Fate of sediments delivered to the sea by Asian large rivers: Long-distance transport and formation of remote alongshore clinothems

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ABSTRACT

Recent studies show that the global flux of river-derived sediment reaching the coasts and oceans is about 15-19 x 10^9 tons per year. New sediment budgets for the major Asian river systems (e.g., Yellow, Yangtze, Mekong, Ganges-Brahmaputra, etc.) suggest that 30-50% of their sediment load has been retained in the lower channel reaches to form an extensive subaerial delta plain, while the rest is discharged to the sea. Of the sediment load reaching the ocean, about half has been found to accumulate near the river mouth as a proximal subaqueous delta clinothem. However, the remaining sediment is found to be transported up to 600-800 km alongshore, ultimately being deposited as a shore-parallel middle-shelf clinothem. These clinoform deposits are generally <100 km in across-shelf width, 20-40 m thick nearshore, and pinch-out gradually seaward at 40-90 m water depth. A secondary nearshore depocenter can usually be found along the shelf away from the river mouth, with mud-lobe accumulation up to 40-50 m thick locally. Except for a few systems with shelf-indenting canyons (e.g., Ganges-Brahmaputra and Indus), most of Asian river-derived sediments are trapped on the inner and middle shelf, unable to reach the deep ocean (i.e., >150 m) despite having been transported hundreds of kilometers from their mouths.

INTRODUCTION

Rivers are the major carriers delivering large amounts of land-derived freshwater, sediment, and natural elements to the global ocean. Collectively, the world's rivers annually discharge about 35,000 km^3 of freshwater and 20-22 x 10^9 tons of solid and dissolved sediment to the ocean (Milliman and Meade, 1983; Milliman and Syvitski, 1992). As a result rivers, especially large ones, play an important role in controlling the physical and biogeochemical features of estuaries and ocean margins (McKee et al., 2004; Meybeck et al., 2006; Bianchi and Allison, 2009). Recent analyses using large-scale watershed models suggest that, under pre-human conditions, worldwide rivers could have carried about 15.5 x 10^9 tons of sediments to the sea annually (Syvitski et al., 2005; Syvitski and Milliman, 2007). New estimates based on historical gauging data from thousands of rivers (Milliman and Farnsworth; in press) show that this number could be closer to 19 x 10^9 tons of suspended sediments per year. Of this total sediment flux, ~70% or ~13 x 10^9 tons is believed to discharge from the eastern and southern Asian Pacific and oceanic margins alone (Milliman and Meade, 1983; Milliman and Syvitski, 1992; Ludwig et al., 1996; Milliman, 1995).

In eastern and southern Asia, about one-third to one-half of river-derived sediments are trapped in the river's low reaches and contribute to extensive floodplain and delta plain development, for example the Yellow (Saito et al., 2000), Yangtze (Hori et al., 2002), Pearl (Zong et al., 2009), Red (Tanabe et al., 2003); Mekong (Nguyen et al., 2000; Ta et al., 2002), Ganges-Brahmaputra (G-B) (Goodbred et al., 2003), and Indus (Giosan et al., 2006). Among the remaining sediments delivered to the ocean, how much is trapped near the river mouth, and how much is able to reach the deep ocean is still not completely clear. This is an important question, since the flux and fate of river-derived material to the oceans play a key role in global environmental change (Bianchi and Allison, 2009), with up to 80% of global organic carbon being preserved in such marine deltaic deposits (Berner, 1982). In this paper we analyze data acquired from Asia's major rivers and deltas (i.e., Yellow, Yangtze, Pearl, Red, Mekong, Ganges-Brahmaputra) that quantitatively define the fate of these large river-derived sediments after being delivered to the coastal ocean.

