Delta Double-Stack: Juxtaposed Holocene and Pleistocene Sequences from the Bengal Basin, Bangladesh

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ABSTRACT

Analogs – ancient and modern – are key to our understanding and interpretation of the stratigraphic record, which is too often incomplete and sparingly exposed. Here we describe an upward-coarsening Holocene delta sequence that sits unconformably on another, remarkably comparable, delta sequence of Pleistocene age. Such a complete and well-preserved Pleistocene example is rare given extended periods of sea-level lowstand and fluvial incision during the past 200 ka. These stacked delta sequences allow us to consider how analogous our well-studied Holocene analogs are. The comparison reveals a nearly identical facies succession, with modest differences only in the relative timing of delta response to rising sea level. One key difference, though, is a unique facies in the Pleistocene sequence suggesting that major floods from the Himalayas impact the Bengal margin, perhaps periodically, during glacial-interglacial climate transitions.

INTRODUCTION

In the modern world of high sea level, our geologic perspective is often dominated by recent and Holocene-age coastal systems where depositional processes and basin setting are well constrained. However, the extended period of relatively stable climate and sea level during the Holocene is exceptional through at least the Quaternary period, bringing to question how representative Holocene sedimentary analogs are within the geologic record. Here we present detailed stratigraphic, paleoenvironmental, and provenance data for a deep borehole from the lower Ganges-Brahmaputra (G-B) delta plain to better understand the longer-term patterns of Quaternary margin evolution.

BACKGROUND AND METHODS

The G-B delta system sits at the eastern, tectonically active cusp of the South Asian continental collision. Here the already complex regional orogen is overprinted by local tectonics of the Bengal Basin, which together affect delta development through overthrusting, compression, strike-slip, and normal faulting (Steckler et al. 2008). In the upstream catchment, erosional fluxes, source terrains, and sediment transport regimes all respond acutely to intense climatic, tectonic, and glacial processes (e.g., Finnegan et al., 2008; Gabet et al., 2008; Montgomery et al., 2004; Pratt et al., 2002). Many of these catchment signals are strongly and rapidly translated downstream and affect the processes and history of development of the G-B delta system (e.g., Goodbred, 2003; Sarkar et al., 2009). However, much work remains to unravel the mechanisms responsible for the depositional history of the G-B margin in relation to fluvial dynamics, sediment flux, and sediment provenance.

Discharge to the G-B delta system is strongly seasonal and driven by runoff from the southwest summer monsoon, during which the rivers transport 80-90% of their water and 95% of their sediment load. Presently, the Ganges and Brahmaputra rivers deliver about one billion tons (10^9) of sediment to the Bengal Basin annually. However, these South Asian fluvial systems are also strongly influenced by long-term climatic variability, with the intensity and distribution of monsoon precipitation varying at orbital periodicities during the Quaternary (Prell and Kutzback, 1987). Under these fluctuations in monsoon strength, the G-B sediment load has varied by a factor of two both higher and lower than present (Goodbred, 2003).

Initial Holocene development of the G-B delta begins around 11,000 yr BP with the widespread trapping of fine-grained sediments on the lowstand exposure surface (Goodbred and Kuehl, 2000). From 11,000-7000 yr BP, monsoon-enhanced sediment discharge was sufficient for the delta to keep pace with rapid sea-level rise. After this period of delta aggradation, the system began prograding with slowing rates of sea-level rise after 7000 yr BP, despite declining sediment input with a weakening mid-Holocene monsoon. During the last 7000 years of relative sea-level highstand, the delta has prograded steadily and the G-B sediment load equally partitioned across the subaerial delta, subaqueous delta, and canyon-fan system (Goodbred and Kuehl, 1999).

