THE GANGES–BRAHMAPUTRA DELTA

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Abstract: Originating in the Himalayan Mountains within distinct drainage basins, the Ganges and Brahmaputra rivers coalesce in the Bengal Basin in Bangladesh, where they form one of the world's great deltas. The delta has extensive subaerial and subaqueous expression, and this paper summarizes the current knowledge of the Late Glacial to Holocene sedimentation from the upper delta plain to the continental shelf break. Sedimentation patterns in the subaerial delta are strongly influenced by tectonics, which has compartmentalized the landscape into a mosaic of subsiding basins and uplifted Holocene and Pleistocene terraces. The Holocene evolution of the delta also has been mediated by changing river discharge, basin filling, and delta-lobe migration. Offshore, a large subaqueous delta is prograding seaward across the shelf, and is intersected in the west by a major submarine canyon which acts both as a barrier for the further westward transport of the rivers' sediment and as a sink for about a third of the rivers' sediment discharge. Subaerial and subaqueous progradation during the Holocene has produced a compound clinoform, a feature which appears to be common for large rivers discharging onto an energetic continental shelf.

INTRODUCTION

The giant delta fed by the Ganges and Brahmaputra Rivers has only recently revealed its secrets to modern observational science. Early seminal studies by Morgan and McIntire (1959) and Coleman (1969) showcased much of the Quaternary geology of the Bengal basin and of the modern river system, respectively; however, it was not until late 1980s and 1990s that the submarine delta was described and numerous studies of coastal and delta-plain environments were published. As such, a comprehensive picture of the entire delta system could only recently be assembled. This paper summarizes the current knowledge of this major sedimentary system, based largely on published research of the last decade.

The Ganges and Brahmaputra Rivers currently contribute about a billion tons (10^{12} kg) of sediment annually to the Bengal Basin, and over the Holocene these sediments have built a deltaic feature with a subaerial surface area of 110,000 km^2. The modern delta continues offshore as a prograding clinoform, extending 125 km across the continental shelf from the river mouths, and about 250 km along shelf from the eastern coast of Bangladesh west to the "Swatch of No Ground" submarine canyon, roughly at the border of India and Bangladesh. Thus, the total area of the combined subaerial and submarine delta is about 140,000 km^2, an area roughly equivalent to the size of Britain.

One of the goals of this summary is to reflect on the lessons of the Ganges–Brahmaputra system with respect to sedimentary processes and deltaic facies compared with other major rivers. This exercise has both academic as well as societal importance as a result of the remarkable intersection of geology and human habitation within delta systems in general, and within the Ganges–Brahmaputra system in particular. Most of the Ganges–Brahmaputra delta is contained within, or seaward, of Bangladesh, a country of some 140 million inhabitants with a population density approaching 1,000 persons per km^2. The southwest sector of the delta extends into India, covering an area of approximately 25,000 km^2, or about 22% of the subaerial surface. People living on the delta have adapted to the harsh realities of frequent flooding and land loss and/or gain characteristic of lowland deltas, but they face an uncertain future as development of river control structures, global sea-level rise, and climate change threaten to alter the dynamic balance between sediment supply, subsidence, and sea level in various regions of the delta.

SETTING

Tectonics and Geologic Setting

While most of the world's major rivers enter the ocean along passive continental margins, the Ganges and Brahmaputra originate in the still rising Himalayan orogenic belt and reach the sea across the tectonically active Bengal Basin. Despite its proximity to the Himalayan foredeep, though, the Bengal Basin is situated seaward of the foreland hinge on a classic trailing-edge margin. Nevertheless, the margin is deformed within this complex, but poorly understood, tectonic setting. As evidence of this activity,

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the Bengal Basin is bordered directly by the Precambrian Shillong Massif and Indian Shield to the north and west, and the Neogene Tripura Fold Belt to the east (Fig. 1). The tectonic activity of the basin has influenced riverine sediment distribution of all parts of the margin. Because of the ongoing collision of the Burmese plate overriding the eastern margin of the Indian continent and its adjacent oceanic crust, the Bengal Basin has been subsiding since the Eocene (Alam et al., 2003). The Eocene carbonate platform formed at the drifting Indian plate can easily be traced in seismic records and boreholes from a few hundred meters depth on the Indian side, dipping southeastwards under deltaic sediments to depths of about 6 km (Reimann and Hiller, 1993). The thickness of deltaic sediments overlying the oceanic crust in the central and eastern basin may reach up to 20 km (Johnson et al., 1976; Curray et al., 2002). Long-term tectonic subsidence in the eastern and southern basin of 1–2 mm y^{-1} has been balanced by the high sediment supply from Himalayan erosion (Alam, 1996). The approximate transition of the Indian continent to oceanic crust, which acts as a hinge line, is marked by high gravity and magnetic anomalies (Sengupta, 1966; Iman and Shaw, 1985).

Except for two possibly fault-bounded terraces that are elevated 3–15 m above the Holocene alluvium (Madhupur and Barind; Fig. 1), the basin surface over which the Ganges and Brahmaputra migrate is of low relief, dipping gently seaward from a mean elevation of 10–15 m in the upper delta plain. At the coast, the Holocene Ganges–Brahmaputra delta has prograded across a broad front (380 km) bordered by the Hoogly River in the west (India) and the Tripura fold belt of eastern Bangladesh.

Rivers

Both the Ganges and Brahmaputra rivers originate in mountains of the Himalaya, but they take distinctly different paths before joining together in the Bengal Basin and debouching to the Bay of Bengal (Fig. 2; Subramanian and Ramanathan, 1996). The Ganges source is the Gangotri glaciers on the southern slopes of the Himalaya. It crosses the Great and Lesser Himalayas southward before descending onto the Indo-Gangetic plain, where it flows eastward towards the Bengal Basin and is fed by numerous large tributaries. The Brahmaputra originates from glaciers along the northern slopes of the Himalayan range, travels eastward along the Tibetan plateau as the Tsangpo, and then traverses abruptly around the Himalayan syntaxis (Nanga Parbat) before descending southward to the Bengal Basin. The combined drainage basin area for the two rivers is about 2 x 10^6 km^2, with 1,114,000 km^2 for the Ganges and 935,000 km^2 for the Brahmaputra (Coleman, 1969).

The mainstream and various tributaries of the Ganges and Brahmaputra rivers drain a variety of geologic source rocks (Fig. 2). The highland streams of the Ganges largely drain Precambrian metamorphic rocks of the Himalaya southern slope, along with some Paleozoic–Mesozoic sedimentary sequences and Pleistocene alluvium. Lowland Ganges streams cross Mesozoic–Tertiary flood basalts, Precambrian metamorphics, and Archean granites and gneisses. In contrast, the Brahmaputra basin is dominated by Mesozoic sandstone, shale, and limestone, with Precambrian acid intrusives and Cambrian sedimentary rocks. The distinct geology of the two drainage basins leads to diagnostic differences in the mineralogy of modern sediments carried by the rivers (Heroy et al., 2003; Huizing, 1971). For the fine sand fraction (250–63 μm), the epidote-to-garnet ratio of Brahmaputra sediments is typically between 1.0 and 2.5, whereas ratios in Ganges sediments are < 1, with a typical value of about 0.5. For the clay-size mineralogy, Brahmaputra sediment is characterized by higher relative abundances of illite (63% vs. 41%), kaolinite (29% vs. 17%), and chlorite (2–3% vs. < 1%), whereas Ganges sediment contains significantly higher smectite (39% vs. 3%).

River waters of the Ganges and Brahmaputra contain a relatively high concentration of Sr (0.91 μmol l^{-1}) with a higher radiogenic $^{87}Sr/^{86}Sr$ ratio of 0.7295 than the global runoff. Therefore, the Sr input of the two rivers is considered to be a substantial source for the global Cenozoic increase of the seawater $^{87}Sr/^{86}Sr$ (Edmond, 1992; Galy et al., 1999). Total dissolved salt concentrations are also relatively high compared to other major rivers—178 mg l^{-1} in the Ganges and 100 mg l^{-1} in the Brahmaputra—and are a result of chemical denudation rates 2–3 times higher than the world average created by high relief and high rainfall in the catchment (Sarin et al., 1989). Combined total flux of dissolved ions to the oceans is 0.13 x 10^{12} kg y^{-1} (3% of world total).

Water and sediment discharge of the rivers is driven largely by the southwest monsoon, with maximum discharge for the Ganges and Brahmaputra occurring during June–November and May–November, respectively (Fig. 3) (Coleman, 1969). River discharge drops dramatically during the northeast monsoon and reaches a low during January–April that is about an order of magnitude below peak discharge. Overall, 80–90% of the water discharge for the Ganges occurs during the southwest monsoon; this figure rises to about 95% for the Brahmaputra (Subramanian and Ramanathan, 1996). Numerous estimates of sediment discharge for the combined system into the Bengal Basin converge at about 10^{12} kg y^{-1} (Abbas and Subramanian, 1984; Goswami, 1985; Subramanian, 1978). However, on the basis of a geochemical mass balance the amount of bedload into the basin could be almost twice as much (Galy and France-Lanord, 2001). Subramanian and Ramanathan (1996) conclude that the bulk of the sediment load for the rivers is delivered during moderate peaks in water discharge that occur during a normal wet season.

Oceanography

The coastal zone is strongly affected by the tidal wave, which has a range of 1.9 m on the western coast and is amplified to 2.8 m along the eastern coast by the funneling effect of the topography (Barua, 1990). Farther upstream in the estuary, the range increases to as much as 5 m. On the basis of 14 temporary stations where the current velocities and suspended-sediment concentrations on the inner shelf were examined, the suspended material is transported mainly southwestwards (Barua, 1990).

Surface circulation in the Bay of Bengal is dominated by reversing wind regimes and high variability of precipitation of the monsoonal seasons. During the summer monsoon, an anticlockwise gyre develops in the northwestern sector of the Bay, which reverses during winter (Tomczak and Godfrey, 1994). Precipitation during the summer monsoon (July–September) increases the joint outflow from the Ganges and Brahmaputra into the northern Bay of Bengal from about 10,000 m^3 s^{-1} to about 100,000 m^3 s^{-1}. During the high-discharge period this fluvial runoff displaces marine waters seaward near the river mouths. Freshwater influence extends over much of the northern Bay, forming a surface layer of reduced salinity 50–100 m thick. Especially during the summer monsoon, the low-density, low-salinity surface layer damps the upwelling of deeper nutrient-rich water near the Indian coast and in general prevents the vertical exchange of water masses (Sheyte et al., 1991). This situation produces a permanent oxygen-minimum zone in the deeper Bay of Bengal, extending from the thermocline between 50–100 m to 600 m (Karstensen, 1999). In the shelf canyon, called the Swatch of No Ground, the slow vertical water exchange rate and the high flux of organic material results in nearly anoxic

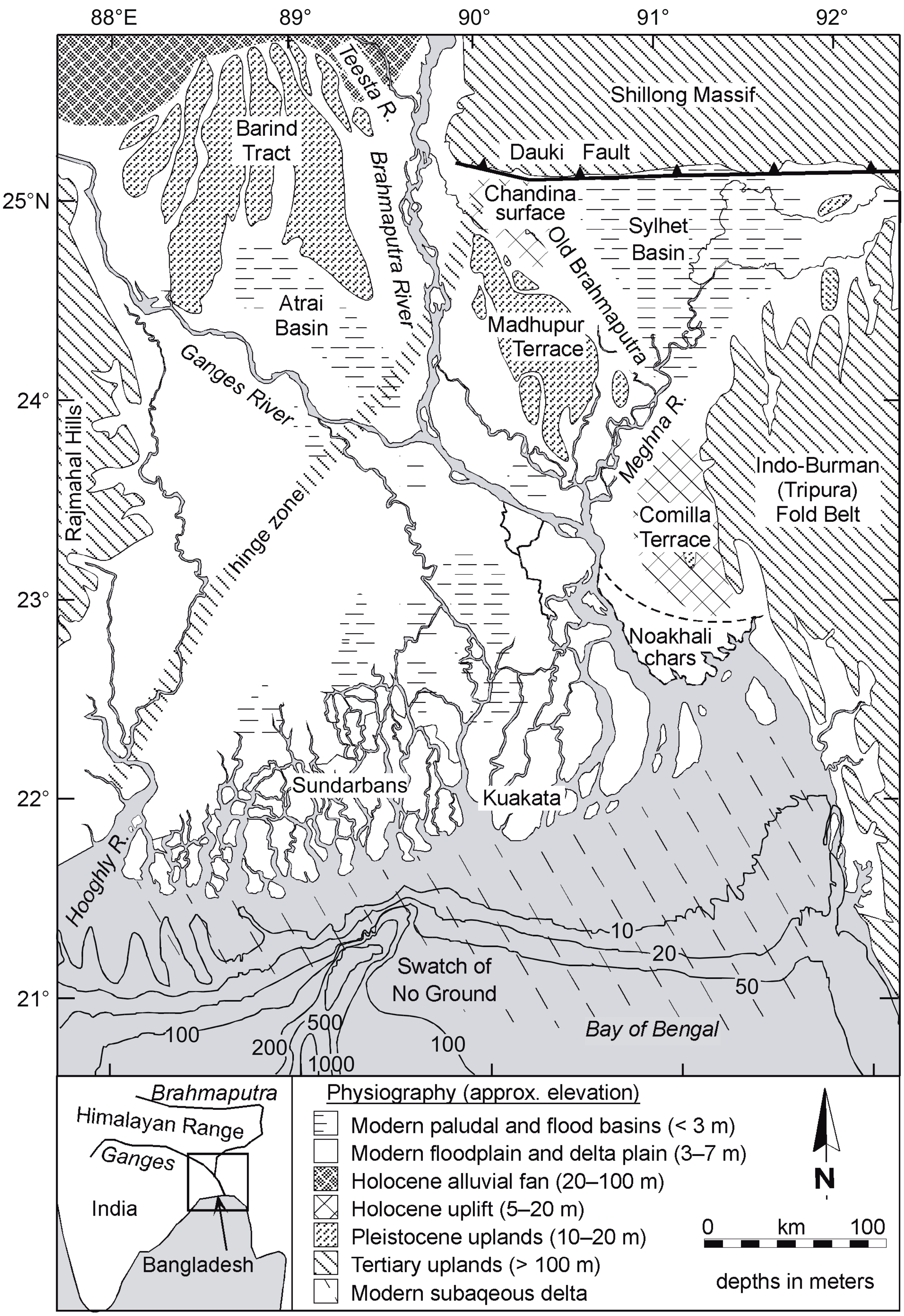

FIG. 1.—Physiographic and tectonic map of the subaerial Ganges–Brahmaputra Delta showing the distribution and ages of landforms in this tectonically complex Bengal Basin. The delta is surrounded by Tertiary uplands and contains uplifted Pleistocene and Holocene regions such as the Barind Tract, Madhupur, and Comilla Terraces.