BACKGROUND AND METHODS

The Himalayas are among the youngest and most active mountain ranges on the planet, with high relief, steep gradients, frequent tectonic activity, intensive Monsoon rainfall, and highly erodable rocks (Clift et al., 2008). Coupled with the seasonal melting of its ~15,000 glaciers and abundant monsoonal rainfall, the Himalaya and surrounding plateaus give rise to seven of the world's largest river systems and account for ~ 30% of the global fluvial sediment flux to the sea (Fig. 1; Milliman and Meade, 1983). Following the worldwide stabilization of sea level ~7000 yr BP, most modern river deltas began to form near their present locations (Stanley and Warne, 1994). We, therefore, focus on riverine sediment transport and depositional processes on the shelf starting from this middle Holocene sea-level highstand, delineating the distribution of river-derived sediments across the delta plain, subaqueous delta, alongshore clinoform, and portions possibly escaping to the slope or deep canyons. These sediment budgets are derived from extensive geological and geophysical surveys off those river mouths in the Bohai, Yellow, East China, and South China seas, using a high-resolution EdgeTech 0512 subbottom Chirp sonar profiler operated at 0.5-6 kHz.

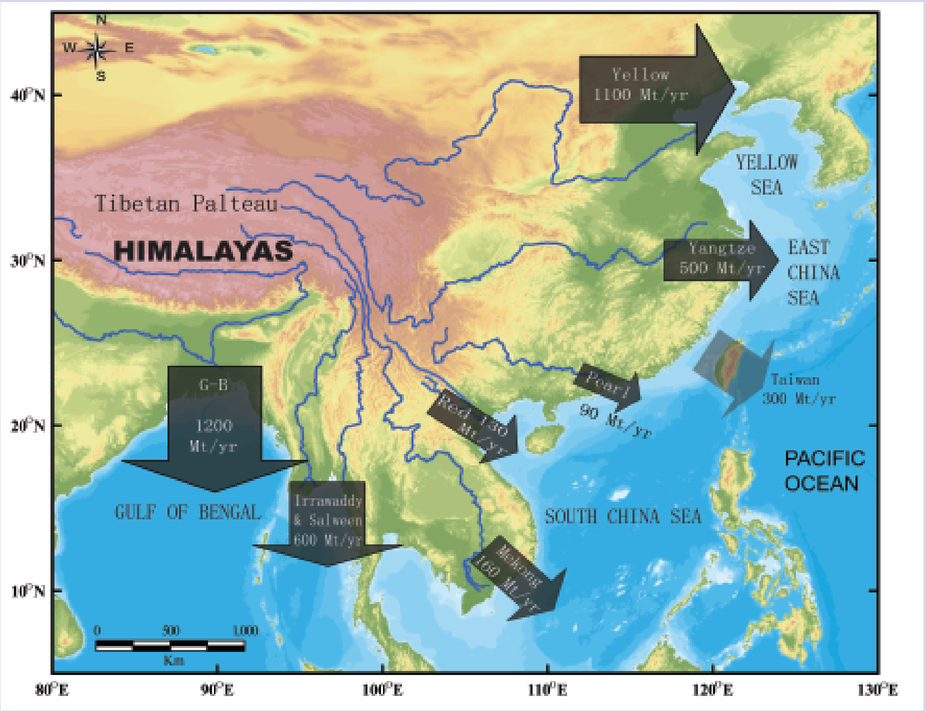

Figure 1. Distribution of the large Asian rivers and their historical annual sediment loads to the sea (Mt = million tons) (data from Milliman and Meade, 1983; Milliman and Syvitski, 1992; Robinson et al., 2007). Sediment fluxes from small mountainous rivers are not included here, such as the annual 300 Mt sediment discharge from Taiwan rivers (e.g., Kao et al., 2008; Liu et al., 2008).

RESULTS AND CASE STUDIES

The Yellow River

The Yellow River, which presently discharges into the western Bohai Sea, is widely recognized as one of the highest sediment loads on Earth, about 1 x 10^9 t/y (Milliman and Syvitski, 1992) (Figs. 1, 2). However, most of its fluvially derived sediment (>90%) appears to temporarily remain trapped within the modern deltaic system (Wright et al., 2001; Wright and Friedrichs, 2006). Yet extensive geological and geophysical surveys conducted in the North and South Yellow Sea reveal a prominent mud wedge that extends southward from the eastern tip of the Shandong Peninsula, some 350 km east of the present-day river mouth (Milliman et al., 1987; Alexander et al., 1991; Liu et al., 2004).