The 123-m long borehole presented in this study was collected near the town of Raipur, Bangladesh, which is located ~10 km east of the modern rivermouth estuary in the southeastern region of the delta (Fig. 1). The borehole was drilled using a reverse-circulating hollow-stem auger with a PVC-lined split-spoon sampler with a recovery rate of 20-30%. A few meters next to the borehole was installed a PVC-cased tubewell from which continuous downhole logs of natural gamma and conductivity were collected using a custom slim-line logging tool. In the lab, core sections were logged for high-resolution imaging, density, and magnetic susceptibility using a Geotek multi-sensor core logger. Grain size (0.1-1000 μm) was measured using a Malvern laser-diffraction particle-size analyzer, and major and trace elements were determined using an Oxford Instruments MDX 1080 multi-dispersive X-ray

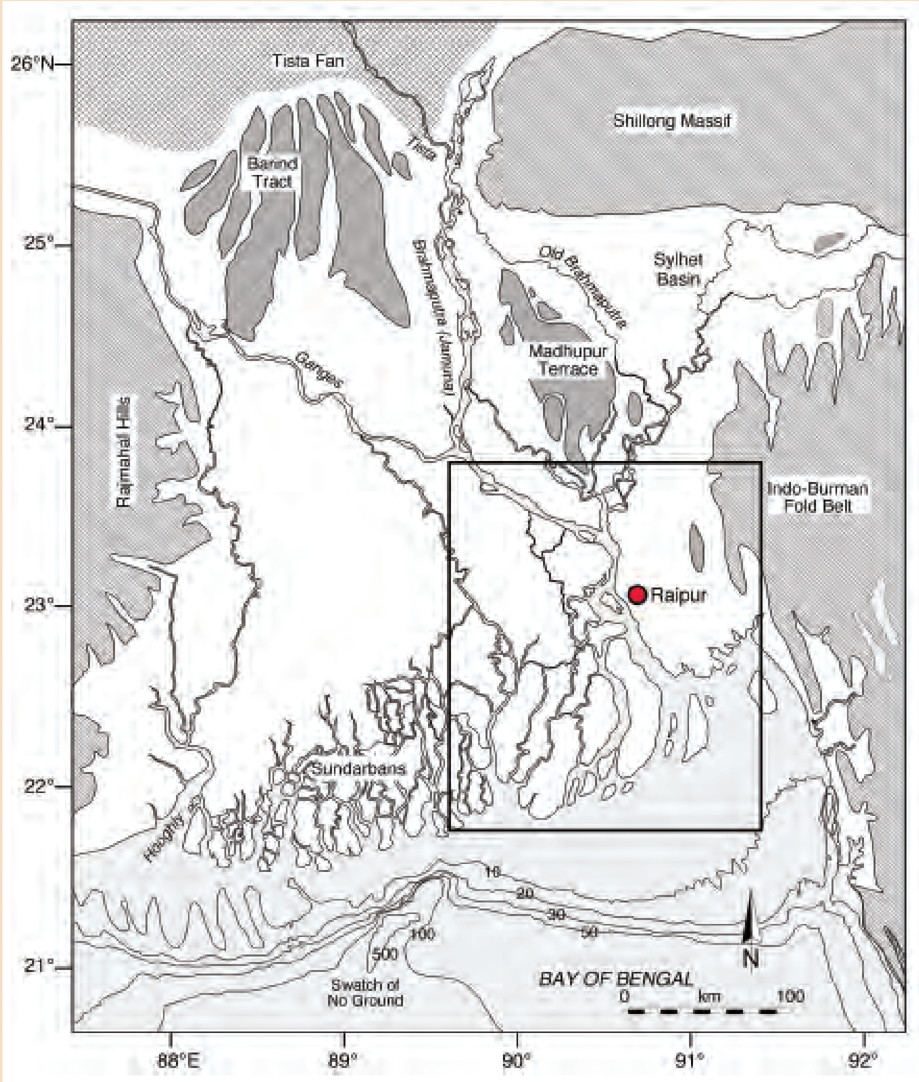

Figure 1. Physiographic map of the Bengal Basin and Ganges-Brahmputra river delta. Location of the 123-m long Raipur borehole is shown on the east bank of the upper rivermouth estuary. Inset box shows the location of Figure 4.

fluorescence spectrometer. All XRF samples were decarbonated by combustion at 600°C for 72 hours and leached with a 15% acetic acid. Three wood samples were radiocarbon dated at the National Ocean Sciences Accelerator Mass Spectrometry Facility and results converted to calendar ages (2σ range) using Calib 5.0.2 software.

