exacerbate the ongoing erosional degradation and submergence by rising sea level of the Mekong Delta.

REFERENCES

Allison, M.A., C.A. Nittrouer, A.S. Ogston, J.C. Mullarney, and T.T. Nguyen. 2017. Sedimentation and survival of the Mekong Delta: A case study of decreased sediment supply and accelerating rates of relative sea level rise. *Oceanography* 30(3):98–109, https://doi.org/10.5670/oceanog.2017.318.

Allison, M.A., H.D. Weathers III, and E.A. Meselhe. In press. Bottom morphology in the Song Hau distributary channel, Mekong River Delta, Vietnam. *Continental Shelf Research*, https://doi.org/10.1016/j.csr.2017.05.010.

Anthony, E.J., G. Brunier, M. Besset, M. Goichot, P. Dussouillez, and V.L. Nguyen. 2015. Linking rapid erosion of the Mekong River delta to human activities. *Scientific Reports* 5:14745, https://doi.org/10.1038/srep14745

Bird, M.I., W.E.N. Austin, C.M. Wurster, L.K. Fifield, M. Mojtahid, and C. Sargeant. 2010. Punctuated eustatic sea-level rise in the early mid-Holocene. *Geology* 38(9):803–806, https://doi.org/10.1130/G31066.1.

Bravard, J.P., M. Goichot, and S. Gaillot. 2013. Geography of sand and gravel mining in the Lower Mekong River. *EchoGéo* 26, https://doi.org/10.4000/echogeo.13659.

Brunier, G., E.J. Anthony, M. Goichot, M. Provansal, and P. Dussouillez. 2014. Recent morphological changes in the Mekong and Bassac river channels, Mekong delta: The marked impact of river-bed mining and implications for delta destabilisation. *Geomorphology* 224:177–191, https://doi.org/10.1016/j.geomorph.2014.07.009.

Coleman, J.M., and O.K. Huh. 2003. *Major World Deltas: A Perspective from Space*. Coastal Studies Institute, Louisiana State University, Baton Rouge, LA, USA, 74 pp.

Cosslett, T.L., and P. Cosslett. 2014. *Water Resources and Food Security in the Vietnam Mekong Delta*. Springer, 178 pp, https://doi.org/10.1007/978-3-319-02198-0.

Darby, S.E., C.R. Hackney, J. Leyland, M. Kummu, H. Lauri, D.R. Parsons, J.L. Best, A.P. Nicholas, and R. Aalto. 2016. Fluvial sediment supply to a mega-delta reduced by shifting tropical-cyclone activity. *Nature* 539(7628):276, https://doi.org/10.1038/nature19809.

DeMaster, D.J., J.P. Liu, E. Eidam, C.A. Nittouer, and T.T. Nguyen. In press. Determining rates of sediment accumulation on the Mekong shelf: Timescales, steady-state assumptions, and radiochemical tracers. *Continental Shelf Research,* https://doi.org/10.1016/j.csr.2017.06.011.

Eidam, E.F., C.A. Nittrouer, A.S. Ogston, D.J. DeMaster, J.P. Liu, T.T. Nguyen, T.N. Nguyen. In press. Dynamic controls on shallow clinoform geometry: Mekong Delta, Vietnam. *Continental Shelf Research*, https://doi.org/10.1016/j.csr.2017.06.001.

Erban, L.E., St.M. Gorelick, and H.A. Zebker. 2014. Groundwater extraction, land subsidence, and sea-level rise in the Mekong Delta, Vietnam. *Environmental Research Letters* 9(8):084010, https://doi.org/10.1088/1748-9326/9/8/084010.

Fagherazzi, S., K.R. Bryan, and W. Nardin. 2017. Buried alive or washed away: The challenging life of mangroves in the Mekong Delta. *Oceanography* 30(3):48–59, https://doi.org/10.5670/oceanog.2017.313.