More recent high-resolution Chirp surveys conducted near the eastern tip of Shandong Peninsula reveal a unique, omega-shaped ("Ω"), distal subaqueous deltaic lobe that is locally up to 40 m thick and overlies the transgressive surface in the Yellow Sea (Fig.2). This distal clinothem is oriented along-shelf and has been deposited since the middle Holocene sea-level highstand, primarily by resuspended Yellow River sediments transported downdrift by coastal currents interacting with local waves, tides and upwelling (Yang and Liu, 2007). Over the past 7000 years, quantitatively analyzed sediment distribution in the Bohai and Yellow seas indicate that nearly 30% of the Yellow River-derived sediment has been resuspended and transported out of the Bohai Sea into the North and South Yellow Sea (Liu et al., 2002; Liu et al., 2004). Overall, modern Yellow River-derived sediments just reach 75m water depth in the central South Yellow Sea, about 700 km from the river mouth (Fig. 2); and so a very small fraction of the modern riverine sediment could escape the shelf or reach the Okinawa Trough.

The Yangtze River

Historically the Yangtze River discharged 500 x 10^6 tons of sediment to the sea annually (Fig.1). Over the last two decades, multiple geological and geophysical studies have been carried at the Yangtze river mouth and adjacent inner shelf to examine the fate of its fluvial sediment (e.g., DeMaster et al., 1985; McKee et al., 1983; Milliman et al., 1985, etc). Recent high-resolution seismic profiling and coring in the inner shelf of the East China Sea has revealed an elongated (~800 km) subaqueous deltaic deposit extending from the modern Yangtze River mouth south toward the Taiwan Strait (Fig. 3). This alongshore-distributed clinoform appears to overlie a

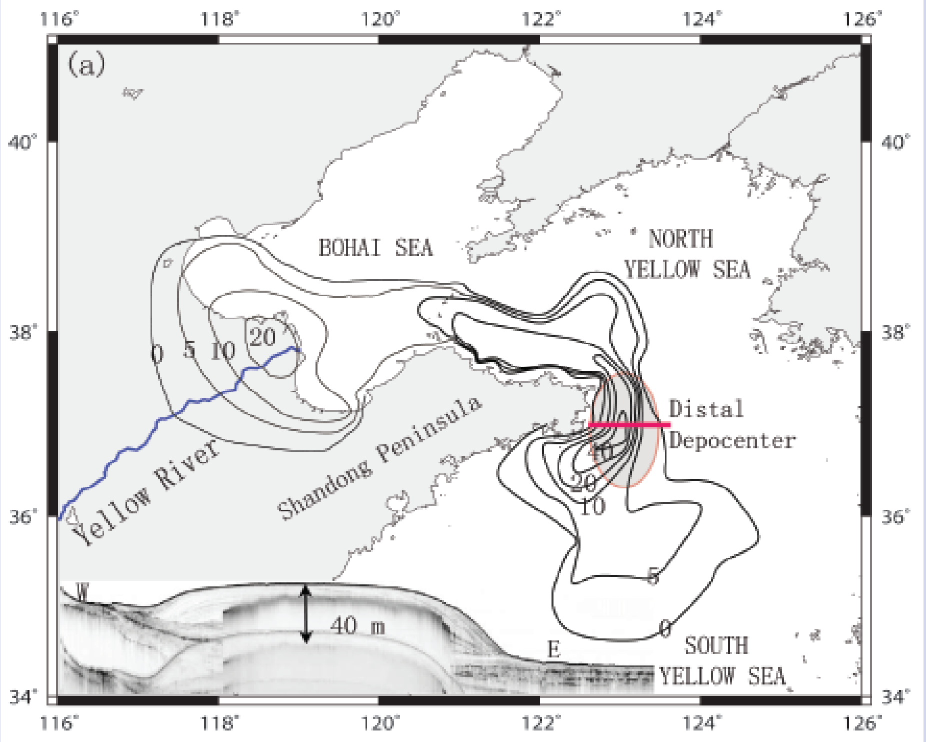

Figure 2. Isopach map of Yellow River-derived sediment discharged to the sea (isopachs in meters). A select seismic profile (red line) across the remote nearshore depocenter is also shown. (data from Liu et al., 2002; Liu et al., 2004; Yang and Liu, 2007).