FACIES AND STRATIGRAPHY

First-order stratigraphy of the 123-m long borehole is straightforward, comprising two upward coarsening deltaic sequences about 56 m (Holocene) and 66 m (Pleistocene) thick (Fig. 2). The Holocene deltaic sequence lies unconformably on the Pleistocene section along a highly weathered sequence boundary. The two sequences share five distinct sedimentary facies, beginning with Facies A at the base and continuing up-sequence to the capping unit Facies E (Fig. 2). A sixth, unrelated facies, Facies X from the Pleistocene sequence, is enigmatic and discussed separately in the next section.

Facies A is defined as a gray to black clay-rich mud with disseminated organics and wood fragments (Fig. 3). The large tree roots and blackish muds are similar to those found today in low-lying areas of the Sundarbans mangrove forest on the lower delta plain (Fig. 1). Although distant from the active rivermouth, this portion of the delta accretes through river plume dispersal by tides and monsoon coastal circulation (Allison and Kepple, 2003). Based on these characteristics Facies A is interpreted to represent the widespread (pre-human) tidal mangrove environments of the lower delta plain (Fig. 4). The overlying Facies B comprises heterolithic sediments with alternating laminae of silty clays and fine sands. The laminae form regular coarse-fine bedding sets, with bundles of 7-10 of these sets varying between sand- and mud-dominant lithologies (Fig. 3). These characteristics define the facies as tidal rhythmites, which today are found in rapidly accreting areas at the shoreline to a few meters water depth (Allison et al., 2003). Specifically, modern tidal rhythmites are deposited as linear tidal bars at the leading edge of the active rivermouth estuary (Fig. 4). Since the contact of Facies B with the underlying Facies A muds is gradational, this suggests a slow conversion of vegetated coastal-plain to intertidal and shallow-subtidal environments.

Facies C marks a transition into sand-dominated sediments, which here are gray to brown, muddy fine sands with discontinuous, bioturbated bedding (Fig. 3). Such deposits are characteristic today of the upper rivermouth estuary where the main channel begins to split into distributaries (Fig 4). This reach of the river is tidally influenced but still dominated by fluvial processes, as indicated by the sandy lithology and coarse, irregular bedding. The estuarine sands of Facies C contrast with the much finer mud-rich tidal rhythmites that underlie them, and this stratigraphic transition reflects a shift from vertical aggradation to a more progradational trajectory of the delta system. Overlying the estuarine sands is the somewhat similar Facies D, which differs in the absence of muds and more frequent, better-preserved bedding, including common mica-rich laminae (Fig. 3). These changes in lithology reflect the transition to a completely fluvial environment, where tidal influence is lost as the system progrades, and muds are no longer trapped by the bidirectional, convergent flow regime.

An important characteristic of both Facies C and D are the patterned grain-size variations that alternately fine and coarsen over 2-5 m intervals. This pattern is robust and observed in both the core-sampled grain-size data and the downhole gamma-ray logs (Fig. 2), with sizes ranging from coarse silts/very fine sands (~100 μm) to fine-medium sands (~250 μm). However, the structure of these units is variable with some examples coarsening upwards and others appearing to fine. This pervasive pattern in the fluvially dominated Facies C and D is interpreted to reflect bar, dune, and chute development within the braided river system (Fig. 4). Such thick, graded

