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Historical Changes in the Ganges-Brahmaputra Delta Front

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ABSTRACT

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Detailed early chartmaking by the British East India Company and the Royal Navy in India and present-day Bangladesh provide one of the most accurate databases available to track the evolution of a major delta front over the last 200 years. Digital databases of shoreline position and shallow bathymetry of the Ganges-Brahmaputra delta front were constructed using geo-referenced and projection-corrected early and modern charts, and using LANDSAT imagery. In contrast with earlier published studies, these databases indicate the Ganges-Brahmaputra has an actively prograding subaerial delta: an average of approximately 7.0 km^2/yr of new land have accreted in the river mouth region since 1792. Digitate shoals, forming in association with accretion of elongate islands in the river mouth region, are coalescing in 8–15 m water depth to form a relatively coarse-grained lobate feature that is prograding over the muddy, subaqueous delta on the inner shelf. The morphology of shoal growth suggests the Ganges-Brahmaputra mouth has evolved eastward over the late Holocene as a series of digitate shoal-channel complexes. West of the active river mouth in historical times, the delta front is sediment starved and is undergoing retreat at rates of about 1.9 km^2/yr.

ADDITIONAL INDEX WORDS: Ganges-Brahmaputra Delta, shoreline change, deltaic sedimentation, coastal subsidence, Bangladesh, India.

INTRODUCTION

The Ganges-Brahmaputra River is one of the three largest riverine sources of water and sediment to the world ocean; 1.06 billion tons/yr according to Milliman and Syvitski (1992). The Ganges and Brahmaputra rivers are young, sediment-rich rivers that drain the Himalayan highlands, and, joining with the Meghna River in Bangladesh, enter the Bay of Bengal through several distributary channels (Figure 1). Sediment and water discharge peaks during the May-November monsoon season. The delta front of the Ganges-Brahmaputra is strongly dominated by tidal processes: tides are semi-diurnal with a range of up to 4 m, and generate shore-normal tidal currents up to 300 cm/sec (Barua *et al.*, 1994). Barua (1990) notes that during periods of low river discharge, the eastern distributary channels (Hatia and Sandwip) serve as flood channels, while net seaward water transport occurs in the Tetulia and Shahbazpur channels to the west (see Figure 2).

Approximately 85% of Bangladesh is underlain by the deltaic and alluvial deposits of these rivers (Alam *et al.*, 1990; Umitsu, 1990), which have formed the 5–15-km-thick Bengal Basin (Curray *et al.*, 1982) since the early Tertiary. A majority of the tidally influenced zone (Figure 1) of the delta is less than 3 m above mean sea level (MSL), with other areas of Holocene alluvium generally less than +15 MSL. The Madhupur tract in central Bangladesh (Figure 1) is a highly-weathered Pleistocene clay uplifted to +10–30 MSL that separates the 18th century Old Brahmaputra channel from the modern (Jamuna) channel of the Brahmaputra.

Research has shown that other large, energetic river mouths, such as the Amazon (Nittrouer *et al.*, 1986; Kuehl *et al.*, 1986), Huangho (Alexander *et al.*, 1991), and Fly (Harris *et al.*, 1993) exhibit delta growth in the form of a subaqueous mud clinoform on the continental shelf. It is believed that tidal focusing and wave-induced seabed reworking inhibit sediment accumulation in the river mouth region, preventing formation of a "Mississippi-model" subaerial delta (Nittrouer *et al.*, 1986). This produces a throat-shaped river mouth containing sandy shoals and islands. Recent studies by Kuehl *et al.* (1989, in press) have identified a subaqueous mud delta on the inner shelf off the Ganges-Brahmaputra River mouths. Sedimentation rates on the foreset beds of this feature reach 9 cm/yr in some areas (Kuehl *et al.*, 1989). Eysink (1983) published evidence, based on a comparison of early (1770's-1780's) maps of the British geographer James Rennell, that while the location of channels and shoal islands in the river mouth area is extremely dynamic, little or no net shoreline progradation has occurred in the last 200 years. Rennell's data led Coleman (1969) and Eysink (1983) to suggest that loss offshore from the strong tidal currents, combined with regional subsidence in the Bengal Basin, offset the large sediment input at the river mouth. Modern texts (Friedman *et al.*, 1992; p. 478) now suggest the Ganges-Brahmaputra mouth region is an estuary, without a subaerial deltaic component.

