

Holocene Depositional Patterns, Neotectonics and Sundarban Mangroves in the Western Ganges-Brahmaputra Delta

Daniel Jean Stanley† and Arghya K. Hait‡

†Deltas-Global Change Program
Paleobiology E-206 NMNH
Smithsonian Institution
Washington, D.C. 20560,
U.S.A.

‡Center for Study of Man and Environment
CK-11, Sector 2
Salt Lake City
Calcutta 700091, India

ABSTRACT

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Litho- and chronostratigraphic analyses of radiocarbon-dated cores are utilized herein to distinguish Holocene deltaic and underlying transgressive units and late Pleistocene alluvial deposits in the western Ganges-Brahmaputra delta. Regional distribution of these facies indicates that neotectonic displacement, including differential land subsidence, of delta plain sectors is one of the major controls of late Quaternary depositional patterns in this depocenter. The spatial and temporal configuration of Holocene deltaic sediment thickness, mud and sand layers, peats interstratified in Holocene sequences, and modern mangrove forests that form the Sundarbans are attributed to NE-SW, and to a lesser extent NW-SE, neotectonic trends. Holocene sedimentary and stratigraphic configurations closely parallel geological structures, some of them deep seated, that affected this region during most of the Tertiary and have continued to the present.

Extensive mangrove forests developed along the NE-SW zone of thickened Holocene deltaic deposits. Their present configuration is related to natural factors, such as eastward tilting of the delta, rapid sediment accumulation (to 0.7 cm/yr), marked land subsidence (to 0.5 cm/yr), and increasing anthropogenic influences, including large-scale land reclamation and decreased river flow influx. The diverse and extensive mangrove tracts of the delta have significant environmental and economic implications for the rapidly growing population, including serving as a buffer zone that helps to reduce the impact of landward-driven tides, storms and cyclones. Interpretation of Holocene facies in the subsurface by means of radiocarbon-dated cores provides a mean to more precisely define the interaction between contemporary Holocene depositional patterns and neotectonics. This information, in turn, can be utilized to develop realistic measures needed to minimize further degradation of this biologically unique ecosystem.

ADDITIONAL INDEX WORDS: Bengal basin, borings, estuaries, Ganges-Brahmaputra delta, Holocene facies, mangroves, neotectonics, Pleistocene facies, population pressure, radiocarbon dating, salinity, sea level, sedimentation rate, subsidence rate, Sundarbans.

INTRODUCTION

The Ganges-Brahmaputra delta, one of the world's largest and most populated, is a low-lying and highly vulnerable coastal environment (DELFT HYDRAULICS, 1989; ALAM, 1996; KUEHL *et al.*, 1997). This delta, with a tidal range of about 3.5 to 5.0 m in the estuaries (CHAUDHURI and CHOUDHURY, 1994) and complex network of estuaries, creeks and islands (Figure 1), is a classic example of a tide-dominated coastal depocenter (GALLOWAY, 1975). The depocenter is positioned at the mouth of the large Ganges-Brahmaputra-Meghna river system (MILLIMAN and MEADE, 1983; SUBRAMANIAN and RAMANATHAN, 1996; KUEHL *et al.*, 1997; ALLISON, 1998a; MICHELS *et al.*, 1998), with an estimated seaward-directed suspended sediment load of 1060×10^6 t/year (MILLIMAN and SYVITSKI, 1992).

This delta harbours the largest single continuous tract of

diverse mangrove forest (Figure 2), a part of which has been set aside as the world's only mangrove tiger preserve (CHANDA, 1977; NASKAR and GUHA BAKSHI, 1987; HUSSAIN and ACHARYA, 1994). Imbalances in the mangrove ecosystem not only causes serious ecological and socio-economic problems, but also further exposes the rapidly growing population (>110 million persons in the deltaic area of Bangladesh and India) in the vulnerable low-lying depocenter to the dangers of storms and cyclonic surges (CHAUDHURI and CHOUDHURY, 1994). In one storm alone, in 1970, nearly 300,000 persons perished (MILLIMAN *et al.*, 1989) and, at the end of 1998, over half of the lower delta plain surface was submerged by rains and floods.

The late Holocene balance between fresh and salt water in the delta is presently being altered by natural factors (such as tilting of the delta towards east and rising sea level) and increased anthropogenic influences (including withdrawal of river water in the upstream region by dams on the Ganges).