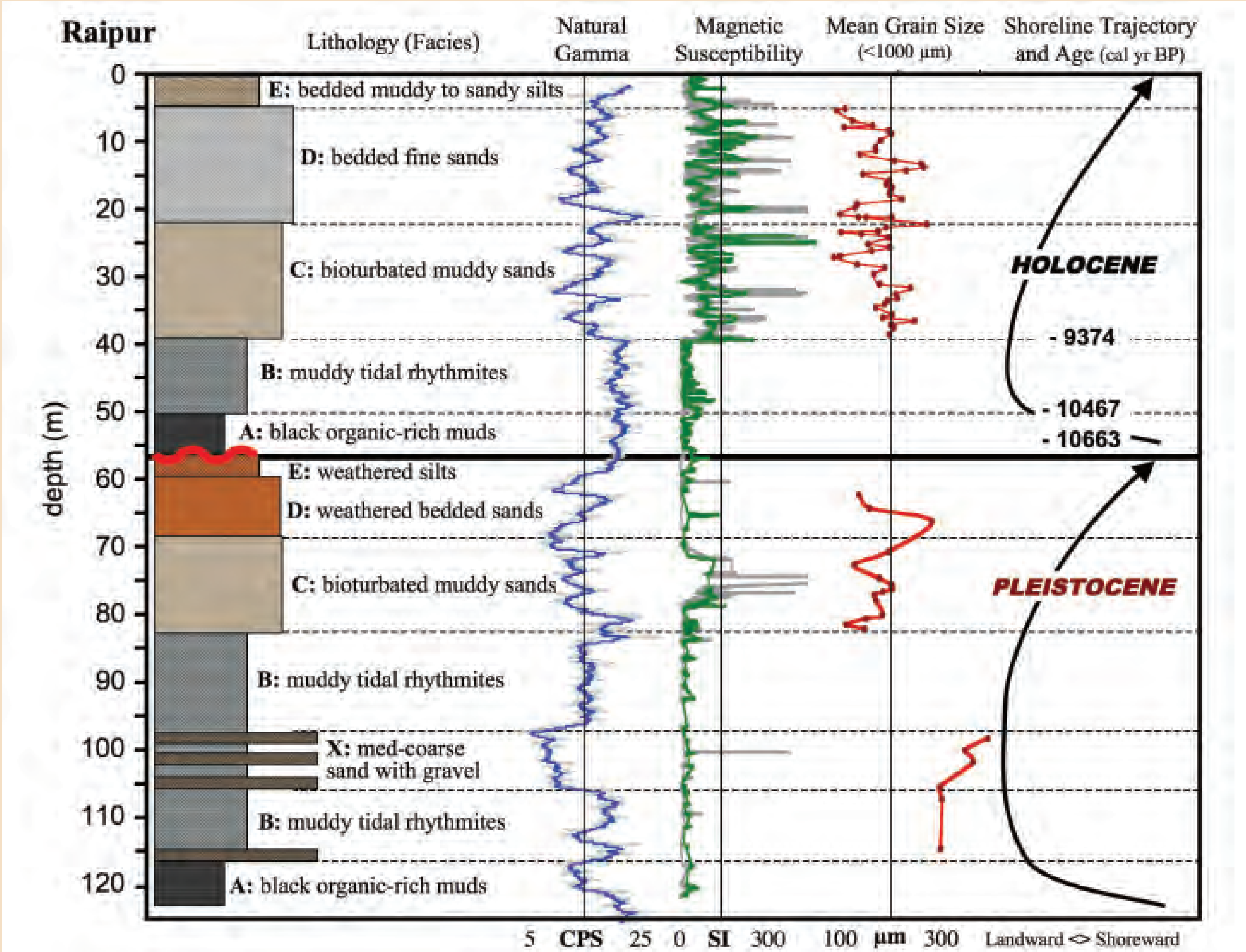

Figure 2. Litholog for the Raipur borehole, including continuous downcore gamma counts (blue), and magnetic susceptibility (green) and grain size measures (red) from the core samples. General transgressive/regressive tendency is plotted in the last column, along with calibrated radiocarbon ages.

sand units are well described from the modern braidbelt, where tall (1-5 m) composite bars and bedforms are exposed during low-river stage (Bristow, 1987). Overlying these channel braidbelt deposits is the silt-dominated Facies E, which ranges from rooted clayey silts to planar or cross-laminated silts to very fine sand (Fig. 3). This facies is typical of the modern floodplain within a few kilometers of the braidbelt (Fig. 4), which is regularly affected by overbank flooding, sheet flow, and local channelization (Allison et al., 1998). The variations of structure and lithology within Facies E reflect seasonal to interannual differences in the fluvial hydrograph and resulting flooding patterns. Facies E is the capping unit of the highstand delta sequence, representing the final infilling of accommodation on the delta plain and the continued progradation of the active delta front (Fig. 2).

AGE AND TIMING

Timing of the Holocene sequence is constrained by three AMS-dated wood fragments from Facies A and B at core depths of 40 m, 50.5 m, and 53 m, with the latter just 3 m above the sequence boundary. The calibrated 2σ age ranges are 9275-9472, 10369-10577, and 10515-10785 cal BP, respectively. The two deeper dates near the sequence base are consistent with results from other portions of the delta, which indicate that delta formation began ~11,000 yr BP.