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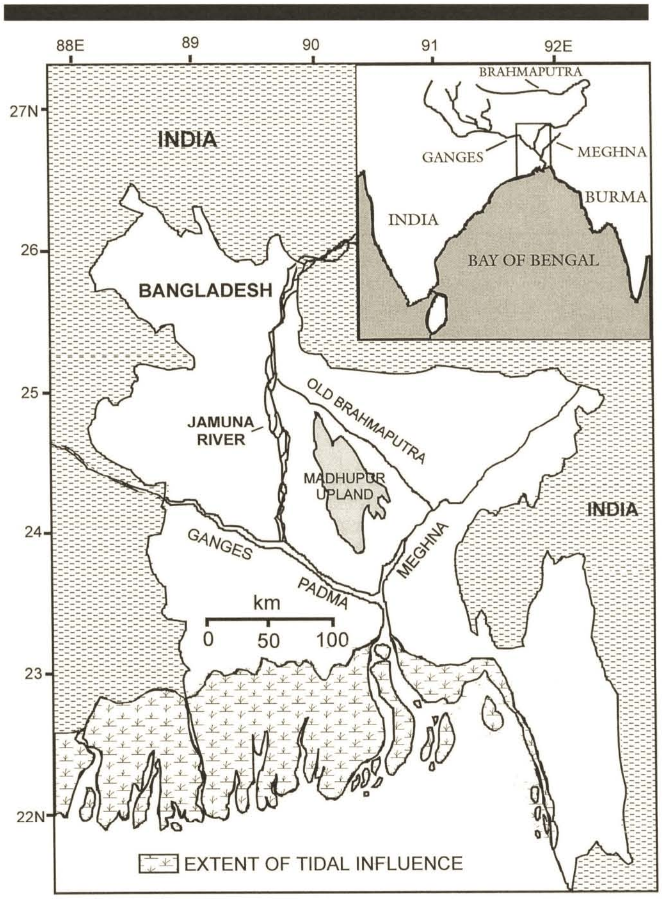

Figure 1. Map of the study area.

While saline penetration occurs in the distributary mouths of the river during low discharge periods (BARUA, 1990), several lines of evidence suggest the description of the Ganges-Brahmaputra mouth as an estuary should be reevaluated. Unlike tropical rivers like the Amazon and Fly, which carry about 70% clay, the Ganges-Brahmaputra is a relatively coarse-grained system, with a sediment load composed of 80% silt and sand (COLEMAN, 1969). In addition, the Ganges-Brahmaputra is the only major river mouth classified as an "estuary" that has a high mean suspended sediment load (1,799 mg/l; LISITZEN, 1972). Detailed chartmaking of the Bay of Bengal conducted by the British East India Company and the Royal Navy in the 18th and 19th centuries was not utilized by EYSINK (1983) in concluding that there has been no shoreline progradation in historical times. The present study was undertaken to evaluate these additional historical sources, and to apply modern image processing and GIS technology to the study of processes in the Ganges-Brahmaputra river mouth. The objective of this paper is to reexamine the question of whether the Ganges-Brahmaputra River has a subaerial deltaic component in order to gain insight into the process of delta formation in energetic river mouths.

MAP GENERATION

Early maps and charts utilized in the present study were obtained as full-size microphotographic transfers from the Map Room and India Office of the British Library. Shoreline geometries for 1792, 1840, and 1904/8 were created using LACAM (1794), LLOYD (1840), and ADMIRALTY (1904;1908), respectively. A LANDSAT mosaic of images from 1984 was used to obtain modern shoreline boundaries. In addition to shoreline position, the 1837–1840 survey of the delta front by Commander Lloyd of the Royal Navy (LLOYD, 1840) includes over 10,000 soundings taken at quarter-fathom intervals in water depths of less than 50 m. This information was compared with modern charts (DMA, 1990) to examine bathymetric changes along the Ganges-Brahmaputra delta front.