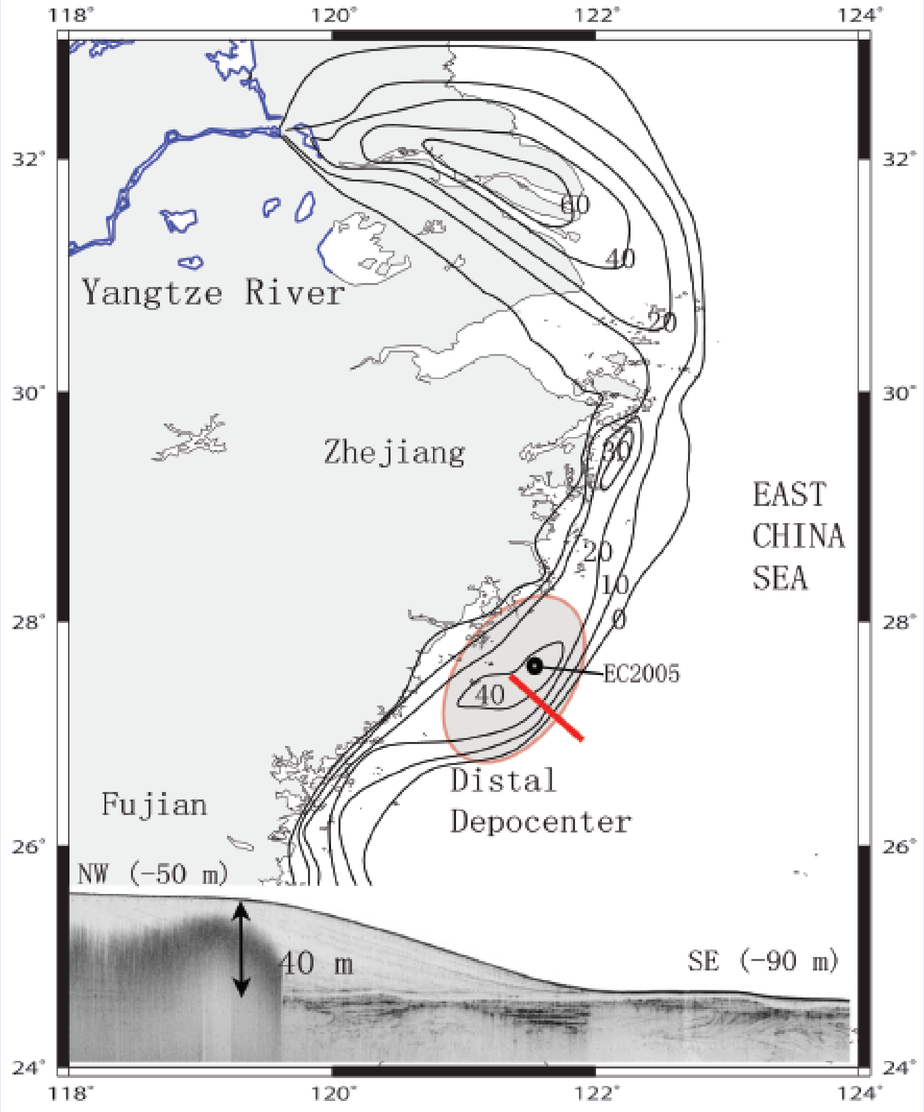

Figure 3. Isopach map of Yangtze River-derived sediment discharged to the sea (isopachs in meters). A select seismic profile (red line) across the remote nearshore depocenter is also shown (data from Liu et al., 2006; Liu et al., 2007). A deep sediment core (EC2005) drilled in 2005 has verified the mud's thickness and age (Xu et al., 2009b).

transgressive sand layer, thins offshore from ~40 m thickness at 20-30 m water depth to < 1-2 m between 60-90 m water depth. The across-shelf distribution is <100 km (Fig. 3). Clay mineral, geochemical, and grain-size analyses indicate that the Yangtze River is the primary source for this longshore-transported clinoform deposit (Liu et al., 2006; Xiao et al., 2006; Xu et al., 2009a; 2009b).