Comparing with sea level, the age-depth relationship places all of the dated samples ~2-3 m below the global eustatic curve (Fig. 5). Correcting these values for the core-site elevation of +2 m would shift the radiocarbon dates very close to eustatic sea level, which is entirely consistent with an interpretation of upper intertidal to shallow subtidal facies. In fact, these radiocarbon ages yield accretion rates of 1 cm/y for the tidally influence Facies A and B, indicating that sediment discharge to the delta was sufficiently large to offset the rapid rate of sea-level rise during the early Holocene. These results also suggest that this portion of the delta has been tectonically stable through the Holocene, or at least that the sum of multiple vectors is neutral, either of which is rare in the Bengal Basin.

The underlying Pleistocene sequence has no absolute age control but most likely dates to marine-isotope stage MIS 5e (~120,000 yr BP). The MIS 5e highstand is estimated to have been +2 to +10 m above present, but more importantly follows >120 m of glacioeustatic rise following the intense MIS 6 glaciation. This large, rapid transgression would have been able to generate adequate accommodation for the 66-m-thick Pleistocene sequence to develop. In contrast sea level at MIS 3 (~45,000 yr BP) was –20 to –50 m below present, which provides only

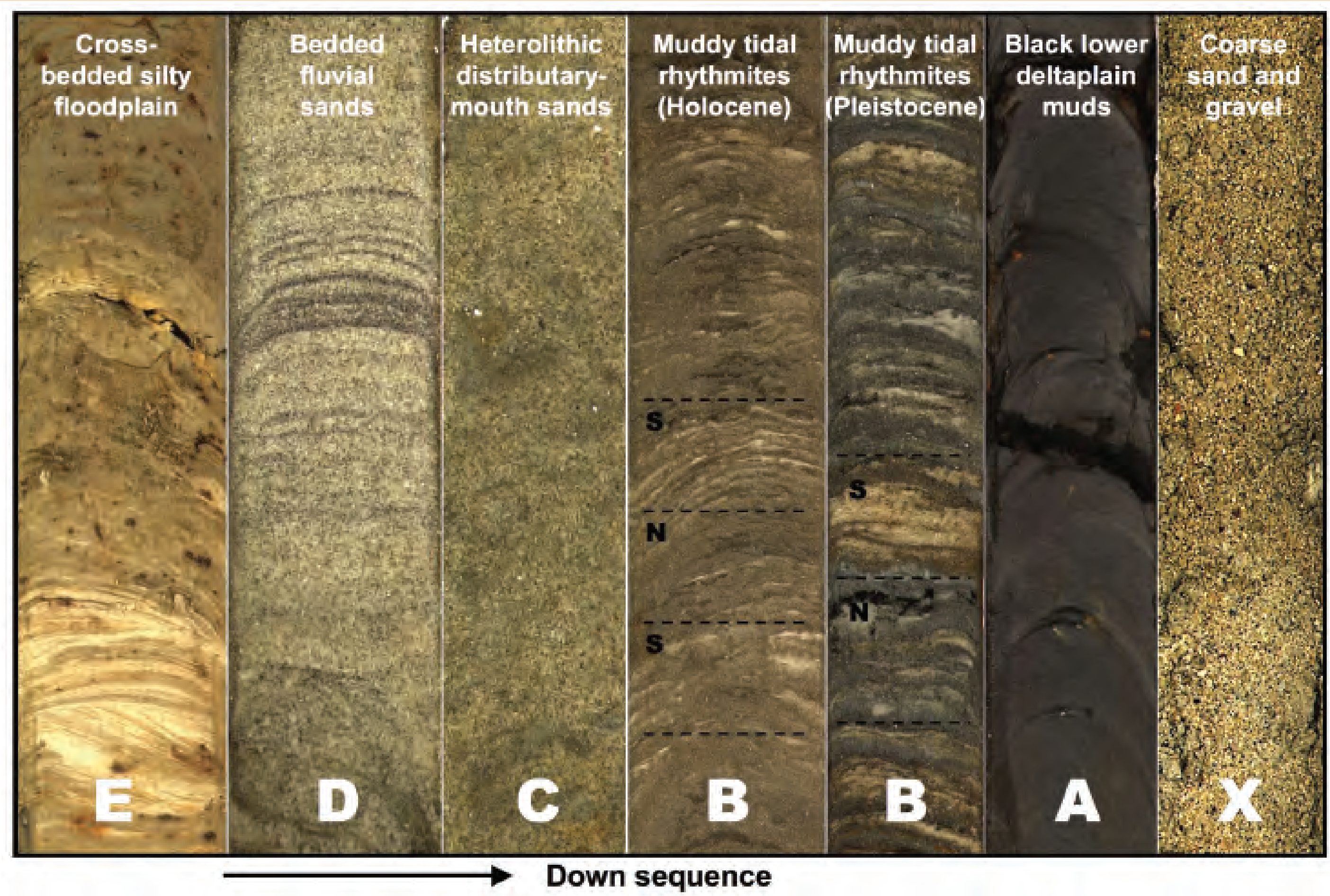

Figure 3. Digital images of sedimentary facies from Raipur borehole (Facies A-E, X). For tidally deposited Facies B, alternating sandy and muddy bundles of laminae are highlighted and correspond to Spring (S) and Neap (N) tidal conditions, respectively.

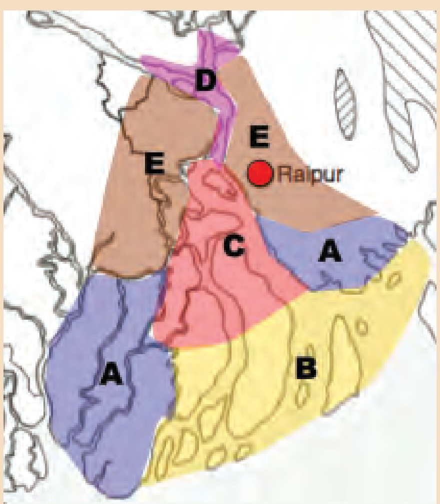

Figure 4. Map showing the distribution of modern environmental analogs for the major sedimentary facies in the Raipur borehole. Note that all facies can be found within or near the rivermouth estuary, indicating that the Raipur stratigraphy reflects a relatively stable highstand delta setting for both the Holocene and Pleistocene sequences. Location of inset map shown in Figure 1.