Ge, Q., J.P. Liu, Z. Xue, and F. Chu. 2014. Dispersal of the Zhujiang River (Pearl River) derived sediment in the Holocene. *Acta Oceanologica Sinica* 33:1–9, https://doi.org/10.1007/s13131-014-0407-8.

Gupta, A. 2009. Geology and landforms of the Mekong Basin. Pp. 29–51 in *The Mekong*. I.C. Campbell, ed., Academic Press, San Diego.

Hanebuth, T.J., U. Proske, Y. Saito, V. Nguyen, and K.O.T. Thi. 2012. Early growth stage of a large delta: Transformation from estuarine-platform to deltaic-progradational conditions (the northeastern Mekong River Delta, Vietnam). *Sedimentary Geology* 261:108–119, https://doi.org/10.1016/j.sedgeo.2012.03.014.

Koehnken, L. 2014. *Discharge Sediment Monitoring Project (DSMP) 2009–2013 Summary & Analysis of Results*. Final Report, Mekong River Commission/Gesellschaft für Internationale Zusammenarbeit, Phnom Penh, Cambodia.

Li, X., J.P. Liu, Y. Saito, and V.L. Nguyen. In press. Recent evolution of the Mekong Delta and the impact of dams. *Earth Science Review*.

Liu, C., Y. He, D.E. Walling, and J.J. Wang. 2013. Changes in the sediment load of the Lancang-Mekong River over the period 1965–2003. *Science China Technological Sciences* 56(4):843–852, https://doi.org/10.1007/s11431-013-5162-0.

Liu, J.P., D.J. DeMaster, C.A. Nittrouer, E.F. Eidam, and T.T. Nguyen. In press. A seismic study of the Mekong subaqueous delta: Proximal versus distal accumulation. *Continental Shelf Research,* https://doi.org/10.1016/j.csr.2017.07.009.

Liu, J.P., A.C. Li, K.H. Xu, D.M. Veiozzi, Z.S. Yang, J.D. Milliman, and D.J. DeMaster. 2006. Sedimentary features of the Yangtze River-derived along-shelf clinoform deposit in the East China Sea. *Continental Shelf Research* 26:2,141–2,156, https://doi.org/10.1016/j.csr.2006.07.013.

Liu, J.P., K.H. Xu, A.C. Li, J.D. Milliman, D.M. Velozzi, S.B. Xiao, and Z.S. Yang. 2007. Flux and fate of Yangtze River sediment delivered to the East China Sea. *Geomorphology* 85:208–224, https://doi.org/10.1016/J.Geomorph.2006.03.023.

Liu, J.P., Z. Xue, K. Ross, H. Wang, Z. Yang, A. Li, and S. Gao. 2009. Fate of sediments delivered to the sea by Asian large rivers: Long-distance transport and formation of remote alongshore clinotherms. *The Sedimentary Record* 7:4–9.

Lu, X.X., M. Kummu, and C. Oeurng. 2014. Reappraisal of sediment dynamics in the Lower Mekong River, Cambodia. *Earth Surface Processes and Landforms* 39:1,855–1,865, https://doi.org/10.1002/esp.3573.

Manh, N.V., N.V. Dung, N.N. Hung, M. Kummu, B. Merz, and H. Apel. 2015. Future sediment dynamics in the Mekong Delta floodplains: Impacts of hydropower development, climate change and sea level rise. *Global and Planetary Change* 127:22–33, https://doi.org/10.1016/j.gloplacha.2015.01.001.

McLachlan, R.L., A.S. Ogston, and M.A. Allison. In press. Implications of tidally-varying bed stress and intermittent estuarine stratification on fine-sediment dynamics through the Mekong's tidal river to estuarine reach. *Continental Shelf Research,* https://doi.org/10.1016/j.csr.2017.07.014.

Mekong River Commission. 2005. *Overview of the Hydrology of the Mekong Basin*. Mekong River Commission, Vientiane Lao PDR.

Milliman, J.D., and K.L. Farnsworth. 2011. *River Discharge to the Coastal Ocean: A Global Synthesis*. Cambridge University Press, Cambridge, New York, 394 pp.