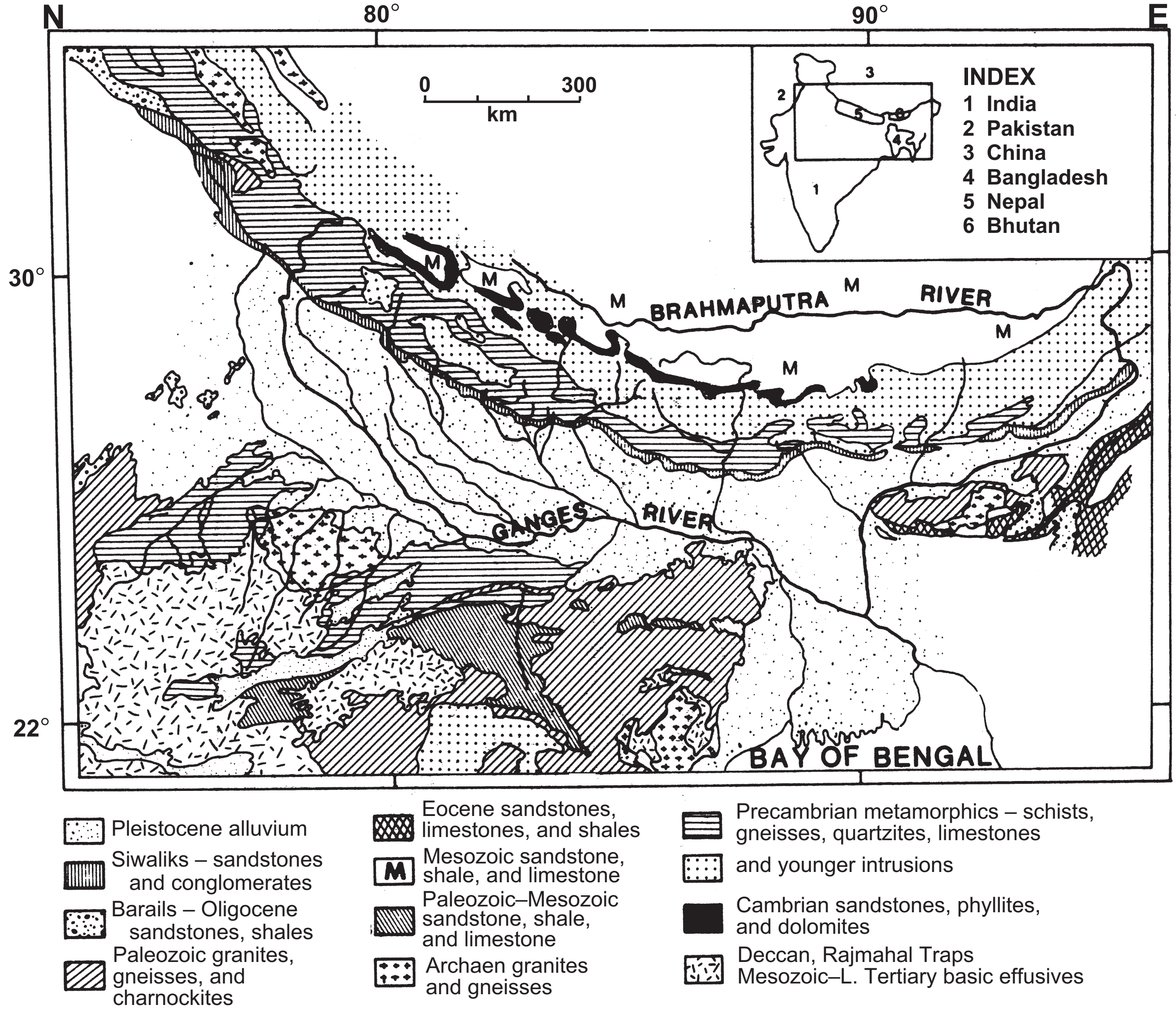

FIG. 2.—Map showing geology of drainage basins for the Ganges and Brahmaputra Rivers. The contrasting geology for the two rivers results in diagnostic mineralogical differences. The Ganges shows a lower epidote/garnet ratio (0.5) than the Brahmaputra (> 1) in the fine sand fraction. For the clay fraction, Brahmaputra sediment is characterized by higher relative abundances of illite (63% vs. 41%), kaolinite (29% vs. 17%), and chlorite (2–3% vs. < 1%); whereas Ganges sediment contains significantly higher smectite (39% vs. 3%).

bottom water (Berner et al., 2003).

The flux of sediment particles in the northern Bay is also governed by the monsoon periodicity. Sediment-trap deployments reveal that most of the lithogenic material is deposited during the summer monsoon, with monthly peak values of 300 mg m^{-2} d^{-1}, whereas most of the biogenic (carbonate and opal) flux is related to the increased convective mixing by wind forcing (Unger et al., 2003).

Cyclones

The northern Indian Ocean and, particularly, the Bay of Bengal are frequently affected by tropical cyclones. The large waves and storm surge produced by these storms mobilize huge amounts of sediment on the shelf and especially on the shallow delta topset and delta front. Consequent flooding of the southern delta islands by this highly turbid water contributes to their vertical growth by sedimentation (Allison and Kepple, 2001). Although the storms have formed in this region in every month of the year because of the relatively warm surface ocean waters in the Bay of Bengal (above 27° C much of the time), they are rare in January–March. Cyclones typically form in the area between 8° and 15° N latitude, with peaks in activity in both the premonsoon (April–May) and post-monsoon (October–November) period, often forming as disturbances in the Intertropical Convergence Zone (ITCZ). Activity decreases during the monsoon when the ITCZ is over south Asia, but it can occur north of 15° N during this period coincident with southward ITCZ

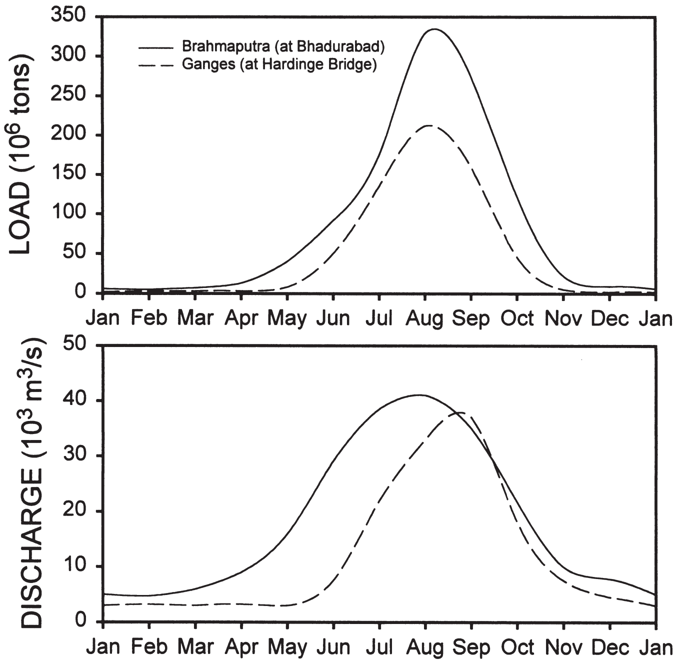

FIG. 3.—Water and suspended-sediment discharge for the Ganges and Brahmaputra Rivers. Water discharge represents monthly averages from 1969 to 1975. Suspended-sediment curves also represent monthly averages; from 1969 to 1970 for the Ganges, and from 1958 to 1962 for the Brahmaputra (from Barua et al., 1994).

migration. Analysis of cyclone frequency in the northern Indian Ocean from the 1870s to 1990s (Singh et al., 2000; Raghavan and Rajesh, 2003) suggests a slight decrease in activity over this period, with an average of almost 9 tropical cyclones per year. However, decadal variations in activity are observed (Kudrass et al., 1998).

Storm tracks of tropical cyclones in the Bay of Bengal between 1877 and 2001 were analyzed by Islam and Peterson (2003), who determined that 133 storms struck the coastline of Bangladesh over this period; 96 of these made landfall over the deltaic plain. Of these storms, 34 reached typhoon strength (> 119 km/hr). The most severe to make landfall on the deltaic plain was the November 1970 typhoon, which had measured peak winds of 222 km/hr and a storm surge of up to 6–10 m, resulting in an estimated 500,000 deaths in Bangladesh. Because the storm-surge-elevation was magnified by the timing of landfall with high tide, storm surge was recorded as far as 200 km inland over the low-elevation deltaic plain.

Coastal Morphology

The gently dipping basin surface continues offshore except along the Chittagong coast on the east side of the delta (Fig. 4), where the continental shelf is marked by a series of north–south trending structural ridges and troughs that mark the offshore extension of the Tripura Fold Belt. Kuehl et al. (1997) observed that these linear basins were floored with large sand waves, suggesting that local steering and intensification of tidal currents prevented the accumulation of fine-grained deltaic sediments. On the west side, opposite the India–Bangladesh border, the shelf surface is incised within 30 km of the shoreline by Swatch of No Ground Canyon, the lowstand course of the Ganges–Brahmaputra that is linked to the Bengal deep sea fan. Other than these features along the longitudinal boundaries of the delta, bathymetric relief on the inner-mid shelf is primarily the product of Ganges–Brahmaputra sedimentation since the Holocene deceleration of sea-level rise. A series of subaqueous shoals extend to about 8 m water depth seaward of the peninsulas and islands that separate the distributary channels (active and inactive) across the entire delta front. These shoals coalesce offshore into a topset platform that forms the inner section of a clinoform (topset–foreset–bottomset) deposit that is actively prograding seaward on the mid-shelf.

ENVIRONMENTS

Upper Delta Plain and Flood Basins

The upper delta plain (UDP) comprises about half of the Ganges–Brahmaputra delta system, extending 200 km landward of the salinity-influenced lower delta plain. This large area is dominated by fluvial processes that are overprinted by downstream coastal evolution and sea-level change. The landward boundary of the UDP is defined by the initiation of distributary development along the Ganges and by a point of frequent channel avulsion along the Brahmaputra (Fig. 5). The adjacent deltaic floodplains are clearly defined along their upland border by outcropping Tertiary uplands, and the downstream edge of the UDP is defined here by the inland dry-season extent of saline water, typically encompassing land > 3 m above sea level.

Physiography.—

In the UDP, several major environments reflect interactions between the fluvial systems and intrabasin tectonics. Among the prominent features of the area are the Barind Tract and the Madhupur Terrace, broad, fluvially dissected surfaces that are composed of much older alluvial deposits (Fig. 6). These elevated deposits are not flooded during the high-water season. Noted as early as the Nineteenth Century (Fergusson, 1863) and first described in detail by Morgan and McIntire (1959), these features have been found to exhibit a strong control on recent river courses, floodwater and sediment distribution, and Holocene delta development (Goodbred et al., 2003). The origin of these elevated sedimentary blocks has traditionally been ascribed to tectonic uplift (Morgan and McIntire, 1959) on the basis of apparent bounding faults, and this interpretation has remained prominent in the literature despite limited evidence. More recent field investigations have noted that previously interpreted fault boundaries may be more consistent with fluvial erosion (R. Caputo, personal communication), raising the possibility that these are geomorphic features (e.g., perhaps former highstand remnants), although a tectonic origin is not precluded. Furthermore, speculated ages for the Barind Tract and the Madhupur Terrace range widely from Holocene to Plio-Pleistocene. Single, unpublished surface exposure dates from each site, though, suggest an age range on the order of 70–130 ka (J. Whitney, personal communication).