30-60 m of accommodation above the preceding MIS 4 lowstand. If the Pleistocene sequence does indeed date to MIS 5e, then this would also require a long-term subsidence rate of about 0.5 mm/yr to account for its current depth (-56 m).

SIMILARITIES AND SURPRISES

The sediments and facies character for the two delta sequences are largely the same, with mean grain size, natural gamma, and magnetic susceptibility patterns highly comparable among the fluvial Facies C, D and E (Fig. 2). The vertical succession of facies is also nearly identical in the Holocene and Pleistocene delta sequences. Taken together these findings suggest that marine and fluvial boundary conditions, as well as response of the delta to post-glacial transgression, were remarkably similar at two times separated by ~100,000 years. This finding of repeatedly similar delta response is especially important for the G-B system, which had been previously recognized as unique in developing several thousand years earlier than other Holocene deltas (Goodbred and Kuehl, 2000). The results here confirm this pattern for the MIS 5/6 post-glacial transgression and suggest that the co-phasing of rapid sea-level rise with a strong monsoon system and high sediment flux can regularly lead to early and thick "transgressive phase" delta aggradation.

Looking further, one aspect in which the sequences differ slightly is their overall thickness, at 56 m for the Holocene and 67 m for the Pleistocene (Fig. 2). Given the similarity in facies succession and delta behavior, though, it is tempting to consider that the Pleistocene's extra ~10 m is a consequence of the higher peak sea level at MIS 5e. If true, this would underscore importance of the magnitude of sea-level excursions in defining sequence thickness given an adequate sediment supply. Another difference lies in thickness of the fluvial facies (C, D, E) versus tidal/coastal facies (A, B), which are a total of 40 m and 16 m thick for the Holocene, and 27 m and 40 m thick for the Pleistocene, respectively. These differences suggest that the coastal-to-fluvial facies transition (i.e., aggradation to progradation) at the Raipur site occurred