Milliman, J.D., and J.P.M. Syvitski. 1992. Geomorphic/tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers. *Journal of Geology* 100:525–544, https://doi.org/10.1086/629606.

Minderhoud, P.S.J., G. Erkens, V.H. Pham, V.T. Bui, L. Erban, H. Kooi, and E. Stouthamer. 2017. Impacts of 25 years of groundwater extraction on subsidence in the Mekong Delta, Vietnam. *Environmental Research Letters* 12(6):064006, https://doi.org/10.1088/1748-9326/aa7146.

Nittrouer, C.A., D.J. DeMaster, E.F. Eidam, T.T. Nguyen, J.P. Liu, A.S. Ogston, and P.V. Phung. 2017. The Mekong continental shelf: The primary sink for deltaic sediment particles and their passengers. *Oceanography* 30(3):60–70, https://doi.org/10.5670/oceanog.2017.314.

Nguyen, V.L., T.K.O. Ta, and M. Tateishi. 2000. Late Holocene depositional environments and coastal evolution of the Mekong River Delta, Southern Vietnam. *Journal of Asian Earth Sciences* 18:427–439, https://doi.org/10.1016/S1367-9120(99)00076-0.

Nguyen, V.L., T.K.O. Ta, M. Tateishi, I. Kobayashi, and Y. Saito. 2005. Holocene evolution of the Mekong River delta, Vietnam. *Journal of the Geological Society of Japan* 111(11):XXI, https://doi.org/10.5575/geosoc.111.11.XXI.

Noh, S., M. Choi, E. Kim, N.P. Dan, B.X. Thanh, N.T.V. Ha, S. Sthiannopkao, and S. Han. 2013. Influence of salinity intrusion on the speciation and partitioning of mercury in the Mekong River delta. *Geochimica et Cosmochimica Acta* 106:379–390, https://doi.org/10.1016/j.gca.2012.12.018.

Nowacki, D.J., A.S. Ogston, C.A. Nittrouer, A.T. Fricke, and P.D.T. Van. 2015. Sediment dynamics in the lower Mekong River: Transition from tidal river to estuary. *Journal of Geophysical Research* 120:6,363–6,383, https://doi.org/10.1002/2015JC010754.

Ogston, A.S., M.A. Allison, R.L. McLachlan, D.J. Nowacki, and J.D. Stephens. 2017. How tidal processes impact the transfer of sediment from source to sink: Mekong River collaborative studies. *Oceanography* 30(3):22–33, https://doi.org/10.5670/oceanog.2017.311.

Phan, L.K., J.S.M. de Vries, and M.J.F. Stive. 2015. Coastal mangrove squeeze in the Mekong Delta. *Journal of Coastal Research* 31(2):233–243, https://doi.org/10.2112/JCOASTRES-D-14-00049.1.

Ross, K. 2011. *Fate of Red River Sediment in the Gulf of Tonkin, Vietnam*. Master's thesis, North Carolina State University, 91 pp.

Schmitt, R.J.P., Z. Rubin, and G.M. Kondolf. In press. Losing ground: Scenarios of land loss as consequence of shifting sediment budgets in the Mekong Delta. *Geomorphology,* https://doi.org/10.1016/j.geomorph.2017.04.029.

Seto, K.C., and M. Fragkias. 2007. Mangrove conversion and aquaculture development in Vietnam: A remote sensing-based approach for evaluating the Ramsar Convention on Wetlands. *Global Environmental Change* 17(3–4):486–500, https://doi.org/10.1016/j.gloenvcha.2007.03.001.

Smajgl, A., T.Q. Toan, D.K. Nhan, J. Ward, N.H. Trung, L.Q. Tri, V.P.D. Tri, and P.T. Vu. 2015. Responding to rising sea levels in the Mekong Delta. *Nature Climate Change* 5(2):167–174, https://doi.org/10.1038/nclimate2469.

Stanley, D.J., and A.G. Warne. 1994. Worldwide initiation of Holocene marine deltas by deceleration of sea-level rise. *Science* 265:228–231, https://doi.org/10.1126/science.265.5169.228.