Total sediment volume of the clinothem is estimated to be about 4.5 x 10^{11} m^3, which represents about 32% of the total Yangtze-derived mud to the sea; the rest is believed to have been trapped in Yangtze's estuary and deltaic system (Liu et al., 2007). The East China Sea's strong tides, waves, coastal currents, winter storms, and offshore upwelling appear to have each played a role in trapping most of these Yangtze-derived sediments on the inner shelf and transporting them southward (Gao, 2007; Liu et al., 2007). The center of this remote deposition has been located on the inner shelf about 400 km south of the river mouth (Fig. 3). Subsequent drilling of this distal depocenter (Fig. 3: site EC2005) has verified its thickness, Holocene age, and Yangtze River sediment origin (Xu et al., 2009a; 2009b).

The Pearl River

The modern Pearl River estuary and delta was developed near its apex at about 6800 yr BP when the local sea level reached its present level (Zong et al., 2009). Most previous studies have focused on the delta plain and estuary (e.g. Owen, 2005; Zong et al., 2006), but to better understand the fate of Pearl River sediment discharged to the sea, we have acquired high-resolution Chirp sonar profiles from the inner shelf of the South China Sea. Combined with onshore borehole data (Zong et al., 2009) we have established a general isopach map of Holocene-age Pearl River-derived mud on the shelf (Fig. 4). Preliminary analysis indicates that the majority of Pearl River sediments are trapped inside the estuary, although sediments that do escape to the shelf are transported alongshore but have not yet formed a large remote nearshore depocenter (Fig. 4).

The Mekong River

The Mekong River, one of the largest rivers in Southeast Asia, flows southward from the Tibetan Plateau to the South China Sea through the Indochinese Peninsula. It has a wide, low-lying delta (Fig. 1), which is the third largest in the world (Nguyen et al., 2000). The river's current sediment discharge is about 160 x 10^6 tons/yr. Compared with other rivers, the Mekong River has a smaller drainage area than the Yangtze, Mississippi, or Ganges-Brahmaputra, but its sediment yield is about twice that of the Mississippi and nearly equal to that of the Yangtze. Recently, the subaerial Mekong River delta has been intensively studied (Nguyen et al., 2000; Ta et al., 2002).

Our recent geophysical and geological surveys off the modern Mekong river mouth in the South China Sea and Gulf of Thailand indicate the majority of the Mekong River derived sediment to the sea has been transported away from the river mouth and deposited along the shore and around the tip of Camau Peninsula (Fig. 5). Near Camau a remote nearshore depocenter is developing about 300 km downdrift of its Mekong River sediment source. In contrast, along the eastern side of the Mekong delta, even close to the river mouth, there is very limited across-shelf transport of modern sediments (<20-km from shore).

Ganges and Brahmaputra Rivers

The Ganges-Brahmaputra (G-B) river annually discharges ~1200 x 10^6 tons of fluvial sediments to its delta plain and the Bay of Bengal. Initial Holocene development of the delta begins ~ 11,000 yr BP under enhanced monsoon rainfall and slowing postglacial sea level (Goodbred and Kuehl, 2000; Goodbred et al., 2003) (Fig.1). High-resolution seismic reflection profiles also reveal a large subaqueous delta with characteristic clinoform stratigraphy, which is estimated to trap about 30% of the G-B derived sediment (Kuehl et al., 1997). Different from the south and southeast Asian river systems, the Bengal shelf is incised by a major canyon, the Swatch of No Ground,