Chart information was digitized and georeferenced on MAPINFO© software using a series of fixed points (*i.e.,* city locations, surveyed benchmarks). Charts from 1792 and 1840 required a longitude correction to compensate for systematic errors in early benchmark surveys. All maps/charts were geocorrected to a standard Mercator projection. LANDSAT images were georeferenced using PCI© image analysis software. The VERTICAL MAPPER© module in MAPINFO was used to calculate area changes between map sets.

RESULTS

Shoreline Change

Table 1 demonstrates that the river mouth region of the Ganges-Brahmaputra delta front east of the Haringhata River (Figure 2, 4) has experienced net land accretion between 1792 and 1984 that averages 7.0 km^2/yr. Comparison of the 1792 and 1840 surveys suggest an even more rapid land accretion rate (14.8 km^{2}yr). However, the large longitude correction and small scale (1:850,000) indicate a relatively large error associated with the 1792 survey. Using Commander Lloyd's more reliable data from 1840 (plotted in Figure 3), gives an average accretion rate of 4.4 km^2/yr. The 1904 survey of the eastern part of the delta is an exception to the overall trend of net land accretion. Although not listed on the 1904 chart, it is evident from the digital overlays that some of the 1904 shorelines are identical with 1840, and hence, are older data plotted for areas not remapped in the 1904 survey. This problem was not observed in the 1908 survey of the western delta (west of the Haringhata River).

West of the Haringhata River and away from the active river mouths, the delta front is undergoing net land loss. Erosion rates of the islands and peninsulas that form the western delta front are progressive over the period (1792–1984); land loss over this area averages 1.9 km^2/yr. Land loss increases to the west (Figure 3); seaward-facing shorelines adjacent to the east bank of the Hoogly River in India have retreated as much as 3–4 km since 1840. Large tidal channels that extend inland have experienced considerable migration (Figure 3), but show no evidence of net infilling or widening. However, minor tidal channels are only plotted in the early data to about 30 km inland from the sea face of the delta, and, hence, any net effect of their growth or silting up is unknown.

Bathymetric Change

Table 2 displays the volume gain or loss in seabed elevation in the river mouth region (Figure 3,4) and in the extreme