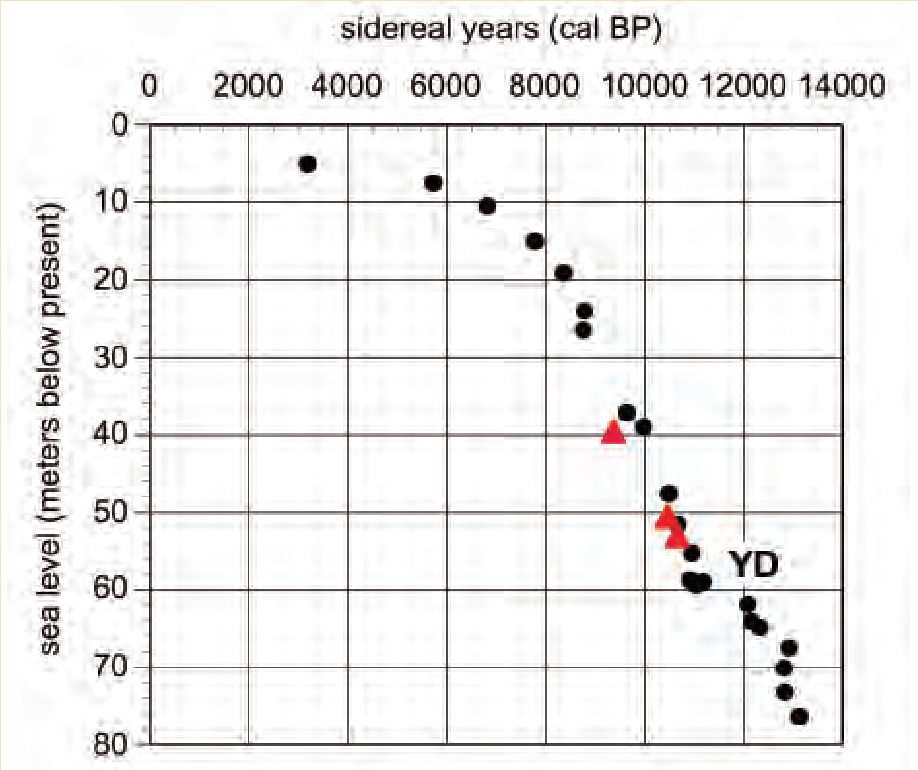

Figure 5. Age-depth relationship for calibrated radiocarbon dates from the Raipur borehole (red triangles) and global eustatic values from Barbados and Huon Peninsula (after Fairbanks, 1989; Edwards et al., 1993). Note that the deepest date lies three meters above the Holocene sequence base, indicating that initial delta development began around 11,000 yr BP shortly after the Younger Dryas (YD) episode. The three Raipur dates also closely track sea level, demonstrating that the G-B delta was largely able to keep pace with rapid sea-level rise (~1 cm/yr) in the earliest Holocene.

comparatively earlier in the Holocene transgression than in the Pleistocene. This pattern, though, is only defined for the Raipur core site and cannot necessarily be extrapolated to the rest of the delta.

Despite so many similarities, there is one major difference with the presence of Facies X in the lower section of the Pleistocene sequence (Fig. 2). Specifically, Facies X is a medium-coarse sand with a small fraction of pea-sized gravel and lithic fragments (Fig. 3). There is no apparent sorting or structure to these deposits, which are at least 50 cm thick. The facies' coarse-grained lithology is anomalous within the 123-m long borehole (Fig. 6) and is also not found in the modern delta system or upstream reaches of the river braidbelts. Perhaps more surprising is that these coarse sediments are found interspersed within the muddy tidal rhythmites of Facies B, placing the coarse sands and gravel at the coast of a fine-grained delta system. The facies' enigmatic lithology and stratigraphic position are confirmed from both the core samples and the continuous downhole natural-gamma logs of the adjacent tubewell (Fig. 2).