Syvitski, J.P.M., A.J. Kettner, I. Overeem, E.H.W. Hutton, M.T. Hannon, G.R. Brakenridge, J. Day, C. Vorosmarty, Y. Saito, L. Giosan, and R.J. Nicholls. 2009. Sinking deltas due to human activities. *Nature Geoscience* 2:681–686, https://doi.org/10.1038/ngeo629.

Szczuciński, W., R. Jagodziński, T.J.J. Hanebuth, K. Stattegger, A. Wetzel, M. Mitręga, D. Unverricht, and P. Van Phach. 2013. Modern sedimentation and sediment dispersal pattern on the continental shelf off the Mekong River delta, South China Sea. *Global and Planetary Change* 110:195–213, https://doi.org/10.1016/j.gloplacha.2013.08.019.

Ta, T.K.O., V.L. Nguyen, M. Tateishi, I. Kobayashi, and Y. Saito. 2005. Holocene delta evolution and depositional models of the Mekong River Delta, southern Vietnam. *SEPM Special Publication* 83:453–466, https://doi.org/10.2110/pec.05.83.0453.

Ta, T.K.O., V.L. Nguyen, M. Tateishi, I. Kobayashi, S. Tanabe, and Y. Saito. 2002. Holocene delta evolution and sediment discharge of the Mekong River, southern Vietnam. *Quaternary Science Reviews* 21:1,807–1,819, https://doi.org/10.1016/S0277-3791(02)00007-0.

Tamura, T., Y. Saito, V.L. Nguyen, T.K.O. Ta, M.D. Bateman, D. Matsumoto, and S. Yamashita. 2012a. Origin and evolution of interdistributary delta plains: Insights from Mekong River delta. *Geology* 40:303–306, https://doi.org/10.1130/G32717.1.

Tamura, T., Y. Saito, M.D. Bateman, V.L. Nguyen, T.K.O. Ta, and D. Matsumoto. 2012b. Luminescence dating of beach ridges for characterizing multidecadal to centennial deltaic shoreline changes during Late Holocene, Mekong River delta. *Marine Geology* 326–328:140–153, https://doi.org/10.1016/j.margeo.2012.08.004.

Tanabe, S., Y. Saito, Q.L. Vu, T.J.J. Hanebuth, Q.L. Ngo, and A. Kitamura. 2006. Holocene evolution of the Song Hong (Red River) delta system, northern Vietnam. *Sedimentary Geology* 187(1–2):29–61, https://doi.org/10.1016/j.sedgeo.2005.12.004.

Thu, P.M., and J. Populus. 2007. Status and changes of mangrove forest in Mekong Delta: Case study in Tra Vinh, Vietnam. *Estuarine, Coastal and Shelf Science* 71(1–2):98–109, https://doi.org/10.1016/j.ecss.2006.08.007.

Unverricht, D., W. Szczuciński, K. Stattegger, R. Jagodziński, X.T. Le, and L.L.W. Kwong. 2013. Modern sedimentation and morphology of the subaqueous Mekong Delta, southern Vietnam. *Global and Planetary Change* 110:223–235, https://doi.org/10.1016/j.gloplacha.2012.12.009.

van Maren, D.S. 2004. *Morphodynamics of a Cyclic Prograding Delta: The Red River, Vietnam*. Dissertation, Erdkunde, Faculty of Geosciences, Utrecht University, 182 pp.

Thanh, V.Q., J. Reyns, C. Wackerman, E.F. Eidam, and D. Roelvink. In press. Modelling suspended sediment dynamics on the subaqueous delta of the Mekong River. *Continental Shelf Research*, https://doi.org/10.1016/j.csr.2017.07.013.

Walling, D.E. 2008. The changing sediment load of the Mekong River. *Ambio* 37(3):150–157.