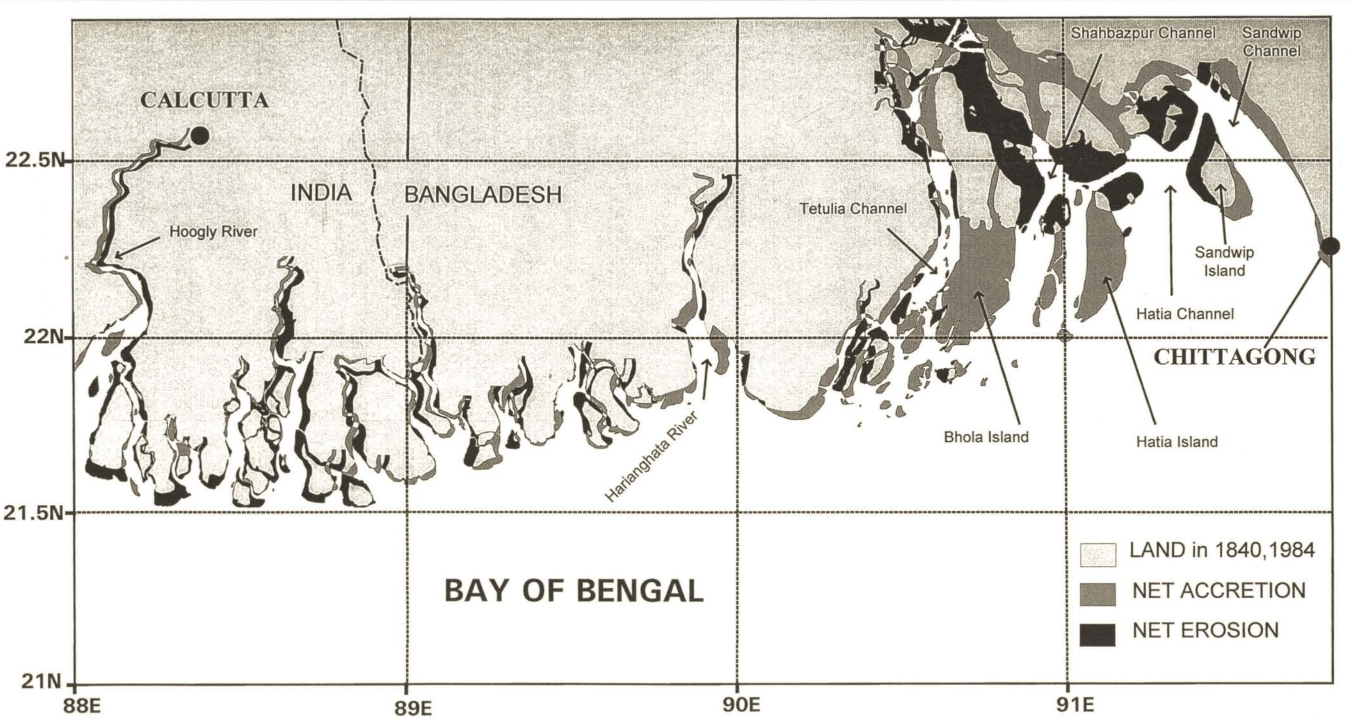

Figure 2. Map overlay of shoreline positions from the Lloyd survey in 1840 and a 1984 LANDSAT mosaic showing land accretion and erosion occurring in the intervening 144 years. Note the concentration of accretion in the area of the present mouths of the Ganges-Brahmaputra (90–92°E), and the net erosion in the older, sediment starved deltaic deposits to the west. Comparison extends inland along distributary channels to the limit of the 1840 survey. Modern surveys show that the tidal channel network continues further inland and several old distributaries (*e.g.*, the Hoogly) remain connected to the Ganges or Padma River channels.

western delta (Figure 4) between 1840 and 1990. The central delta front region is not included in these calculations because these areas were not remapped in the 1990 survey. Each depth interval between isobaths in Table 2 reflects a 1990 region where changes (either higher or lower elevation) from the 1840 bathymetry are recorded as volumes and averaged for the entire region. These regions are then averaged overall to provide a net value of volume change in areas of less than 50 m water depth (40 m in the western delta). Land areas are assumed to be 2 m above mean sea level for the calculations. This methodology does not differentiate between bathymetric changes caused by seabed accretion/erosion from changes induced by regional subsidence/uplift.

Table 1. *Shoreline land area change of the delta front between 1792 and 1984.*

Date	River Mouth Area (km^2)	Western Delta Area (km^2)
1792	5,122.4	5,500.0
1840	5,830.7	5,359.1
1904/8	5,447.3**	5,255.4
1984	6,468.3	5,131.9
Total (1792–1984)	**+1,345.9**	**−368.1**

**May reflect reuse of 1840 data in some areas

DISCUSSION

Pathways of River Sediment Dispersal

Comparison of historical and modern data for shorelines and shallow bathymetry demonstrate the progressive growth of a deltaic feature at the mouths of the Ganges-Brahmaputra River in Bangladesh. These results contradict the EYSINK (1983) study. This is attributed to the inaccuracy of the earliest surveys used by Eysink, as well as difficulties in georeferencing maps possessing different projections without modern computer tools. EYSINK (1983) does note that Survey of Pakistan maps of the river mouth region in 1940 and 1963 show net shoreline progradation that averages 12.1 km^2/yr; in relative agreement with the 7.0 km^2/yr since 1792 observed in the present study considering the nature of the data and the probable interannual variations in river sediment supply and marine reworking (*i.e.*, as by cyclones). The Eysink total also includes areas further upriver, beyond the boundaries of the historical datasets utilized in the present study. Significantly, UMITSU (1990) places the maximum sea level transgression on the delta front at 6.5–7 ka. Comparing this paleoshoreline with the modern indicates about 30,000–35,000 km^2 of shoreline progradation, an average of 4–5 km^2/yr; in close agreement with the most reliable data from the Lloyd survey (4.4 km^2/yr).