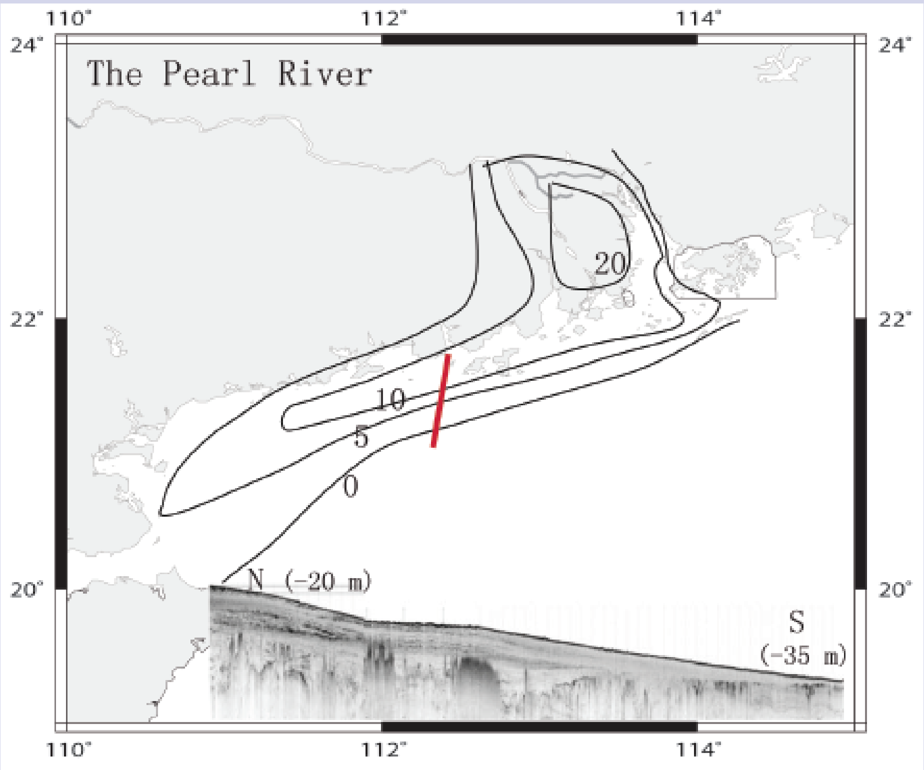

Figure 4. Isopach map of Pearl River-derived sediment discharged to the sea (isopachs in meters). A select seismic profile (red line) across the remote alongshore-distributed sediment is also shown. (onshore data from Zong et al., 2009).

which directly connects the Ganges-Brahmaputra rivers to the Bengal Fan. It is believed that this canyon behaves like a conduit in transporting a large portion of the G-B sediment load to the deep ocean (Hubscher and Spiess, 2005; Kuehl et al., 1997; Kottke et al., 2003).

DISCUSSION AND CONCLUSIONS

Previous studies have found that rapid sediment deposition and centers of accumulation are located offshore of many large river mouths, such as Ganges-Brahmaputra, Mississippi, Nile, Yellow rivers, etc. (Kuehl et al., 1997; Stanley and Warne, 1994; Bornhold et al., 1986). Typically, there is an across-shelf morphology where the subaqueous delta progrades directly off the river mouth, and are characterized by flat topsets, steeper foresets, and gradual bottomset deposits. It is the nearshore oceanographic processes that transport fluvial sediments across the shallow-water topset area to the deep-water bottomsets that result in rapid accumulation on the middle shelf and development of the sigmoid-shaped ("S") clinoform (i.e., Kuehl et al., 1986). Important mechanisms that influence across-shelf sediment transport include wind-driven flows, internal waves, wave-orbital flows, infragravity phenomena, buoyant plumes, and surf-zone processes (Nittrouer and Wright, 1994).

At the same time, more studies of suspended-sediment transport on high-energy continental shelves indicate a strong along-shelf transport with only a minor across-shelf component, e.g. Amazon, Po, Ebro, Eel, Columbia, etc (Wright and Nittrouer, 1995; Driscoll and Karner, 1999; Nittrouer et al., 1996; Cattaneo et al., 2004). The combined effect of oceanographic processes (tidal, wave and current) redistributed most of large river-derived sediments along the shelf, extending hundreds of kilometers from the river mouths and the proximal subaqueous deltas. For example the Amazon River's suspended mud is transported alongshore and accumulates > 1500 km from the river mouth (Nittrouer et al., 1986; Allison et al., 2000).