Wang, H.J., Y. Saito, Y. Zhang, N.S. Bi, X.X. Sun, and Z.S. Yang. 2011. Recent changes of sediment flux to the western Pacific Ocean from major rivers in East and Southeast Asia. *Earth-Science Reviews* 108:80–100, https://doi.org/10.1016/j.earscirev.2011.06.003.

Wessel, P., and W.H.F. Smith. 1996. A global, self-consistent, hierarchical, high-resolution shoreline database. *Journal of Geophysical Research* 101:8,741–8,743, https://doi.org/10.1029/96JB00104.

Wild, T.B., and D.P. Loucks. 2014. Managing flow, sediment, and hydropower regimes in the Sre Pok, Se San, and Se Kong Rivers of the Mekong basin. *Water Resources Research* 50(6):5,141–5,157.

WWF (World Wildlife Fund). 2016. Greater Mekong: A biological treasure trove. http://wwf.panda.org/what_we_do/where_we_work/greatermekong/discovering_the_greater_mekong/species/new_species.

Xing, F., E.A. Meselhe, M.A. Allison, and H.D. Weathers III. In press. Analysis and numerical modeling of the flow and sand dynamics in the lower Song Hau channel, Mekong Delta. *Continental Shelf Research*.

Xue, Z., R. He, J.P. Liu, and J.C. Warner. 2012. Modeling transport and deposition of the Mekong River sediment. *Continental Shelf Research* 37:66–78, https://doi.org/10.1016/j.csr.2012.02.010.

Xue, Z., J.P. Liu, D.J. DeMaster, V.L. Nguyen, and T.K.O. Ta. 2010. Late Holocene evolution of the Mekong subaqueous delta, southern Vietnam. *Marine Geology* 269:46–60, https://doi.org/10.1016/j.margeo.2009.12.005.

Xue, Z., J.P. Liu, and Q.A. Ge. 2011. Changes in hydrology and sediment delivery of the Mekong River in the last 50 years: Connection to damming, monsoon, and ENSO. *Earth Surface Processes and Landforms* 36:296–308, https://doi.org/10.1002/esp.2036.

ACKNOWLEDGMENTS

The authors are grateful for financial help and support from the US Office of Naval Research, Vietnam Academy of Science and Technology, NAFOSTED Vietnam project (105.01-2012.25), and give special thanks to the program managers for this project: Thomas G. Drake, Joan S. Cleveland, Errol G. Rowe, and Reginald A. Beach. Rich Nguyen provided tremendous assistance with all kinds of logistic concerns throughout the project. We are indebted to the tireless efforts of Charles A. Nittrouer and Andrea Ogston as the project leaders and editors, Mead Allison as a reviewer and editor, and Emily Eidam for inputs and editing. We also appreciate the efforts and contributions of our Vietnamese colleagues, particularly those graduate students, staff, and crew members who are not listed as coauthors. In addition, we are grateful for the assistance of Jennifer Glass and Deborah Nittrouer during the field portion of this study.

AUTHORS

J. Paul Liu (jpliu@ncsu.edu) and **David J. DeMaster** are Professors, Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, Raleigh, NC, USA. **Thanh T. Nguyen** is a scientist in the Vietnam Academy of Science and Technology (VAST) Institute of Marine Geology and Geophysics, Hanoi, Vietnam. **Yoshiki Saito** is Prime Senior Scientist, Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan, and Professor, Estuary Research Center, Shimane University, Matsue, Japan. **Van Lap Nguyen** and **Thi Kim Oanh Ta** are Senior Scientists, Institute of Resource Geography, VAST, Ho Chi Minh City, Vietnam. **Xing Li** is Professor, School of Geography, Geomatics and Planning, Jiangsu Normal University, Xuzhou, China.

ARTICLE CITATION

Liu, J.P., D.J. DeMaster, T.T. Nguyen, Y. Saito, V.L. Nguyen, T.K.O. Ta, and X. Li. 2017. Stratigraphic formation of the Mekong River Delta and its recent shoreline changes. *Oceanography* 30(3):72–83, https://doi.org/10.5670/oceanog.2017.316.