Considering only the more reliable data from LLOYD (1840)

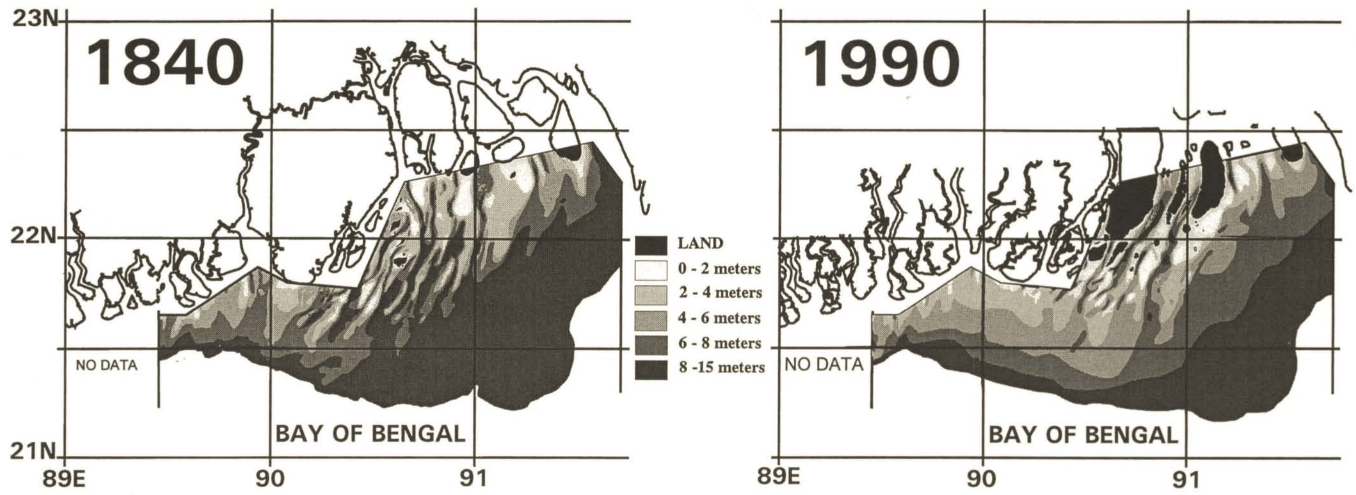

Figure 3. Bathymetry of the delta front in the area of the Ganges-Brahmaputra River mouths from the Lloyd survey in 1840 and from Defense Mapping Agency charts (1990). Within the study box (12,530 km²), islands and their associated subaqueous shoals have accreted seaward as much as 50 km during the period. The 6–8 m isobaths also demonstrate that individual digitate shoals are coalescing offshore to form a lobate feature of coarse grained material on the inner shelf.

in Table 1 and 2, and assuming an average land elevation change from MSL to +2 m, an estimated 9.7×10^6 tons of annual land accretion (at a sediment density of 1100 kg/m³) occurs in the river mouth region (*i.e.,* east of the Haringhata River). This first-order estimate serves to illustrate that only 1–2% of the annual sediment Ganges-Brahmaputra sediment discharge is necessary to account for observed land accretion rates. West of the Haringhata to the mouth of the Hoogly River in India, there has been net shoreline erosion since 1840, equivalent to an annual release of 3.5×10^6 tons of sediment. These areas, distal to the present river sediment point source, are probably eroding in response to eustatic and