Our studies here indicate that the sediments of the large Asian large rivers are also transported alongshore great distances from the river mouth, often forming a large-scale alongshore clinothem far from its source (Figs. 2-6). Different from the classic sigmoid shape, the distal clinoforms observed in the Yellow Sea indicate an omega-shape (Ω), with a bidirectional (landward and seaward) dipping convex sedimentary body (Yang and Liu, 2007). Along-shelf sediment transport dramatically modifies the morphology of deltas, subaqueous delta, and mid-shelf deposits and imparts a shore-parallel trend clinoform deposit.

The clinoform deposits described here may contain important sedimentary records for climate and/or environmental changes. For example, since the sediment of a clinoform deposit is derived mainly from the "parent"

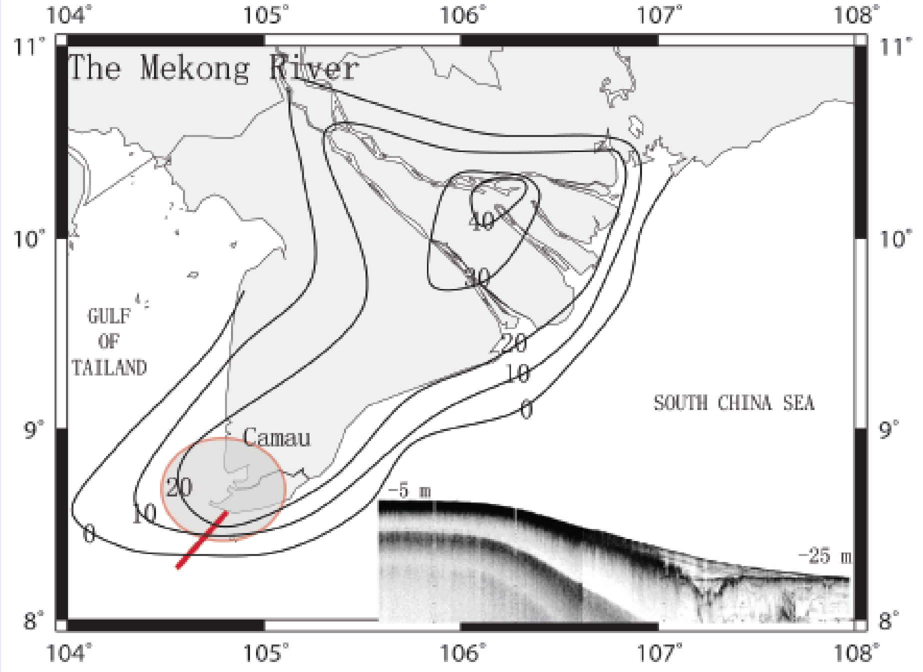

Figure 5. Isopach map of Mekong River-derived sediment discharged to the sea (isopachs in meters). A select seismic profile (red line) across the remote nearshore depocenter is also shown. (onshore data from Nguyen et al., 2000; Ta et al., 2002)