The UDP is also influenced by "terraces" younger and less pronounced than the well-developed Barind Tract and Madhupur Terrace. These younger features include the Chandina and Comilla surfaces (Fig. 1), whose slightly incised drainage network, limited flooding, and unweathered sediments suggest moderate uplift of historical age (Coates et al., 1988; Coates, 1990). Both of these surfaces lie along the old Brahmaputra river course, which was abandoned after the late 1700s (Ascoli, 1912), and it is not unlikely

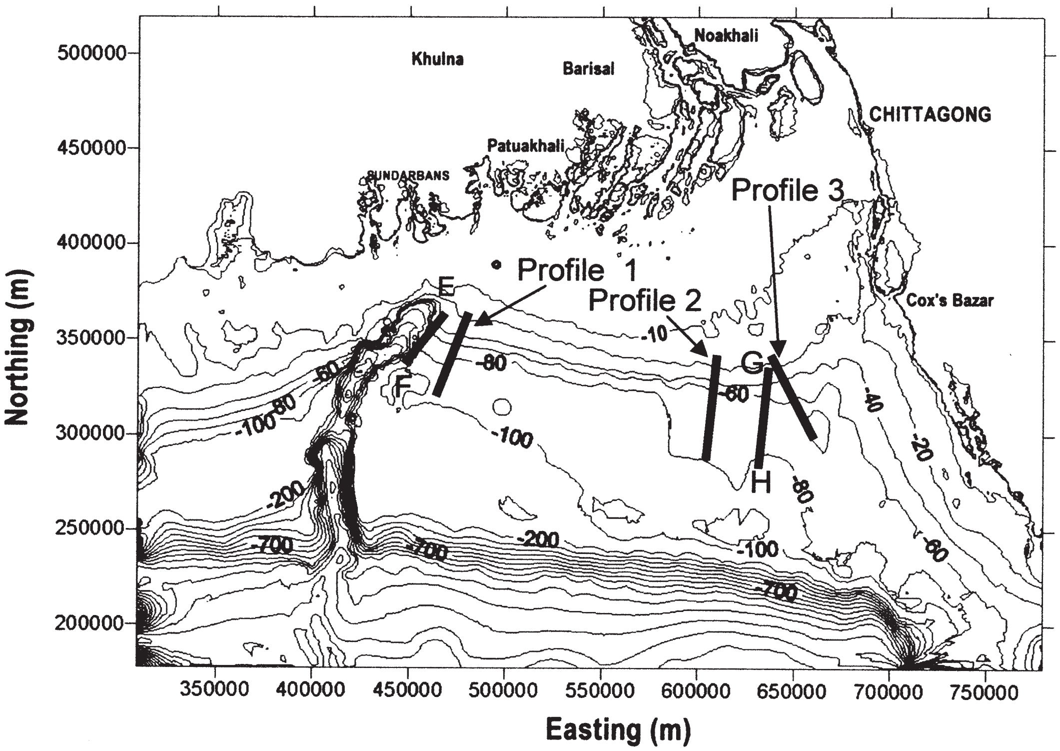

FIG. 4.—Bathymetric chart of the shelf and upper slope of the Ganges–Brahmaputra Delta (contours in meters). Transects are shown for boomer and 3.5 kHz reflection profiles (Figs. 11 and 13). The shelf clinoform morphology (subaqueous delta) can be clearly seen as inner shelf topsets grade into more steeply dipping foresets on the mid-shelf. A major feature of this shelf is the giant submarine canyon (Swatch of No Ground), which indents the shelf to the 20 m isobath on the western side of the Delta. This canyon currently acts as a conduit for the off-shelf transport of about 30% of the present river sediment discharge.

that these features and events are related, but formal studies are needed to test this assertion. Furthermore, the apparently young ages (< 10^3 yr) of the Chandina and Comilla surfaces and their elevation above major flooding imply a tectonic origin rather than being purely morphological features. Regardless of the absolute age and origin of elevated surfaces in the Bengal Basin, they clearly serve to partition the UDP into discrete sub-basins between which there is limited exchange of sediment and which, in many cases, contain distinct stratigraphy. These sub-basins can be divided into two major types, (1) relatively narrow alluvial corridors ("valley plains") and (2) broad, low-lying flood basins.

At present, and historically, the upper reaches of both the Ganges and Brahmaputra rivers flow 50–100 km through relatively narrow (40–80 km) corridors between adjacent uplands or terraces (Fig. 5). The corridors are situated mainly between the Tertiary uplands that bound the Bengal Basin and the intrabasinal highs discussed above. Within these restricted alluvial pathways, the occupying channel braidbelts are 5–15 km wide (i.e., up to 30% of the corridor width) and thus dominate sedimentation patterns (Goodbred et al., 2003). The river-channel braidbelts deposit almost solely sand-size sediments (Coleman, 1969), but overbank flooding also distributes fine-grained sediments across half of the alluvial corridors at any given time (Allison et al., 1998). At longer timescales (> 10^2 yr), however, most fine-grained floodplain deposits are removed by channel avulsion and braidbelt migration, leading to a predominance of clean channel sands in the subsurface stratigraphy (Fig. 7). This reworking process is presumably enhanced by the restricted space for channel migration within corridors. Despite this apparently limited accommodation space, the corridors are not merely throughputs for riverine sediment. In fact, channel aggradation and floodplain accretion sequester an appreciable portion of the fluvial load. Judging by ^{210}Pb- and ^{137}Cs-derived accretion rates, the Brahmaputra braidbelt traps > 50 x 10^9 kg y^{-1} of primarily coarse-grained sediment at rates > 10 mm y^{-1}, with the another 30 x 10^9 kg y^{-1} of fine material deposited on the adjacent floodplains at rates of 1–3 mm y^{-1} (Allison et al., 1998; Goodbred and Kuehl, 1998).

Major floodbasins also characterize large portions of the UDP, with the most prominent feature being the Sylhet basin. This broad depression covers about 10,000 km^2 in the northeast delta (Fig. 1). It is bordered by the Indo-Burman foldbelt, and the Madhupur Terrace to the east and west, respectively, and is bound by the Dauki Fault and Shillong Massif (cratonic fragment) to the north. Owing to north–south compression since at least the Pliocene, the Sylhet basin has supported long-term subsidence rates of 1–4 mm y^{-1} (Johnson and Alam, 1991; Goodbred and Kuehl, 2000a). This continuous generation of accommodation has favored the deposition and preservation of fine-grained sediments, which constitute 50% or more of the stratigraphic sequence (Goodbred et al., 2003). During the Holocene, the main trunk of the Brahmaputra River has periodically flowed through the Sylhet Basin, with major avulsions occurring at periods less than a few thousand years. Stratigraphy also suggests that its course at these times was restricted to the western part of the basin, near its pre–Twentieth Century channel (Fig. 1). Recent sedimentation rates in the Sylhet are 2–5 mm y^{-1}, thereby accounting for about 75 x 10^9 kg y^{-1} of the Brahmaputra load that is sequestered to this large basin (Goodbred and Kuehl, 1998).

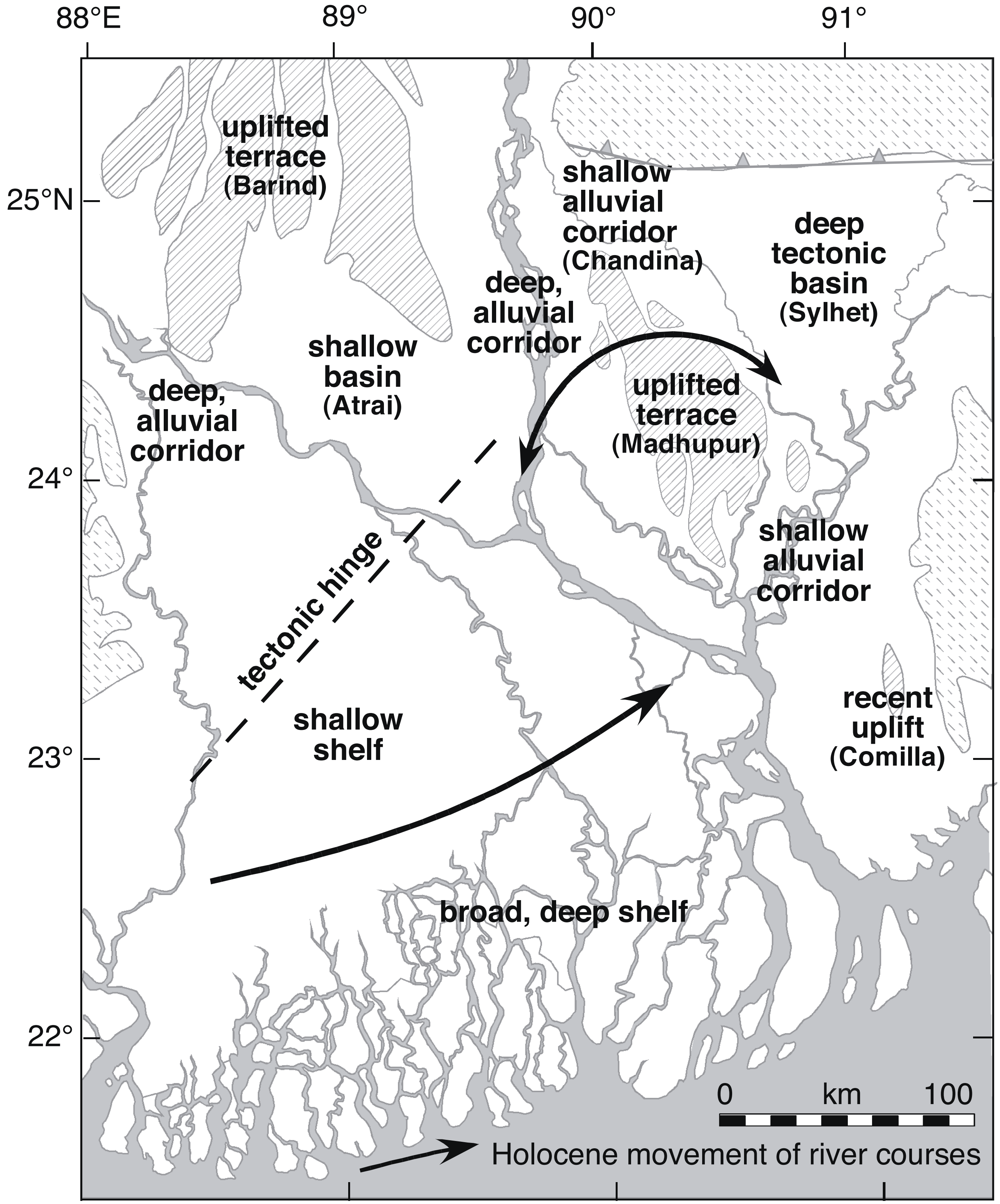

FIG. 5.—Map of tectonomorphic features and controls on the Ganges–Brahmaputra rivers and delta system. Note that areas of uplift serve to partition the delta into numerous sub-basins that each have characteristics salient to the nature of sedimentation and stratigraphic preservation (Goodbred et al., 2003). The large arrows show general Holocene pathways for the major river channels. The Ganges course is characterized by a stepwise eastward migration during the Holocene, whereas the Brahmaputra has largely occupied either its present or recent courses, switching on the order of every one thousand to two thousand years.