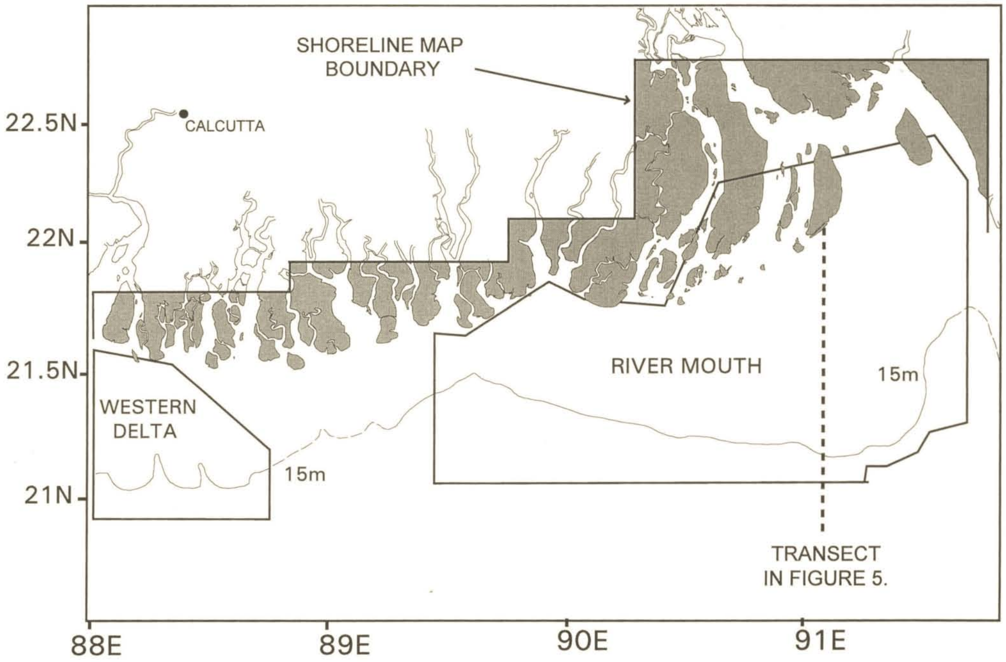

Figure 4. Map of the shoreline and bathymetric boundaries used for calculating land accretion/erosion and changes in sediment volume offshore. Offshore areas in the area of 89°E are not included because they have not been remapped since the Lloyd survey. Location of the transect in Figure 5 is noted.

Table 2. *Delta front bathymetric change between 1840 and 1990.*

Water Depth (m)	Volume of Gain(+)/Loss(−) in Seabed Elevation (× 10^7 m^3) River Mouth	Western Delta
Land (+2 m elevation)	(+) 203.8	(−) 3.7
0–5	(−) 738.1	(+) 107.9
5–10	(+) 2,960.1	(−) 300.2
10–15	(+) 188.9	(−) 20.6
15–20	(+) 398.9	(−) 482.7
20–30	(+) 749.3	(−) 148.0
30–40	(+) 684.4	(−) 19.3
40–50	(+) 379.1	No data
Net value	**(+) 4,826.6**	**(−) 866.4**

subsidence-induced rises in relative sea level (RSL). Westward sediment fining and increased sediment accumulation rates on the Bay of Bengal inner shelf (Kuehl *et al.*, 1989) suggest that shelf sediment dispersal is toward the west, and hence, sediment erosion in the western delta is not contributing to the land accretion in the river mouth area.

Figure 3 demonstrates that the bulk of accretion in the Ganges-Brahmaputra river mouth area occurs subaqueously on the inner shelf between 90° and 92°E longitude. These are the topset (<20 m water depth) and upper foreset (20–50 m) areas of the subaqueous delta identified by Kuehl *et al.* (1989; in press). Within the 12,530 km^2 study area outlined in Figure 4, bathymetric changes between 1840 and 1990 indicate an increase in sediment volume of 3.0×10^{10} m^3 (22.1×10^7 tons/yr) in the topset area and 1.8×10^{10} m^3 (13.3×10^7 tons/yr) in the upper foreset area (assuming $\rho_{dry} = 1100$ g/cm^3). This corresponds to an estimated 21% and 12.5% of the annual Ganges-Brahmaputra sediment budget, respectively, or an average of 2.8×10^4 tons/km^2/yr. Together, these estimates for the last 150 years exceed a Holocene average for the entire delta front of 27% (including the entire subaqueous delta) calculated by Kuehl *et al.* (in press) using Umitsu's (1990) Holocene stratigraphic thicknesses since the onset of estuarine infilling. In the 1410 km^2 of the western delta (Figure 4) mapped in 1840 and 1990, a decrease in sediment volume of 8.5×10^9 m^3 (6.3×10^7 tons/yr) occurs in water depths to 40 m, indicating net erosion and/or increasing RSL of 4.5×10^4 tons/km^2/yr.