So what is the origin of these deposits? They are almost certainly fluvially transported, containing neither mud matrix or angular clasts of a debris flow, nor shell or sorting of marine processes. Geochemical analysis of the sediments reveals low Sr concentrations (70-80 ppm) compared with those of Ganges (90-120 ppm) or Brahmaputra (150-200 ppm) sands, but which are typical of the nearby Tista river (Singh and France-Lanord, 2002). The Tista is a medium-sized Himalayan river that forms a sand/gravel alluvial fan at the northern edge of the Bengal Basin (Fig. 1). Although no coarse Tista sediments reach the delta today, it remains the most likely source given the coarse texture and geochemical character of the sediments. Therefore, we suggest that Facies X is the product of high-energy floods such as bursts of glacial, landslide, or tectonically dammed lakes within the Tista or nearby Himalayan catchment. Precedence for such large bursts is already documented from ice-dammed lake terraces along the Tibetan reach of the Brahmaputra river, which date to the early Holocene (Montgomery et al., 2006). Comparable sands and gravels are found at the same depths in the upper Bengal basin, which is exclusively fluvial, but may correlate with the unusual coarse deposits at the coast.

CONCLUSIONS

The Holocene and Pleistocene sections are sufficiently alike to conclude that delta formation, sequence development, fluvial processes, and marine boundary conditions must also have been remarkably similar at these times. These results help codify the model of a strong South Asian monsoon driving immense sediment flux to the Bengal margin, where tides and coastal circulation efficiently distribute sediments across a broad delta plain at rates sufficient to offset even rapid rates of sea-level rise. This pattern of behavior may also yield insight as to how the Ganges-Brahmaputra and other monsoon delta systems could respond to future changes in climate and sea level, whereby a stronger monsoon and sediment flux could mitigate the impacts of rising ocean levels.

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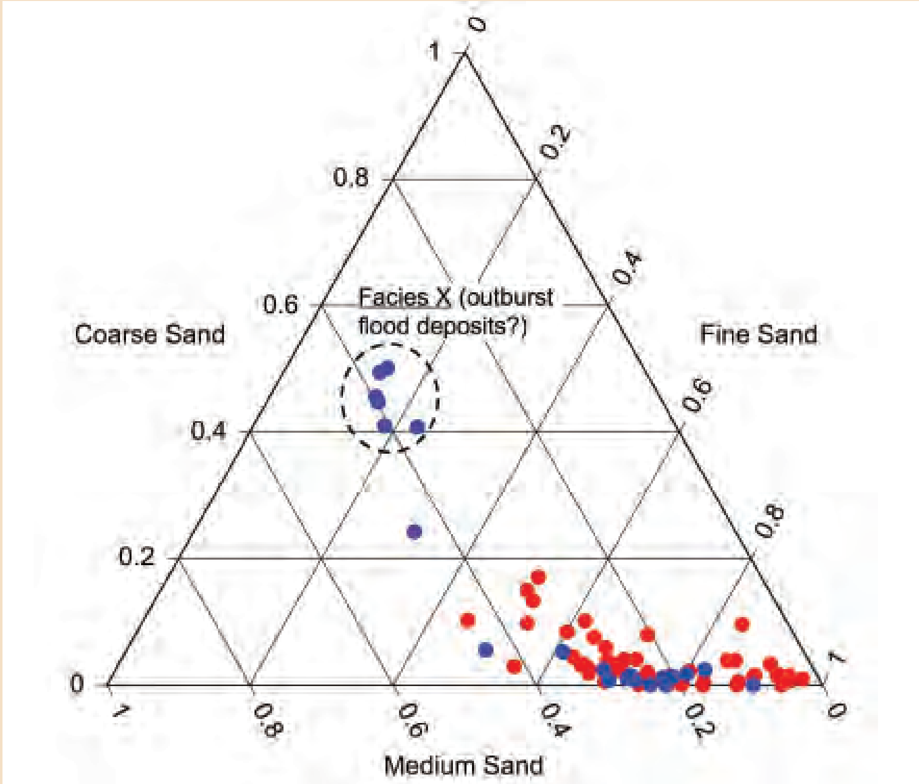

Figure 6. Ternary plot of grain-size distributions for the sand fraction only (63-1000 µm). Data include samples from the Holocene (red) and Pleistocene (blue) sequences. Note that both sequences share the same general grain size distribution for the fluvial sands, except for the anomalously coarse Facies X from the Pleistocene, which is entirely distinct within the borehole stratigraphy.

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