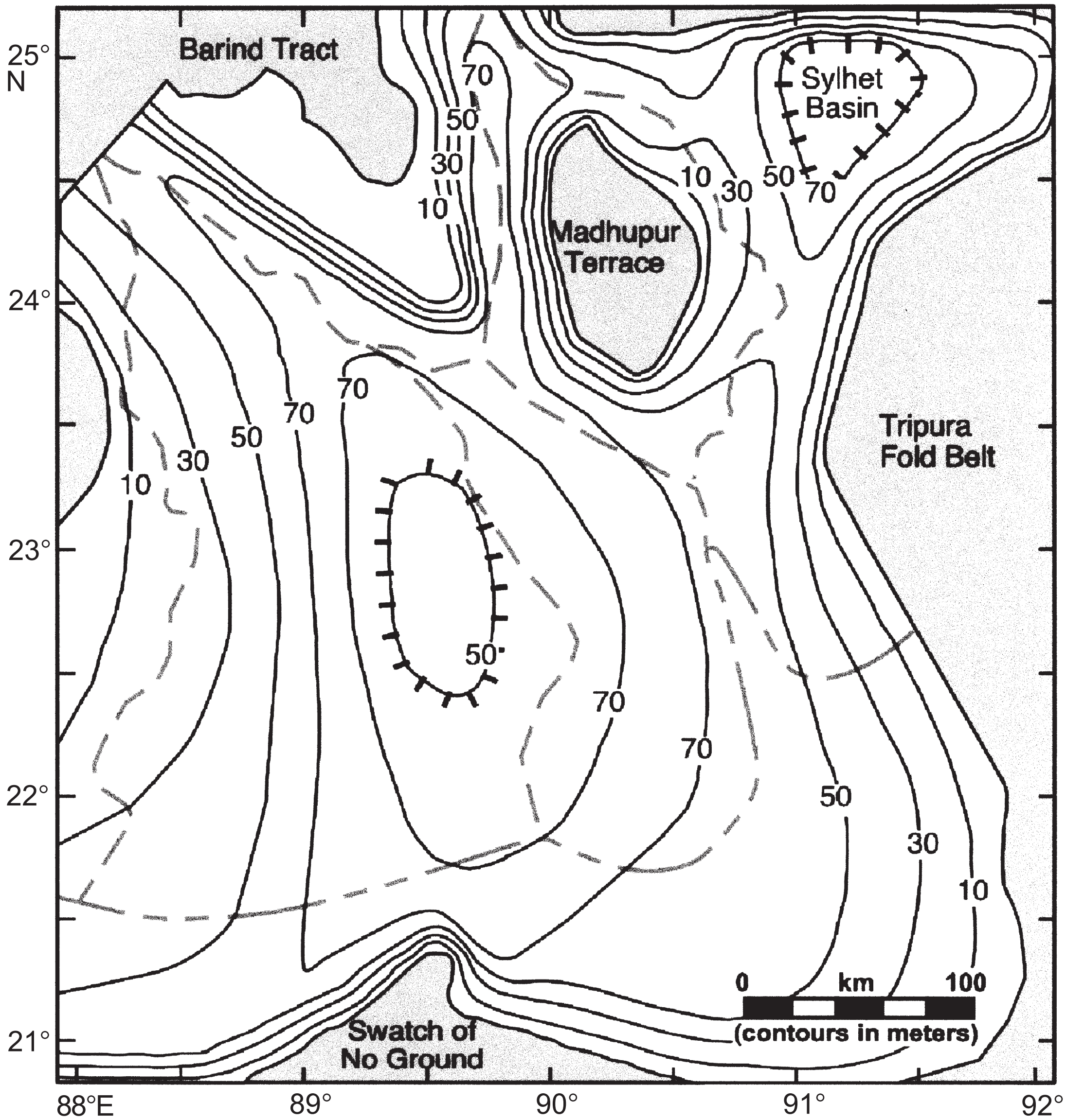

FIG. 6.—Isopach map of Ganges–Brahmaputra fluviodeltaic sediments, including subaerial and subaqueous deposits, deposited from ~ 12,000 yr BP to present. Representative cross sections of delta stratigraphy are shown in Figure 7. The dashed gray lines represent the modern river channels and shoreline. Total volume stored in the delta is about 8.5 x 10^{12} m^3, nearly 60% of which was deposited under the strengthened monsoon and increased river discharge of the early Holocene. Thickest sequences are in the alluvial lowstand valleys and in the subsiding Sylhet Basin. Representative cross sections of delta stratigraphy are shown in Figure 7. The dashed gray lines represent the modern river channels and shoreline.

The other major floodbasin in the delta is the Atrai basin (~ 1500 km^2), which is situated upstream of the Ganges and Brahmaputra confluence (Fig. 1). Unlike the Sylhet, the Atrai is not tectonically controlled but rather is a function of poor drainage caused by both natural and artificially raised levees along the major river channels. Holocene sediments in the basin are comparatively thin (< 10 m) and overlie Barind Tract sediments, which dip shallowly south of their surface exposure. What the Sylhet and Atrai basins have in common are extended periods (up to 6 months) of annual flooding that is 2–6 m deep. Such conditions favor the trapping of fine-grained sediments, which dominate the stratigraphy in both areas (Goodbred and Kuehl, 2000a).

Stratigraphy.—

At a general scale, shallow stratigraphic sequences within the UDP are relatively simple and comprise only a few sedimentary facies. As might be expected, the most common stratigraphy is a fining-up sequence where fine-grained floodplain sediments overlie sandy channel deposits. In these settings, the capping mud unit is typically 0.5–3 m thick and silt dominated, with predominantly oxidized conditions and rapid soil development (Brammer, 1996). Iron-carbonate (mainly Ganges floodplain) and iron-oxide concretions and root casts are not uncommon, and bioturbation by plants and burrowing is also rapid relative to accretion (Goodbred, 1999). These characteristics

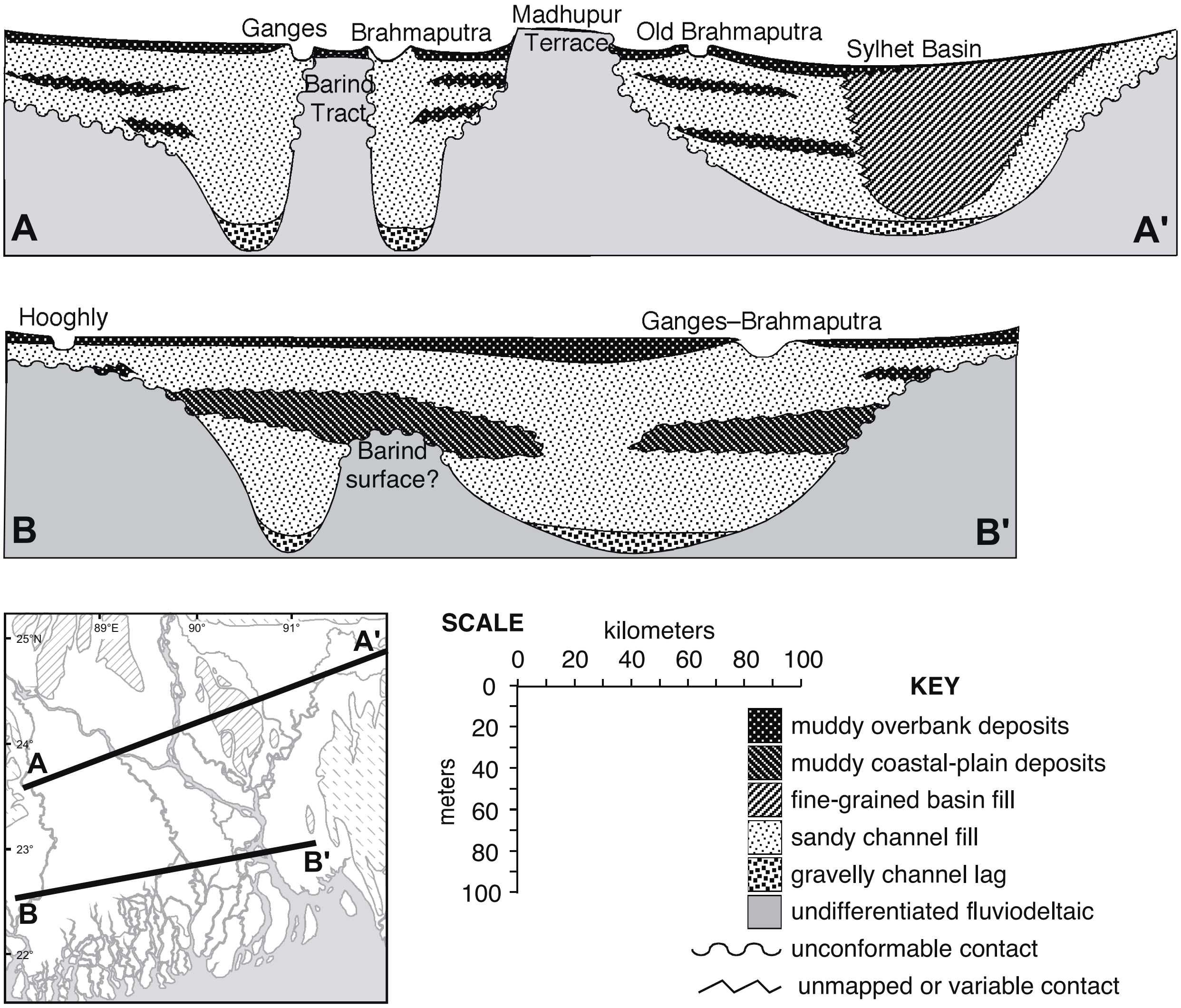

FIG. 7.—Generalized cross sections of the Bengal Basin showing typical distribution of coarse- and fine-grained postglacial fluviodeltaic deposits. Muddy floodplain deposits are not well preserved and tend to be highly localized within the stratigraphy, which is dominated by course silts and fine sands. Important exceptions to the coarse-grained stratigraphy are the tectonically subsiding Sylhet Basin and also the coastal plain, where a thick muddy mangrove facies reflects initial delta formation in the early Holocene.

typify the "floodplain soil" facies, which is the most common and widespread unit in the shallow stratigraphy of the UDP. Interestingly, this thin facies is rare in the subsurface, where preserved mud units are relatively local and almost always < 5 m thick. Presumably the surface soil facies is almost wholly removed by channel migration and avulsions on timescales > 1,000 yr (Goodbred et al., 2003). A related fine-grained facies can be found in local depressions called *bils*. The origin of bils is not well known, but they are apparently small interfluvial basins or channel-abandonment features. In the bils, mud deposits tend to be more clay rich than the adjacent floodplain soils and may reach 7 m thick. The sediments are more reducing under permanently flooded conditions, and concretions are generally absent. Bils are also the only sites in the UDP where organic-rich deposits are found. Even there they are relatively uncommon, forming discrete layers (5–20 cm thick) with combustible-carbon values < 30% dry wt. It is worth noting that organic content in all other settings of the UDP is < 2% dry wt. However, like the thin floodplain soils these bil deposits do not appear to be well preserved in the stratigraphy.

More significant in the overall stratigraphy are "floodbasin muds" of the Sylhet Basin. Here, continuous mud sequences are tens of meters thick and in places reach 80 m of fine-grained Holocene deposits (Figs. 6, 7). Unlike the thin floodplain soils, these deposits accumulate more rapidly because of tectonic subsidence and are thus better preserved (Goodbred et al., 2003), although their organic content remains low (< 2% dry wt). The sediments of the floodbasins are silt-dominated, similar to most of the Ganges–Brahmaputra surficial deposits. In the modern floodbasin deposits, sedimentary structure is limited and soil development is fairly rapid (Brammer, 1996; Goodbred, 1999). However, deposits of the early Holocene during rapid sea-level rise are likely to have more primary structure preserved. Overall, the Sylhet basin is a major repository for fine-grained sediments transported by the Brahmaputra at multiple timescales from modern to the Pliocene.

In most of the UDP outside of Sylhet Basin, sandy deposits ubiquitously constitute the shallow stratigraphy from ~ 3 m to > 20 m deep. These coarse deposits are generally clean, relatively unweathered, fine to very fine sands with several percent heavy minerals (Heroy et al., 2003). Primary structure in the form of cross-stratification and planar beds are abundant and defined by micaceous and heavy-mineral layers at scales of millimeters to decimeters (Coleman, 1969; Bristow, 1993). Although detailed facies analyses have not been made outside of the modern river channel, limited trenches and pits in the floodplain suggest that underlying sand facies reflect channel deposits and bar complexes rather than splays or other fluvial subenvironments.

Lower Delta Plain and Delta Front

The lower delta plain (LDP) of the Ganges–Brahmaputra, defined here as the subaerial delta inland to the limit of saline penetration during periods of low river discharge, is a zone up to 100 km wide that increases only minimally in elevation inland (elevations are typically < 3 m above mean sea level at the northern limit of salt-water intrusion). Early colonial records from the Seventeenth and Eighteenth Centuries suggest that most of the LDP in Bangladesh and the adjacent Indian state of West Bengal was mangrove forest, but today reclamation for agriculture and logging have reduced the mangrove swamp to 5,993 km^2, primarily in Sunderbans National Park. In the Sunderbans, distributary channels associated with relict courses of the Ganges River subdivide the region into a series of north–south oriented, elongate peninsulas, which are dissected, in turn, by smaller anastomosing tidal channels. Farther east on the Kuakata peninsula, earthen coastal embankments (e.g., polders) created for cyclone protection and agricultural development have eliminated most of the smaller tidal channels that subdivide the peninsulas into islands. In the active distributaries of the Ganges–Brahmaputra that form the Meghna estuary, much of the island and peninsula land areas came under cultivation in the late Twentieth Century, or are used for tree (mangrove) farms.

The modern sediment character of the LDP is outlined in Allison et al. (2003). Surface sediments are generally silts to clayey silts (mode 6.5–7.5 ϕ) with < 5% sand. Clay content is slightly higher in the western LDP relative to the Meghna estuary. Total organic carbon content (TOC) is generally low, ranging from 0.05 to 1.1% except in the upper ~ 10 cm of sediments containing leaf litter in mangrove-vegetated areas. Clay mineralogy is mainly illite (40–65%), with lesser amounts of smectite, kaolinite, and chlorite. The upper 2 m of the LDP sediment column is predominantly two sedimentary facies: mottled mud in the Sunderbans and established agricultural areas in Kuakata, and interbedded mud in the Meghna estuary region. Interbedded mud also underlies the Mottled mud at 2–3 m depth in the Sunderbans. The only other observed facies in surficial sediments (peaty mud) is found in clay-rich peat basins immediately landward of the LDP. These basins are the product of internal drainage and standing-water conditions produced in areas between relict Ganges distributaries (Brammer, 1996; Goodbred, 1999).

Mottled mud is formed by partial homogenization of primary sedimentary structures by rooting, burrowing, or agricultural disturbance (Figs. 8A, 9). Mangrove areas often show overprinting by root structures and faint, laterally discontinuous centimeter-scale interbeds of silt-rich and silt-poor beds and laminae. Interbedded mud consists of millimeter- to centimeter-scale silt laminae separated by clayey silts (Figs. 8B, 9). Laminations often exhibit cyclicities in the thickness of clay–silt couplets that is characteristic of tidalites. Allison and Kepple (2001) have shown with ^{137}Cs geochronology that the LDP surface is accumulating sediment today at rates of up to 1.1 cm y^{-1}, with a trend of decreasing accumulation with increasing distance inland from the Bay of Bengal. They determined that this sediment is likely Ganges–Brahmaputra suspended sediment being advected alongshore by the westward-flowing coastal current (Barua et al., 1994) and transported inland during coastal setup events that inundate the LDP. Coastal setup is produced seasonally by the southwest monsoon, and episodically by cyclonic storms tracking north in the Bay of Bengal. The layers found in the interbedded mud facies are produced by this cyclic or episodic sediment flux, and preserved in surface LDP sediments in the Meghna estuary region by limited agricultural disturbance.