Before these figures for subaerial and subaqueous sediment accumulation and erosion of Ganges-Brahmaputra delta can be considered quantitative, a better understanding of subsidence-induced RSL change along this section of coastline is required. Long-term tide gauge records from the Indian subcontinent (Emery and Aubrey, 1989) range from −1.3 to +2.1 mm/yr of RSL rise, with an average of +0.5 mm/yr. However, the closest stations to the delta are in the Calcutta area at the extreme western edge of the Bengal Basin. Anecdotal information of buried historical structures and buried coastal forests collected by Morgan and Mcintire (1959) and Coleman (1969) led these authors to suggest that subsidence-induced RSL rise may approach 1–2 cm/yr in some areas of the delta plain. Several NE-SW trending structural troughs and gravimetric highs extend across the Bengal Basin, possibly indicating that regional subsidence-uplift patterns may overlay the overall sediment accretion trend in the river mouth region. These patterns are likely to be at least partially responsible for the rapid switching of river channels in the alluvial plain of the Ganges-Brahmaputra observed in historical times. West of the active delta front, these trends may exacerbate shoreline retreat and bathymetric deepening induced by eustatic sea level rise and erosion by waves, tidal currents, and cyclonic storms. A comparison of average infilling/erosion rates in the river mouth and western delta (+2.8 vs -4.5×10^4 tons/km^2/yr) suggests that RSL rise is quite dramatic in areas not receiving significant Ganges-Brahmaputra sediment in historical times. River mouth infilling rates may be considerably higher than the figures presented in this paper, in order to compensate for the delta-wide rise in RSL.

Morphology of the Ganges-Brahmaputra Delta

Delta front morphologic changes in historical times give evidence of the overall effect of sediment accumulation on delta growth. The transect of seafloor elevation change in the river mouth region (Figure 5) indicates that there is aggradation and progradation of the outer topset and foreset region. This supports the observations of subaqueous delta growth made by Kuehl *et al.* (1989) using sediment geochronology data. Figure 3 demonstrates that there is also a second depocenter of delta growth centered in the upper topset region (<15 m water depth) immediately seaward of the river mouths. Modern deposits of fine sands and silts (mean diameter 2–6 ϕ) mantle much of this region, with generally finer mud deposits further seaward on the outer topset and foreset region (Kuehl *et al.*, 1989). During the period from 1792-present, two processes are observed in this inner topset region. Bhola and Hatia Islands (Figure 2), and the shoals extending seaward from their downstream ends, have accreted on the seaward end by up to 50 km. In addition, across the entire river mouth region, but particularly on the eastern side, these coarse-grained deposits are coalescing to form a lobate feature at about 8–15 m water depth. Upriver, there has been a complex rerouting of channels flowing between the island-shoal complexes.

Delta front morphology changes occurring in historical times suggests an overall mechanism for Ganges-Brahmaputra delta growth during the Holocene. Because of the strong tidal influence in the mouth region, the river discharges through several distributary channels. Newly formed islands and associated subaqueous sand shoals accrete south-southeastward (seaward) forming a digitate river mouth region. This digitate morphology is present across the entire delta front to the mouth of the Hoogly River in India, suggesting that the Ganges tributary has progressively moved eastward during the Holocene, occupying and abandoning a series of distributary channels that are left behind as moribund tidal channels no longer receiving significant water and sediment from the main river. Progressive downstream abandonment of distributaries of the lower Ganges has been observed in historic times (ISPAN, 1995). Silting up and reduced competence with continued channel extension by growth of the interdistributary island-shoal complex may ex-