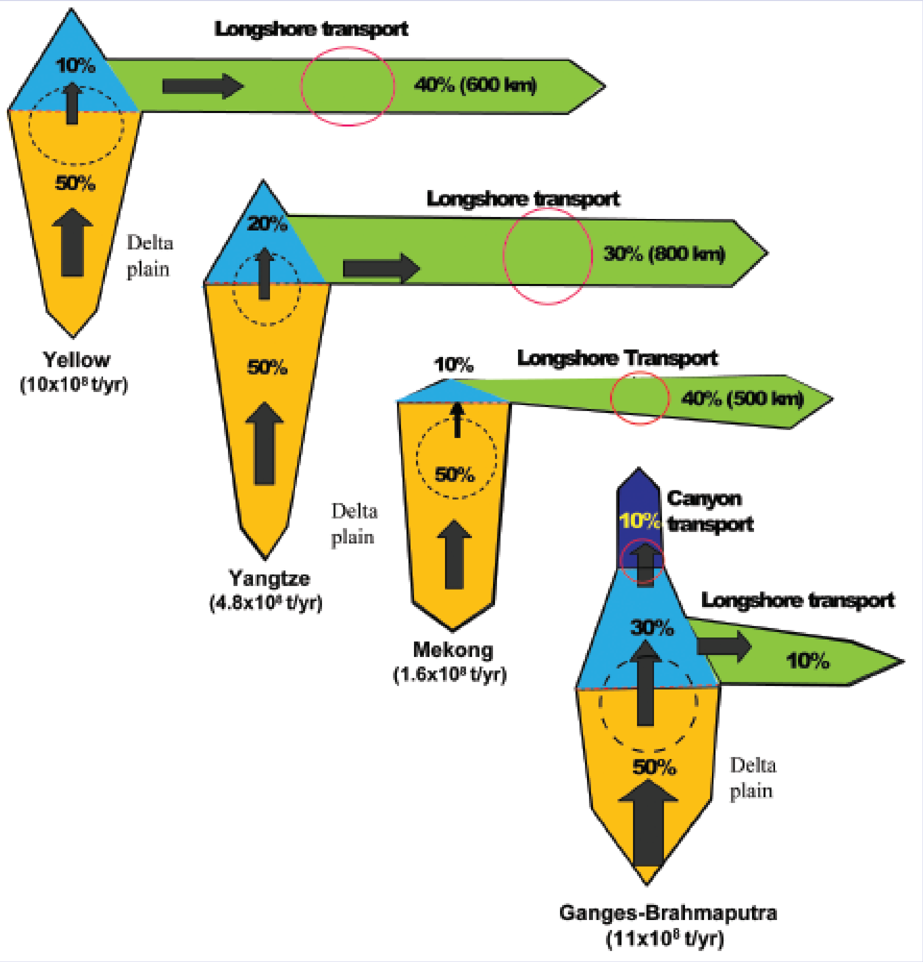

Figure 6. Conceptual model of the fate of Asian large river-derived sediment delivered to the coasts and seas. The dash circles represent the proximal depocenter near the river mouth, the red circles represent the remote nearshore depocenter 300-400 km away from the river mouth.

river, variations in river discharge due to runoff, land use, and sediment yields from the catchment (Syvitski and Milliman, 2007) may be recorded in the stratigraphy and morphology of these deposits. Recently, attempts have been made (Xiao et al., 2006) to analyze the influence of climate changes on the Yangtze-derived mud deposits on the East China Sea inner-shelf, using data sets of grain size and geochemical parameters obtained from sediment cores. Although the shelf deposits are complex in terms of sequence continuity and hydrodynamic reworking, this research topic is worth exploring in the future.

Large river systems are generally buffered from high-frequency variations in discharge because of their size, and so typically have steady long-term water and sediment fluxes. From previous studies, it is observed that ~30-50% of large-river sediments are trapped within the river mouth estuary and lower delta plain, while the larger remaining fraction is discharged to the sea (Fig. 6). Of the total discharge ~20-30% typically accumulates on the shelf adjacent to the river mouth, often as a mid-shelf subaqueous delta system. However, a substantial portion of fluvial sediment discharge to the ocean (~30-40%) is found to be transported along the shore far from the river mouth (600-1500 km), where it may form an alongshore clinoform deposit that is generally < 100 km in width and up to 20-40 m thick (Fig. 6). Thus, except for a few cases with shelf-indenting canyons (G-B, Indus, and Danube, etc.), most of modern river-derived fluvial sediment is not able to reach the deep ocean directly. In this way large river systems may take a more positive, widespread, and constructive role in the development of coastal and nearshore areas than previously considered.

ACKNOWLEDGEMENTS

Financial supports of a series of projects are from China and US National Science Foundation, Office of Naval Research, Chinese Academy of Science and North Carolina State University. We are grateful for the careful and thorough review and editing from Steve Goodbred.

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Accepted November 2009