Historical and satellite-era remote-sensing studies (Martin and Hart, 1997; Allison, 1998a) have shown that the Meghna estuary region has been experiencing shoreline accretion at rates of 5.5–16 km^2/yr over the past several centuries. Accretion is mainly a process of seaward extension of interdistributary islands, coupled with a welding of individual islands farther up the estuary into peninsulas by silting up of tidal channels separating islands. The seaward faces of interdistributary islands have digitate subaqueous shoals that extend up to 80 km offshore and merge into a broad, lobate apron at 6–8 m water depth. These shoals have accreted seaward as much as 50 km since 1840 (Allison, 1998a). The term *delta front* is used here to refer to shallow-water deposits immediately off the river-mouth region where coarse-grained sediments are primarily deposited. The Ganges–Brahmaputra subaerial delta is advancing along a delta front 150 km wide that is punctuated alongshore by ebb- and flood-dominated channels and shoals extending from interdistributary islands (Fig. 1). The lobate apron merges offshore at about 10–15 m water depth with the lower-gradient topset beds of the subaqueous clinoform. The subaqueous delta-front deposits are not well sampled, but seismic transects from Kuehl et al. (1997) suggest that the highly reflective surface (limited seismic penetration) is characteristic of sands, covered by ephemeral silty layers (Kuehl et al., 1989). Meghna estuary islands show a fining-upward sequence with cross-bedded, muddy sands at depth (5–6 m), equivalent to shoal deposits, buried by the shoal-island complex consisting of interbedded mud and sand (Allison et al., 2003). West of the active river mouths opposite the Sunderbans, relict distributary shoals are found on the innermost shelf. Sea-facing shorelines have eroded as much as 3–4 km since 1792 (Allison, 1998b).

Sediment cores collected from the LDP on the Kuakata peninsula and in the Sunderbans show the same (~ 7 m thick) fining-upward stratigraphic transition from subtidal shoal to intertidal shoal to supratidal flat (seasonally flooded mangrove) as is observed in the modern prograding shoal-island complexes in the Meghna estuary (Allison et al., 2003). Borehole data from the LDP (Goodbred and Kuehl, 2000a) indicates that this progradational sequence lies directly on an early Holocene transgressive shelf sand. Several studies (Banerjee and Sen, 1988; Umitsu, 1993; Goodbred and Kuehl, 2000a) have shown that the entire modern LDP is seaward of the maximum sea-level transgression, and hence began prograding after about 5,000–6,000 yr BP. Limited radiocarbon data from the LDP sequence (summarized in Allison et al., 2003) suggest that the LDP accreted in a west-to-east pattern beginning about 5,000 yr BP in the Indian Sunderbans. The eastward shift of distributaries was related to the Ganges: the Brahmaputra was infilling shallow inland areas north and south of the Madhupur uplands. Radiocarbon and clay-mineral evidence (Heroy et al., 2003; Allison et al., 2003) suggests that the Sunderbans and Kuakata LDP deposits were created by the

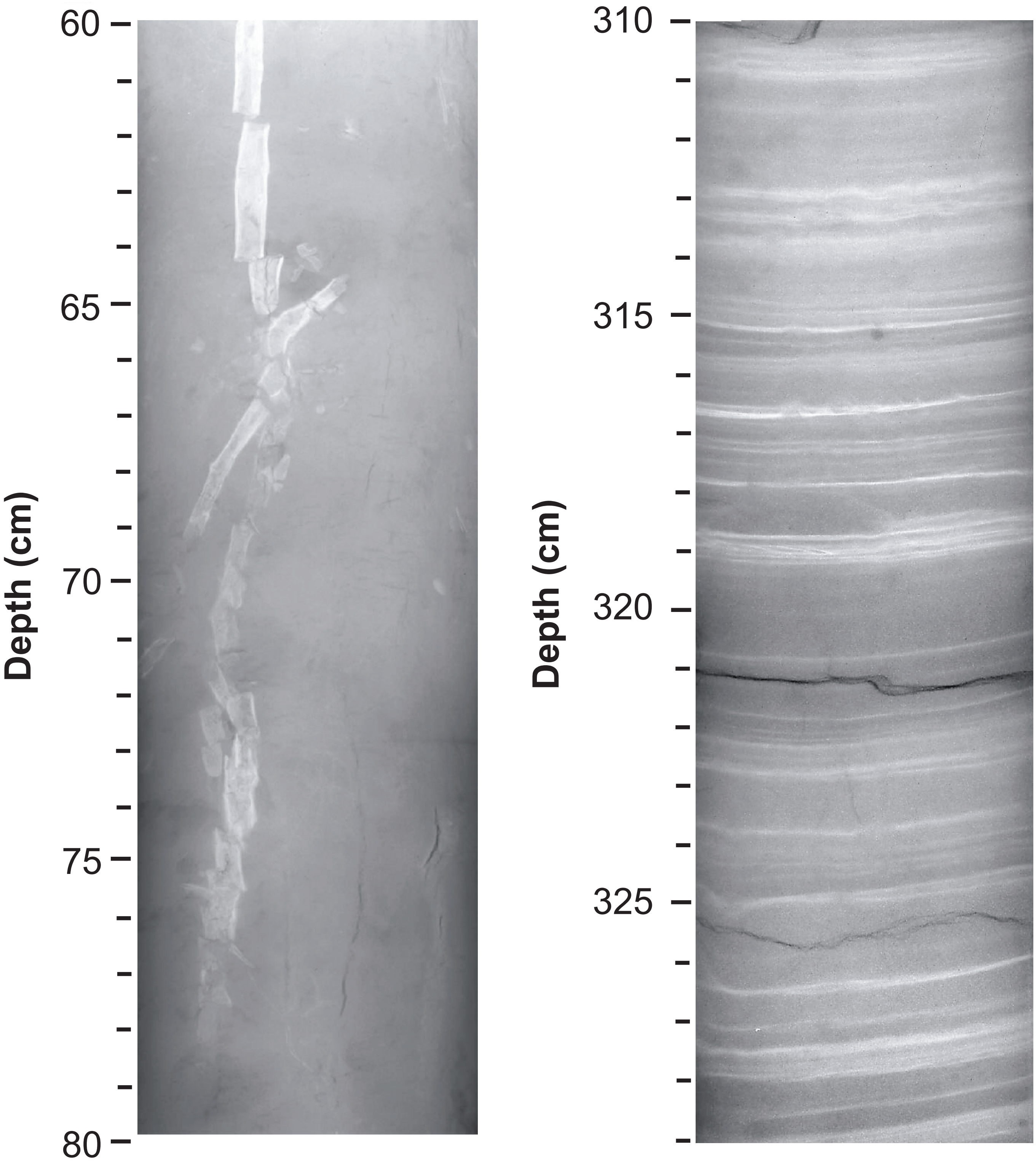

FIG. 8.—X-radiography positives from vibracores of typical facies in the delta plain. **A)** Except near active, major river channels, the delta plain is nearly everywhere capped by 1–3 m of muddy overbank deposits that are well mixed, showing little to no primary sediment structure. Weathering in these deposits has advanced to various states, forming soils with Fe-rich roots casts (shown) and concretions (not shown) that are most commonly siderite, rarely pyrite. **B)** Below the muddy surficial floodplain deposits are thick sequences (5–30 m) of muddy sand to sand deposits reflecting higher-energy fluvial or fluviotidal deposition. Shown is a typical tidalite sequence from the lower delta plain with alternating silt and sand layers tuned to fortnightly tidal cycles. In the upper delta plain, tidalites are replaced by clean, cross-bedded sands deposited in fluvially dominated settings.

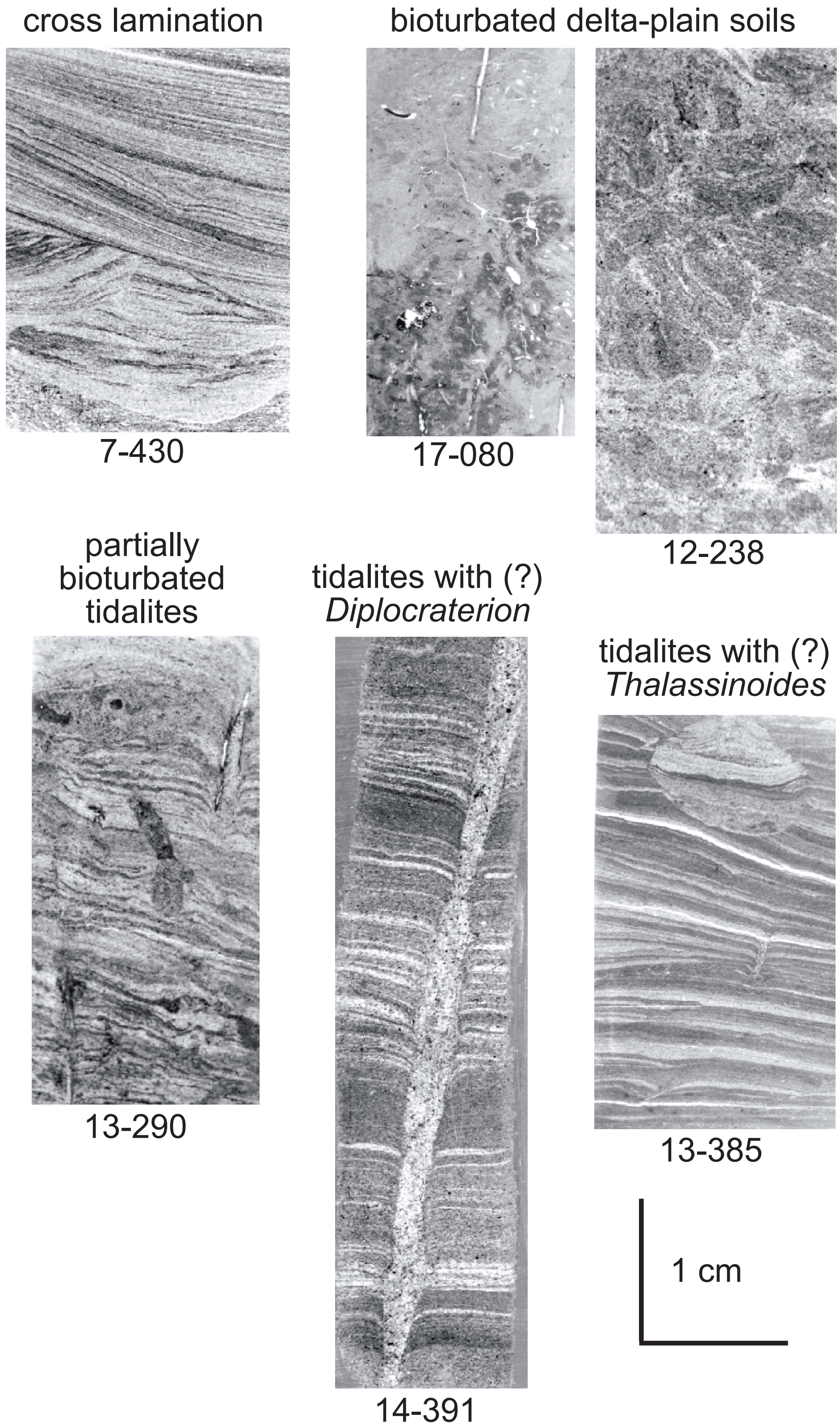

FIG. 9.—Petrographic thin sections showing fine-scale bedding and mixing in various settings of the delta plain (lower label, #-##, indicates core number followed by depth in centimeters). Note that sections < 3 m deep show the most mixing, reflecting soil development under upward-fining, reduced-sedimentation conditions. Section 7-430 shows the typical sandy, cross-bedded deposits that dominate upper-delta-plain facies below the capping floodplain muds. In the tidal deposits millimeter-scale beds appear to be deposited on each tidal cycle, with observable fortnightly spring–neap changes.

Ganges, and only in the last several hundred years has combined Ganges–Brahmaputra delta-front progradation been occurring in the Meghna estuary region.

Subaqueous Delta

The existence of an accretionary subaqueous delta on the Bengal shelf was first suggested by Kuehl et al. (1989) and later confirmed by Kuehl et al. (1997) and Michels et al. (1998) (Fig. 10). Topset beds extend seaward from the delta front to water depths of about 30 m, judging by the subtle change in seabed surface gradients observed in high-resolution seismic profiling (e.g., Fig. 11). Gradients increase from < 0.1° in the topset region to values ranging from 0.20° to 0.27° in the foreset region. The transition to bottomset beds occurs at depths ranging from 80 m for the western shelf, shoaling to 60 m for the eastern shelf, with bottomset gradients of < 0.1°. Consistent with other accretionary subaqueous deltas and with their sigmoidal geometry, maximum accumulations rates occur in the foreset region (5–9 cm y^{-1} based on ^{210}Pb, ^{14}C, and ^{32}Si geochronologies), with dramatically lower rates << 1 cm y^{-1} in topset and bottomset regions.