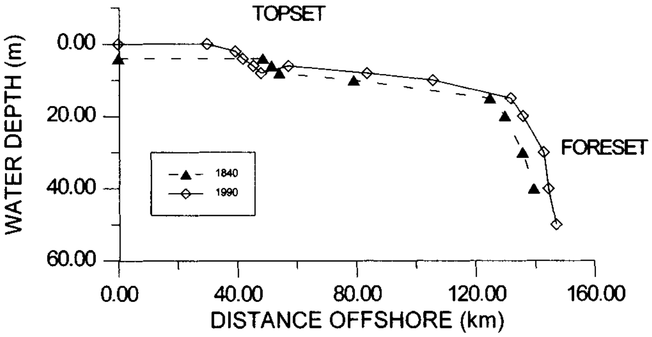

Figure 5. A comparison cross-shore transect of bathymetry across the inner shelf from the Lloyd survey in 1840 with modern charts (1990). Note the overall accretion along the outer topset and foreset areas of the subaqueous mud delta first identified by KUEHL *et al.* (1989). Net accretion is also present in the inner topset area, corresponding to the growth and coalescence of the digitate shoals at the river mouths.

plain the eventual abandonment of channels. The Hoogly is an exception to this process; its connection to the Ganges is kept open by human modification (Hossain, 1993). The shoal growth and channel abandonment process is best observed in historical times in the Tetulia channel-Bhola Island area (Figure 2). Control(s) on eastward migration of the river are unresolved, but may be related to basin tectonics. Further seaward, these digitate shoal complexes merge into a relatively coarse sediment sheet draped over older and finer-grained topset sediments of the mud clinoform accreting offshore.

The development of a subaerial delta over a subaqueous mud delta in the Ganges-Brahmaputra system differs from Amazon and Fly River morphologies, which lack the subaerial component (NITTROUER *et al.*, 1986; HARRIS *et al.*, 1993). All are energetic, macrotidal river mouths, but the Ganges-Brahmaputra possesses a significantly larger fraction of "coarse" material that remains inshore to occlude the river mouth. Grain size of river sediment load has recently been recognized by ORTON and READING (1993) to have as significant an effect on delta morphology as the triad of sediment volume, wave, and tidal energies (WRIGHT and COLEMAN, 1973). Each of the digitate island-shoal complexes in the Ganges-Brahmaputra system can be considered the equivalent of distributary lobes in the Mississippi model of delta growth. Sunderbans National Park in western Bangladesh is the only section of the delta front that remains in a relatively natural state. This area suggests that, unlike lobes in the Mississippi, which are colonized by saline and freshwater marshes, before human disturbance, the entire Ganges-Brahmaputra delta front was probably a vast network of mangrove-colonized islands separated by old distributary channels interconnected through minor channels. This has been confirmed by the limited coring to date of the delta front conducted by UMITSU (1990).

CONCLUSIONS

Historical data indicates the following about the Ganges-Brahmaputra delta front:

(1) The mouth of the Ganges-Brahmaputra does exhibit the characteristics of an actively prograding subaerial delta. An average of 7.0 km^2/yr of new land has accreted in this area since 1792 (4.4 km^2/yr since 1840). This accounts for about 1–2% of the overall river sediment budget.

(2) The deltaic region at the river mouth has two depocenters of progradation/aggradation, with a subaqueous mud delta forming offshore (cf. KUEHL *et al.*, 1989) and a subaerial delta forming above the inner topset beds of the subaqueous delta.

(3) Bathymetric changes observed on the delta front east of the Haringhata River between 1840 and 1990 indicate that about 21% of the annual river sediment budget is supplying aggradation and progradation of the topset depocenter, and an additional 12.5% is sequestered in the upper foreset area (20–50 m water depth).

(4) The morphology of shoal evolution in the river mouth region suggests that the Ganges-Brahmaputra has evolved by a series of eastward steps of the river mouth that are controlled by channel margin accretion and infilling, followed by channel abandonment.

(5) The shoreline and shallow offshore areas of the western delta front are in a net erosional state. Seaward-facing shoreline areas have retreated as much as 3–4 km since 1792. This is attributed to the area being composed of inactive deltaic digitate shoal complexes that receive minimal modern Ganges-Brahmaputra sediment.

(6) Shoreline erosion and increasing depths offshore are a function of eustatic sea level rise and erosion by oceanographic processes, possibly exacerbated by regional subsidence

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