Volumetric and mass estimates of the subaqueous delta from boomer records indicate that the subaqueous delta contains about 30% of present river sediment discharge, extrapolated to about 10 ka (Kuehl et al., 1997). This estimate is also consistent with contemporary sedimentation rates and a budget determined by high-resolution seismic profiles and core samples dated by ^{210}Pb, ^{137}Cs, ^{14}C, and ^{32}Si, which reveal accumulation in the clinoform of 20% (Michels et al., 1998) to 30% (Suckow et al., 2001) of the estimated annual sediment load of the Ganges and Brahmaputra (10^{12} kg y^{-1}). The clinoform progrades seaward about 20 m y^{-1} across the Late Pleistocene deltaic floodplain surface presently exposed on the outer shelf.

Topset Beds.—

Although seabed surface texture of the topset region ranges from fine sand to clay, field data and acoustic observations suggest that this area is composed mainly of sand and silt. High-resolution acoustic studies using Parasound (3.5 kHz) show a strong bottom reflector with virtually no sub-bottom penetration (Michels et al., 1998). Multi-frequency (boomer) studies show limited sub-bottom penetration (15 m maximum) with strong reflectors just beneath the surface, consistent with the inferred coarse texture (Kuehl et al., 1997). This interpretation is also supported by seven vibracores (up to 3 m length) collected at the seaward edge of the topset region. Sediment texture in these cores is highly variable, but average sand:silt:clay is ~ 4:3:3. Cores reveal fining-upward beds (up to 70 cm thick) of fine to very fine, micaceous sand. Lacquer peels from these sands (Fig. 12) reveal thin lamination throughout. The bases of these units sometimes are marked by centimeter-size clay balls, and occasionally shells. The absence of bioturbation suggests rapid deposition and physical reworking, perhaps induced by frequent cyclone-generated waves and currents (Kuehl et al., 1991; Segall and Kuehl, 1994). A veneer of muddy sediment is observed from gravity cores from some locations, apparently indicating the presence of ephemeral mud deposits. Deep-water wave hindcasting using gale-force winds (average seven occurrences per year) yield near-bed orbital velocities that exceed the critical threshold of bottom sediments by an order of magnitude (Barua et al., 1994).

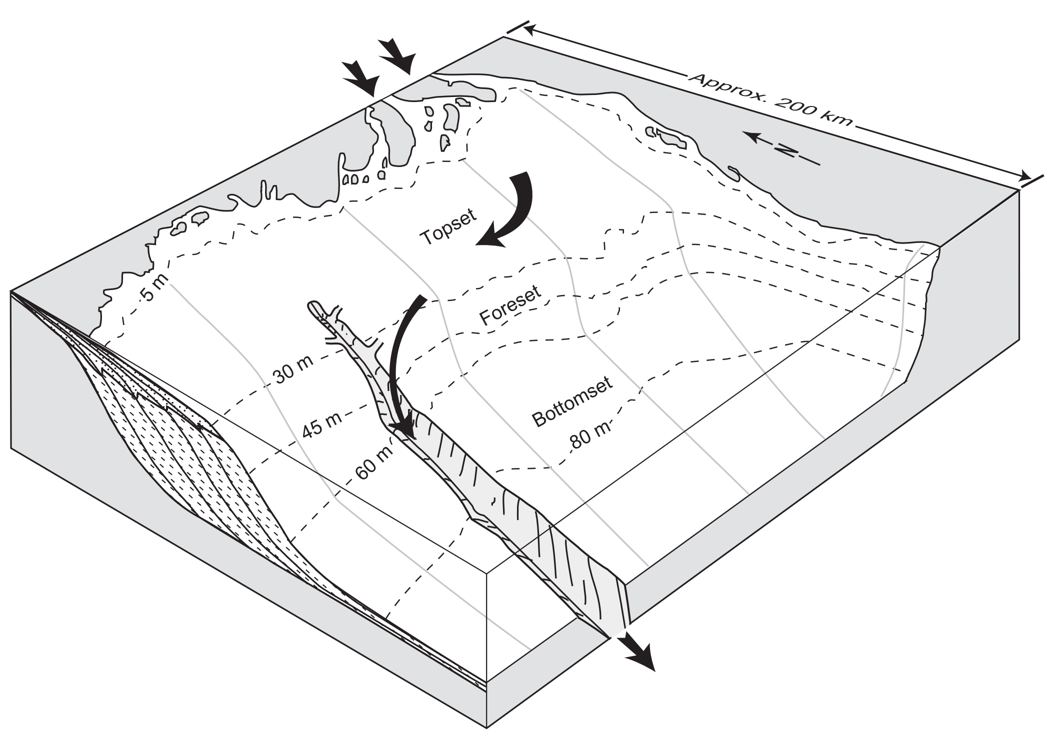

FIG. 10.—Cartoon showing the general morphology and inferred sediment transport pathways for the Ganges–Brahmaputra subaqueous delta. Currently, the major input to the shelf is from the eastern distributaries. The delta foresets are advancing seaward across the mid-shelf region at about 50 m/yr. A significant fraction (about 30%) of the rivers discharge is trapped within the canyon, which is episodically evacuated, presumably by turbidity currents which feed the Bengal Fan.

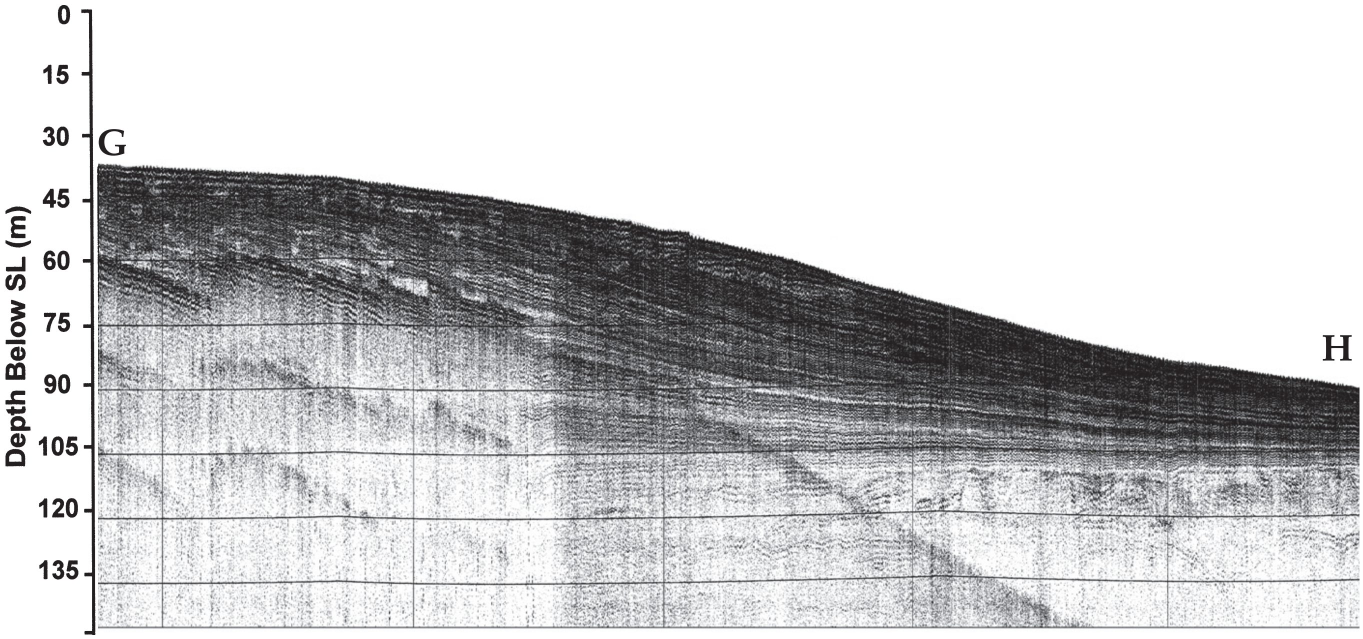

FIG. 11.—High-resolution (Boomer) profile from the Ganges–Brahmaputra subaqueous delta (see Fig. 3 for location). The sand and mud clinoform overlies the transgressive surface characterized by truncated bedding and channel-fill features.

Foreset Beds.—

Sea-bed texture fines seaward to a sandy mud in the foreset region (sand:silt:clay ~ 1:7:2), and the resulting increase in acoustic penetration reveals that the Pleistocene units underlying the clinoform are often erosionally truncated, with abundant cut-and-fill features characteristic of former channels active at the last glacial maximum (LGM). Within the foreset clinoform deposits, closely spaced, nearly parallel reflectors diverge from the topset to the mid-foreset region and converge farther seaward towards the bottomset region. Acoustically transparent beds are a common feature of the foreset region, covering an area of a few kilometers to tens of kilometers along and across the region, with a typical thickness of about 5 m. Parasound records demonstrate an increase in abundance of the transparent beds in the study area from west to east, with the vertical stacking of as many as five such layers for the eastern profiles (Fig. 13) (Michels et al,. 1998).

Compared to the topset beds, the proportion of sand and silt significantly decreases with increasing water depth. Most of the still numerous distinct sand and silt layers have sharp basal contacts, and fine upward. The upper mud sections are frequently bioturbated and may contain some thin-shelled mollusc shells and centimeter-size echinoid sand dollars. More than 50% of the foreset beds consist of these graded units, indicating that most accumulation in the foreset bed happens during discrete rapid-accumulation events and that the more continuous supply of sediment is relatively small. Storms and tropical cyclones, which dominate the sediment transport into the Swatch of No Ground (see below), have most probably also deposited the graded sequences of the foreset beds. However, the much smaller number of graded beds per time unit (< 0.5 graded beds y^{-1}) compared to the Swatch of No Ground tempestites (3 graded beds y^{-1}), is an indicator of nondeposition or even erosion along the foreset beds (Michels et al., 1998).

At the transition from foreset to bottomset beds, acoustically transparent beds form 1-km-wide lobes, occasionally displaying a terrace-like morphology. Vibracores collected from transparent and adjacent stratified beds reveal distinctly different characteristics. Stratigraphic and grain-size analyses (Fig. 14A) indicate that the acoustically transparent beds are unsorted and homogeneous. Thin-section photomicrographs reveal distinctive and contrasting structure from stratified and homogeneous beds (Fig. 14B), consistent with field observations. From the above evidence, we conclude that the acoustically transparent beds represent large-scale sediment gravity flows. Although the exact nature of these flows is unknown, the available data suggest that flow densities are moderately high, enough to prohibit the development of graded beds, but low enough that turbulent mixing can effectively homogenize the sea bed. The increasing frequency of transparent beds toward the river mouth is accompanied by a progressive decrease in foreset slope, from 0.27° to about 0.20°. Presumably, the increasing incidence of sediment gravity flows in the east causes a reequilibration of foreset slope, resulting in the lower observed gradient.

Because of the influence of strong cyclones in the Bay of Bengal, it is tempting to speculate that large wind-driven waves could trigger mass movement in the foreset region. However, major cyclones influence the area about once a year, whereas only about four distinct gravity flows have been observed in the past 250 years (Michels et al., 1998). Thus, although cyclones cannot be ruled out as a possible trigger, other factors should be considered. As another possibility, tectonic activity along the boundary between the Indian and Burmese plates creates strong earthquakes. For example, five quakes between magnitude 4.6 and 6.5 have occurred since 1955. Therefore, high rates of sedimentation, leading to pore pressurization, coupled with earthquake and/or cyclone activity, are the primary suspects in triggering sediment gravity flows in the foreset region of the Ganges–Brahmaputra subaqueous delta.

FIG. 12.—Lacquer peel from the sandy topset region showing thin lamination throughout.

Bottomset Beds and Outer Shelf.—

Extending from the toe of the foresets seaward to water depths of about 100 m, bottomset clinoform beds display regular horizontal bedding overlying the transgressive surface. The thickness of the bottomset beds as a unit, and as individual layers, decreases rapidly seaward. Most of the acoustically transparent slump deposits end near the gradual change in slope marking the transition to the foreset beds. The extent of bottomset beds onto the shelf differs considerably with respect to water depth, from 75 m in eastern delta to 120 m in the western part. Measured sedimentation rates in the western sector, close to the Swatch of No Ground, are close to 0.2 cm y^{-1} (Suckow et al., 2001). Correspondingly, bioturbation is more effective, and only some thick sand–silt layers are preserved in the predominantly muddy sequence.

The outer shelf, from the toe of the bottomsets to the shelf break at 150 m, exhibits outcropping relict deposits containing oolitic beach ridges (Wiedicke et al., 1999) and possible lowstand deltaic sequences (Hübscher et al., 1998). The modern submarine delta with its clinoforms is prograding southward over this Late Pleistocene–early Holocene transgressive surface. The surficial deposits on the outer shelf are discontinuous layers of muddy sand palimpsest, consisting of reworked fluvial sand mixed with Holocene biogenic debris (Michels et al., 1998). In the seismic records, numerous cut-and-fill structures and a stacked sequence of seaward-propagating clinoforms indicate that the outer shelf is built from sea-level-lowstand deltas (Hübscher et al., 1998). During the LGM, the former coastline on the central Bengal shelf was formed by a set of oolitic beach ridges in present water depth of 120–130 m. The occurrence of these ooids as far west as the margins of Swatch of No Ground Canyon (Sengupta et al. 1992) is an indication that this section of coastline had at least seasonally clear water, a situation which contrasts markedly with the present conditions. Apparently most of the fluvial mud was trapped within the valley that today forms the shelf canyon and was transferred directly to the Bengal deep-sea fan (Weber et al., 1997). In addition, the reduced fluvial runoff at LGM (Kudrass et al., 1998) also may have reduced the supply of mud to the former coastline. The shelf break lies at relatively great water depths of approximately 150 m.

SWATCH OF NO GROUND (SoNG)

The most prominent feature on the Bengal shelf is the deeply incised Swatch of No Ground canyon (SoNG). The SoNG bisects the shelf and ends in an amphitheater at the 20 m isobath, within 30 km of the modern shoreline. The canyon directly intersects the prograding foreset beds of the submarine delta and then deepens to > 500 m within 50 km of the coast and to 1200 m by the shelf break. The canyon itself is 20–30 km wide, with steep walls (> 10°) on its eastern side and shallower slopes (~ 5°) on the western wall. Both of the walls of the canyon are dissected by gullies, which apparently constitute a network for sediment transport into the canyon (Kuehl et al., 1989; Kuehl et al., 1997; Kottke et al., 2003).

Sedimentation fundamentally differs between eastern and western side of the SoNG. At the steep eastern wall, growth faults indicate a long-term instability (Kuehl et al. 1997; Kottke et al. 2003). The more gentle western wall is formed by a set of terraces and broad depressions, the latter of which serve as pathways for about 10 mud flows in a 100 m sedimentary column corresponding on the average to a slide event every fifth year. Most of the mudflows end or coalesce on the broad U-shaped canyon floor, where they interfinger with bedded sediments. Between the pathways for the mudflows and some deeply incised gullies, more steady sedimentation prevails, as

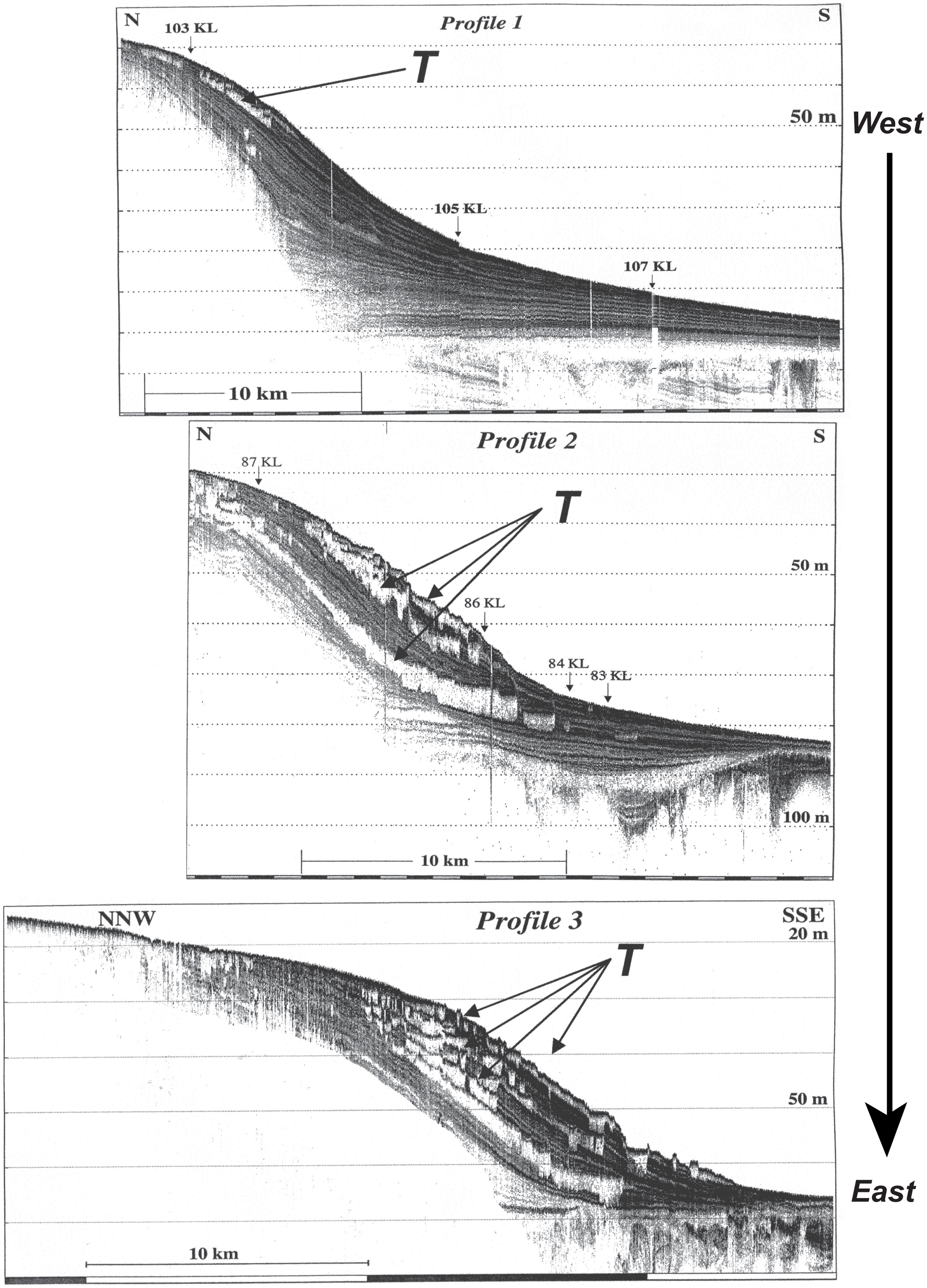

FIG. 13.—Three high-resolution (3.5 kHz) across-shelf profiles from west to east showing the increasing frequency of acoustically transparent layers (**T**) toward the active river mouths. These transparent layers are interpreted to represent sediment gravity flows, perhaps initiated by earthquakes common to the area. Profile 3 shows terraces formed by these flows deposited in the outer foreset and bottomset regions.

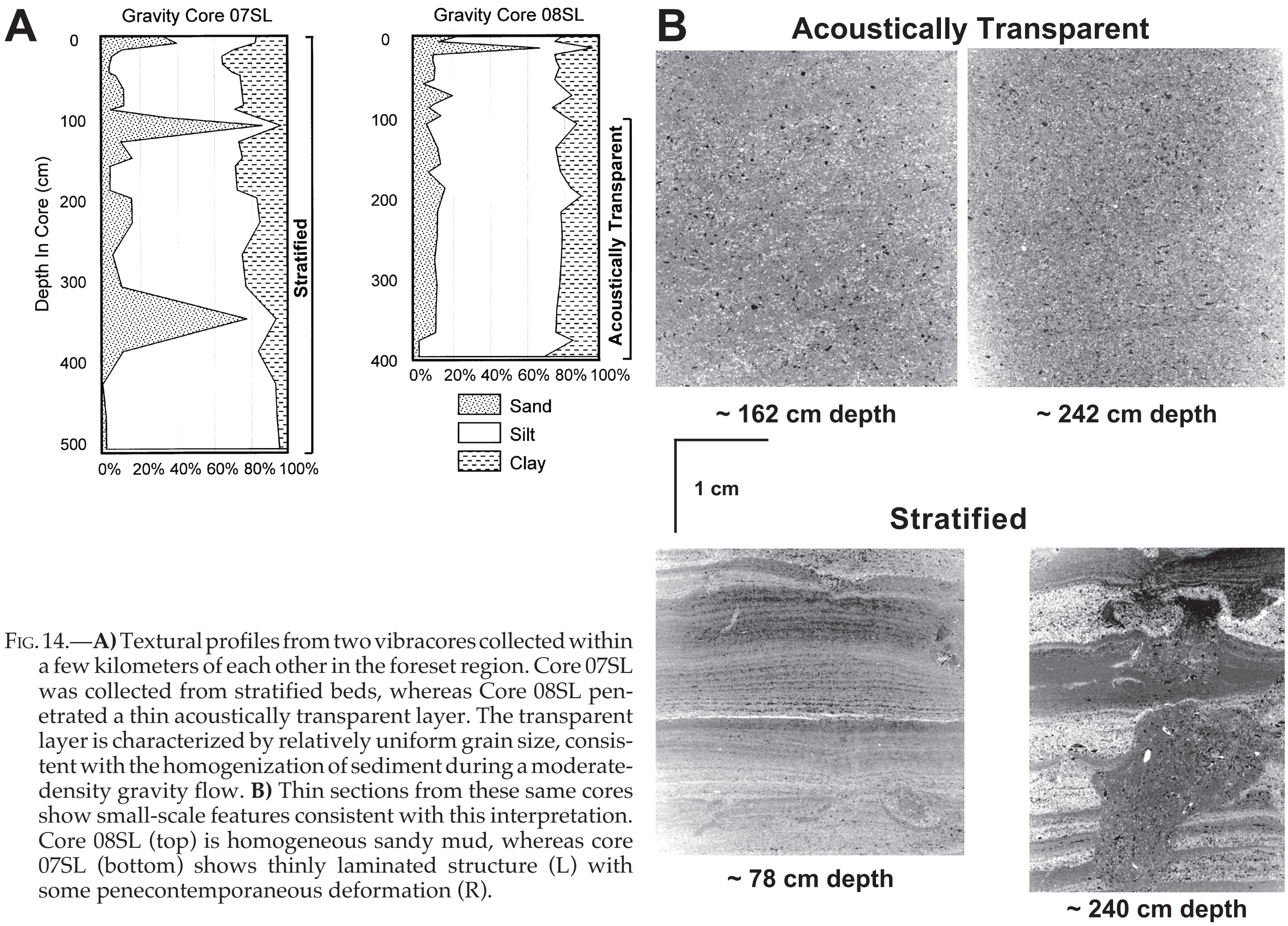

FIG. 14.—**A)** Textural profiles from two vibracores collected within a few kilometers of each other in the foreset region. Core 07SL was collected from stratified beds, whereas Core 08SL penetrated a thin acoustically transparent layer. The transparent layer is characterized by relatively uniform grain size, consistent with the homogenization of sediment during a moderate-density gravity flow. **B)** Thin sections from these same cores show small-scale features consistent with this interpretation. Core 08SL (top) is homogeneous sandy mud, whereas core 07SL (bottom) shows thinly laminated structure (L) with some penecontemporaneous deformation (R).

seen in the seismic records of draped, parallel-bedded sequences. Sedimentation rates in these areas are an order of magnitude higher than in the foreset beds, ranging from 50 cm y^{-1} at 230 m water depth to 20 cm y^{-1} at a site 15 km downcanyon at 570 m water depth (Michels et al., 2003). The draped sequence consists predominantly of graded sand–silt–clay sequences and numerous laminated mud sequences.

The graded units of the dated cores are assumed to have settled from suspension-rich surface water produced by the passage of storm- and cyclone-agitated water masses over the deep-water sediment trap of the shelf canyon. Indeed, the most prominent graded deposits appear to be correlated with the historical record of cyclones of the last 30 years (Kudrass et al., 1998).

The enormously high sedimentation rate in the upper reaches of the SoNG should have resulted in a rapid filling of the whole canyon. The present form of the canyon seems to be maintained by episodic mass wasting affecting the whole canyon, events that happened approximately 150 and 280 years BP (Michels et al., 2003). This episodic emptying is probably how sediments are transferred by turbidity currents to feed the huge Bengal fan, extending as far as to the Equator, more than 2000 km away.

LATE GLACIAL AND HOLOCENE DEVELOPMENT

At the lowstand LGM, approximately 18 ka, the Ganges–Brahmaputra river system had incised near to base level across most of the Bengal Basin, although the upstream extent of incision is not well known. The best constraint is along the Brahmaputra paleovalley, which is known to be ~ 110 m deep at the Jamuna Bridge site 200 km upstream of the modern coast (JICA, 1976). Outside of the alluvial valleys, most of the Bengal Basin was composed of broad, lateritic uplands situated at 45–55 m below present sea level (Goodbred and Kuehl, 2000a). Similar lateritic remains occasionally crop out on the outer shelf (Michels et al., 1998). The formation of ooids and oolitic beach ridges along the former coast, at 20–18 ka, indicate low terrigenous input (Wiedicke et al., 1999) as glacial rivers discharged into the fjord-like SoNG with generally reduced fluvial runoff (Kudrass et al., 2001). By ~ 15 ka, though, increasing rates of sedimentation are recorded contemporaneously with a strengthening summer monsoon and enhanced precipitation over the catchment (Goodbred, 2003). Intensification of the summer monsoon continued into the early Holocene, when higher-than-present precipitation (Prell and Kutzbach, 1987; Gasse et al., 1991; Kudrass et al., 1998; Goodbred and Kuehl, 2003) led to tremendous G–B sediment discharges of ~ 2.5 x 10^{12} kg y^{-1}, or more than 2.5 x the modern load, continuing for several thousand years (Goodbred and Kuehl, 2000b).

The initial period of high sediment discharge is recorded on the fan by the rapid growth of the still active channel–levee system of the Bengal fan between 13 and 9 ka (Weber et al., 1997). Supply to the fan dwindled once the lowstand surface of the Bengal Basin was transgressed, leading to deltaic sediment trapping (Goodbred and Kuehl, 2000a). This initiation of delta formation at 10–11 ka is widely marked on the LDP by deposition of fine-grained mud (i.e., lower delta mud facies) over the lowstand laterite and alluvial sand units. These muds reflect an intertidal mangrove environment containing abundant wood fragments and estuarine shells (Umitsu, 1993). This relatively sensitive coastal setting persisted with little apparent change for the next 2000–4000 years, suggesting that shoreline position was relatively stable during a period in which eustatic sea level rose 30–35 m at a mean rate of ~ 1 cm y^{-1}. Such rapid glacio-eustasy was offset by the immense Ganges–Brahmaputra sediment discharge created by the strengthened monsoon (Goodbred and Kuehl, 2000b; Goodbred, 2003).

In addition to widespread coastal-plain deposition in the early Holocene, major fluvial and flood-basin sequences accreted across the UDP. Sandy channel sequences continued to be deposited in the central alluvial valleys, as well as sequestered to the backflooded Sylhet Basin from ~ 11 to 9 ka (Goodbred and Kuehl, 2000a). Fine-grained sediments were deposited in the Sylhet Basin after ~ 9 ka, indicating that the Brahmaputra flowed along its western (modern) course and delivered most of its coarse load to the coast. This bypassing of inland basins such as the Sylhet likely enhanced shoreline stability during the last phase of rapid sea-level rise. Although the Ganges–Brahmaputra delta sequence was largely aggradational from 11 to 7 ka, pollen abundances from coastal deposits indicate that peak marine influence occurred near the end of this period (Banerjee and Sen, 1988; Umitsu, 1993), corresponding to the maximum transgression. After 7 ka, much of the delta switched to a progradational mode, with alluvial sands prograding widely across the coastal plain as well as the initiation of subaqueous delta development (Goodbred and Kuehl, 2000a; Kuehl et al., 1997). This change characterizes the Ganges–Brahmaputra as a compound delta system with prograding subaerial and subaqueous clinoforms.

Mid-Holocene progradation was most prominent in the western delta, where the Ganges system discharged, and the coast there appears to have approached its present extent by 6 to ~ 5 ka (Allison et al., 2003). In the eastern delta, though, rapid infilling of the Sylhet Basin (> 2 cm y^{-1}) from ~ 7.5 to 6 ka indicates that the Brahmaputra River had switched to its eastern course, into the basin. Thus, much of the Brahmaputra load was sequestered inland, starving the eastern delta front and leading to a maximum transgression 1000–2000 years later than for the Ganges-fed western delta. By 5–6 ka, widespread deposition of muddy floodplain deposits in the Sylhet basin indicates that the Brahmaputra had switched again to its western course.

The main Ganges course migrated or avulsed eastward after ~ 5 ka, creating subaerial deposits extending to the modern coastline (Allison et al., 2003), while the Brahmaputra underwent at least one more cycle of course changes in the late Holocene, switching back to its modern western course only ~ 150 years ago (Fergusson, 1863). With slowed sea-level rise during this period (i.e., production of accommodation space), most of the Brahmaputra load likely bypassed the Sylhet basin and reached the coast. Progradation of the shoreline on the eastern side of the delta appears to have begun after about 3 ka, but constraints are limited because of a lack of radiocarbon dates, with infilling of the modern river-mouth estuary (Meghana estuary) accelerating after the last switch of the Brahamputra to its western course about 150 years ago. On the shelf, the muddy subaqueous delta continued to develop throughout the mid–late Holocene, with the modern foresets prograding up to 15–20 m/yr, the base of which presently reaches the ~ 80 m isobath on the outer shelf (Kuehl et al., 1997; Michels et al., 1998).

SPECIAL ATTRIBUTES OF THE GANGES–BRAHMAPUTRA DELTA

The enormous sediment load of the rivers has had a dramatic influence on the Holocene evolution of the Ganges–Brahmaputra delta, resulting in two phases of subaerial progradation in the Holocene. Goodbred and Kuehl (2000a) and Goodbred (2003) outline how strengthening of the southwest monsoon combined with rapid warming in the Himalayas during 11–7 ka to create sediment supply more than double that of the present. This led to deposition of a delta-plain unit ~ 50 m thick at a pace that exceeded the rate of sea-level rise. As this sediment pulse declined to present levels, sea-level transgression resumed and sediment infilling in inland areas of the Bengal Basin postponed resumption of the progradation of the present LDP until after 5 ka. In contrast, for most other deltas, Holocene delta progradation was restricted to a single phase after deceleration of the rate of sea-level rise (7.4–9.5 ka; Stanley and Warne, 1994).

The relative coarseness of the Ganges–Brahmaputra sediment load also has shaped the modern delta in combination with the large volume of sediment delivered. In the UDP, this can be observed in the rate at which channel avulsions occur (10^2 year intervals) and in the extreme rates of lateral migration within existing channel complexes (up to 800 m/yr) (Coleman, 1969; ISPAN, 1995; Goodbred and Kuehl, 2000b). This is particularly true in the high-gradient Brahmaputra, whose braided reach in Bangladesh has a median grain size in the channel bed of 0.22 mm (Barua et al., 1994) and a sediment load that is 80% silt and sand (Coleman, 1969). Clearly grain size is a contributing factor to rapid aggradation in the UDP and within river channels that leads to lateral migration and avulsion.

In the LDP, grain size may play a role in reducing sediment-compaction-induced subsidence relative to other deltas. In the Mississippi LDP, for instance, the dewatering of high-porosity, clay-rich Holocene sediments is a major part of the rapid subsidence (1–2 cm y^{-1}; Penland et al., 1989) that led to enormous loss of LDP wetlands to submergence in the Twentieth Century (Baumann et al., 1984; Walker et al., 1987; Boesch et al., 1994; Penland et al., 2000). Allison and Kepple (2001) have suggested that despite the thick Holocene section and overall deltaic sediment thicknesses up to 16 km (Paul and Lian, 1975) in the Ganges–Brahmaputra LDP, rates of relative regional sea-level rise are only 0.1–0.4 cm y^{-1}, at or below the rate new sediment is supplied by the coastal setup influx.

Whereas the magnitude of compaction-induced subsidence in the LDP may be relatively small, elsewhere in the Ganges–Brahmaputra delta subsidence rates are much higher, reflecting the complex tectonic setting of the delta. For example, as discussed above, high subsidence and resulting accommodation in the Sylhet and other inland basins apparently had a major influence on delta evolution as well as the timing and magnitude of sediment supply to the ocean. Moreover, it seems likely that subsidence rates in the Sylhet, while controlled primarily by tectonics, also reflect self-compaction of the finer-grained sediments that are deposited there. Unlike other "passive" margins, the tectonic control on the Ganges–Brahmaputra delta is quite striking. In addition to the inland basins mentioned above, relative motion (i.e., both uplift and subsidence) in the Bengal basin clearly has had a strong influence on the rivers' drainage patterns and more generally in dictating the basin boundaries.

Another special characteristic of the delta is the presence of a major submarine canyon, "Swatch of No Ground," which apparently has served as an important conduit for off-shelf escape of the sediment of the Ganges–Brahmaputra rivers throughout the

Late Quaternary. The location of the canyon may be constrained by a major NE–SW trending trough, and if so, is another example of the tectonic control on the dispersal of the rivers' sediment load. In any case, the canyon clearly is an important barrier for the westward transport of sediments to the Indian shelf (Segall and Kuehl, 1992), but it could also serve to limit the seaward progradation of the subaqueous delta. We have estimated that the amount of sediment accumulating in the subaqueous delta is equal to that escaping to the Bengal fan through the canyon (Goodbred and Kuehl, 1999). Hence, it is tempting to speculate that in the absence of such a major sediment sink the seaward progradation of the subaqueous delta, as well as its lateral extent, would be much greater. At present, the outer Bengal shelf does not receive a significant supply of modern river sediment, as evidenced by the exposed Pleistocene surface and oolitic beach ridges.

Although the subaqueous delta of the Ganges–Brahmaputra has many similarities to other major clinoforms forming off large rivers (e.g., Amazon, Huanghe, Fly), it also reveals significant differences. In particular, sand dominates the texture of topset beds for the Ganges–Brahmaputra subaqueous delta, whereas most other major subaqueous deltas are predominantly mud. The overall morphology of the modern delta front and subaqueous delta of the Ganges–Brahmaputra is that of a compound clinoform that generally coarsens up, with a capping of finer-grained supratidal muds (Fig. 15). Over the Holocene, as the delta progrades, much of this fine-grained cap is removed by river migration and is replaced in the stratigraphic record by channel fill. The high sand content of topset beds for the Ganges–Brahmaputra system is in part related to its relatively coarse sediment load, but also to the energetic shallow shelf setting punctuated by frequent cyclones and the resulting wave- and wind-induced bottom resuspension and winnowing. The coarse nature of this system makes the distinction between delta front and subaqueous delta more difficult than in other systems, where typically it is defined on the basis of the textural change from sand or mixed sand and mud, to mud (e.g., Fly; Dalrymple et al., 2003; Harris et al., 1993). At present, we lack sufficient

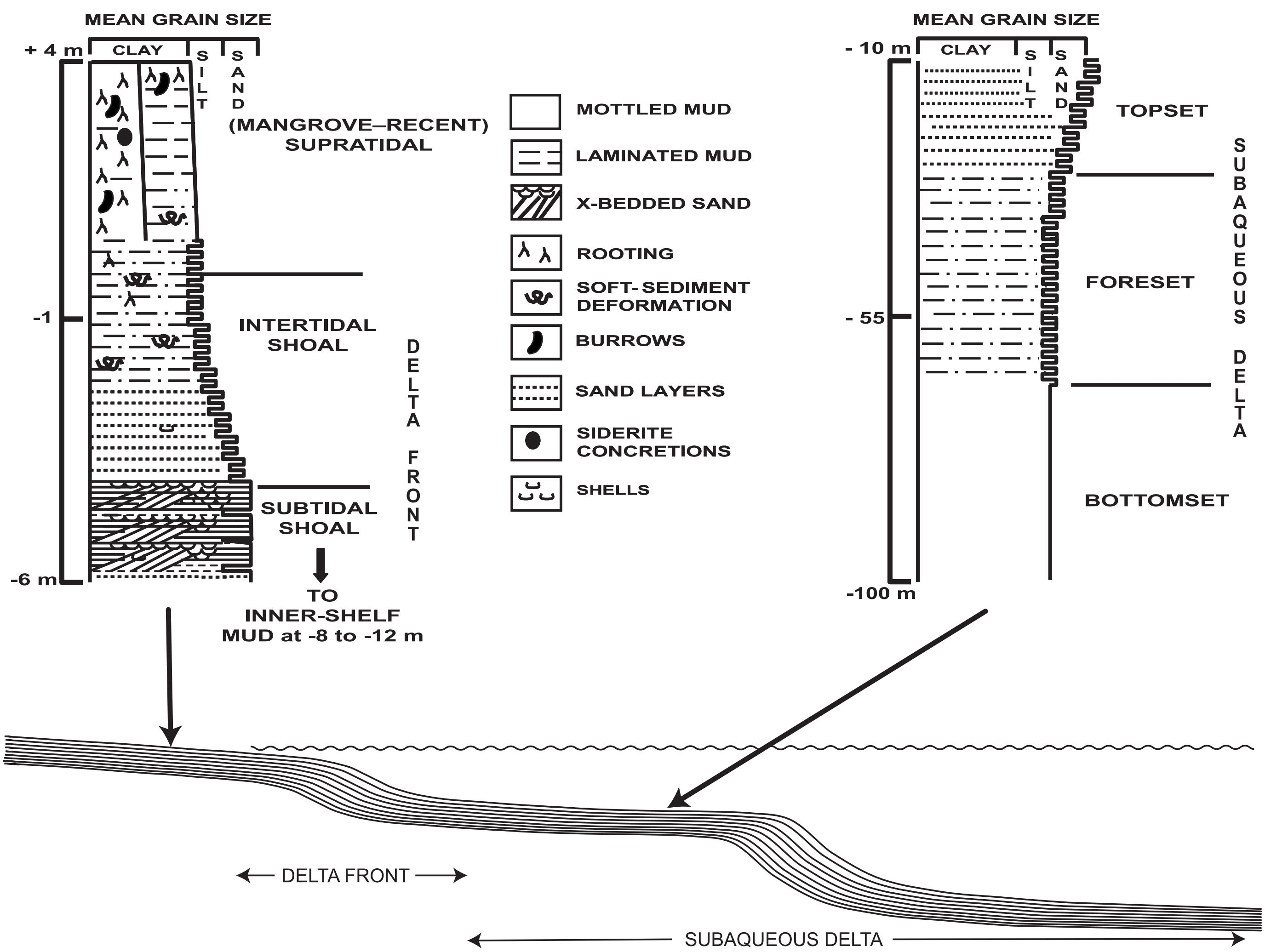

FIG. 15.—Cartoon showing facies succession of the modern Ganges–Brahmaputra Delta (top) with respect to the dual clinoform which comprises the subaerial and subaqueous regions (bottom). The formation of such features appears to be relatively common where large rivers discharge into an energetic marine shelf. The thin fine-grained cap of supratidal muds has a low likelihood of preservation during progradation, inasmuch as it is likely reworked by channel migration.

continuous stratigraphic control to determine whether our distinction between delta front and topset, based on surface morphology and shallow seismic reflection, could be resolved clearly at the outcrop scale.

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