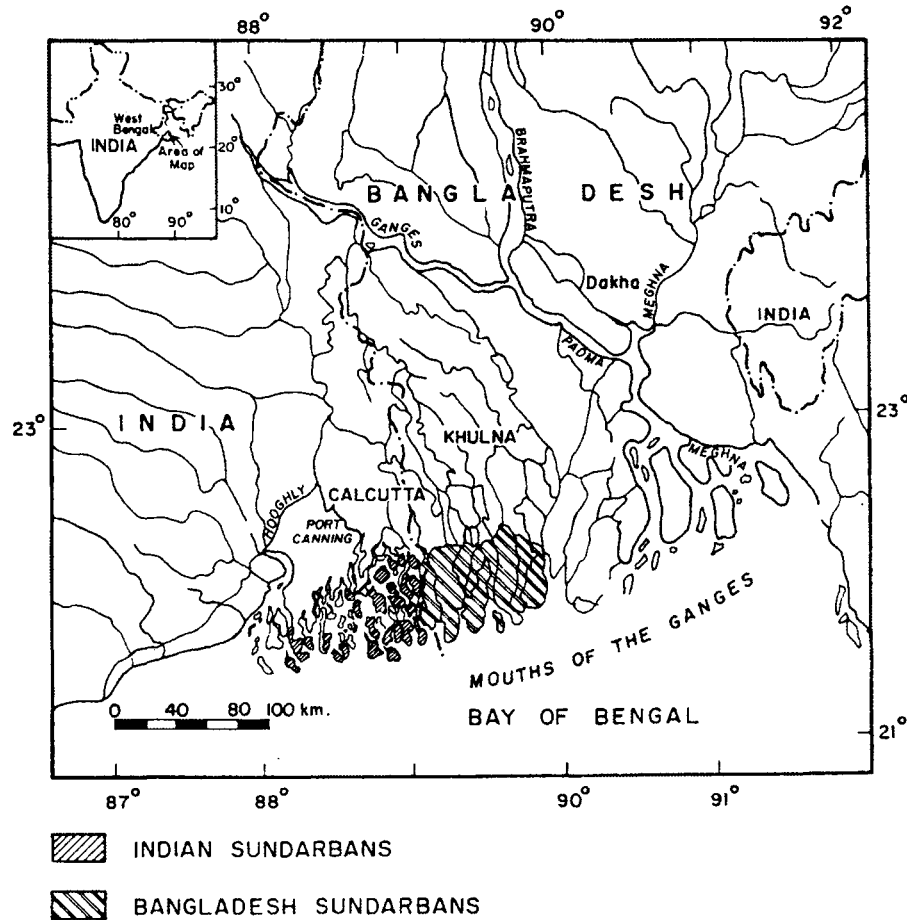


Figure 1. Map of the Ganges-Brahmaputra delta (delineated in Figure 2) and adjacent areas in India and Bangladesh (after HUSSAIN and ACHARYA, 1994). Sundarbans are mangrove forests and swamps.

These changes are inducing enhanced saline intrusion northward, a phenomenon that adversely impacts mangroves and increases salinity in both soil and ground water (MILLIMAN *et al.*, 1989; SANYAL, 1990; NAZRUL-ISLAM, 1993; ALAM, 1996; BLASCO *et al.*, 1996; ALLISON, 1998a). Formulation of effective coastal zone protection contingency plans requires measurement of ongoing changes in sediment input (SUBRAMANIAN and RAMANATHAN, 1996) and evaluation of recent impact of land subsidence that affects sedimentation in this delta region.

Previous studies indicate that subsidence may be affecting the low-lying plain of the Ganges-Brahmaputra delta (MORGAN and MCINTIRE, 1959; MILLIMAN *et al.*, 1989; ALAM, 1996; ROY and CHATTOPADHYAY, 1997). Preliminary radiometric and paleobiological data indicate that land has been lowered relative to sea level in recent time (ALAM, 1996; CHANDA and HAIT, 1996; HAIT *et al.*, 1996a). One of the most useful methods to calculate the Holocene average rate of subsidence is by measurement of the present subsurface depth of dated late Quaternary sediment core sections (STANLEY, 1997). To date, there has been only a limited number of borings recovered in the delta and an insufficient number of ra-

diocarbon-dated core sections to define late Pleistocene and Holocene subsurface environments (HAIT *et al.*, 1996a). A study of drill cores along a N-S axis in the Bangladesh sector, forming the eastern two-thirds of the Ganges-Brahmaputra delta, has revealed the general late Quaternary lithostratigraphy (UMITSU, 1993). However, to date there has been no accurate region-wide correlation between cores because of insufficiently detailed lithologic criteria and too few radiocarbon-dated sections to accurately define the stratigraphic framework, including delineation of Holocene units and the Holocene-Pleistocene boundary.

The present study refines the late Quaternary stratigraphy of a suite of longcores recovered from the southwestern part (India) of the Ganges-Brahmaputra delta. Herein, petrologic analysis coupled with radiometric dating (both conventional and AMS methods are used) define Holocene and late Pleistocene subsurface units, and enables these to be correlated across this part of the delta. This information also provides a means to calculate rates of Holocene sediment accumulation and land subsidence. The distribution and geometry of subsurface Holocene deposits is related to some neotectonic structures that have recently affected the western delta and

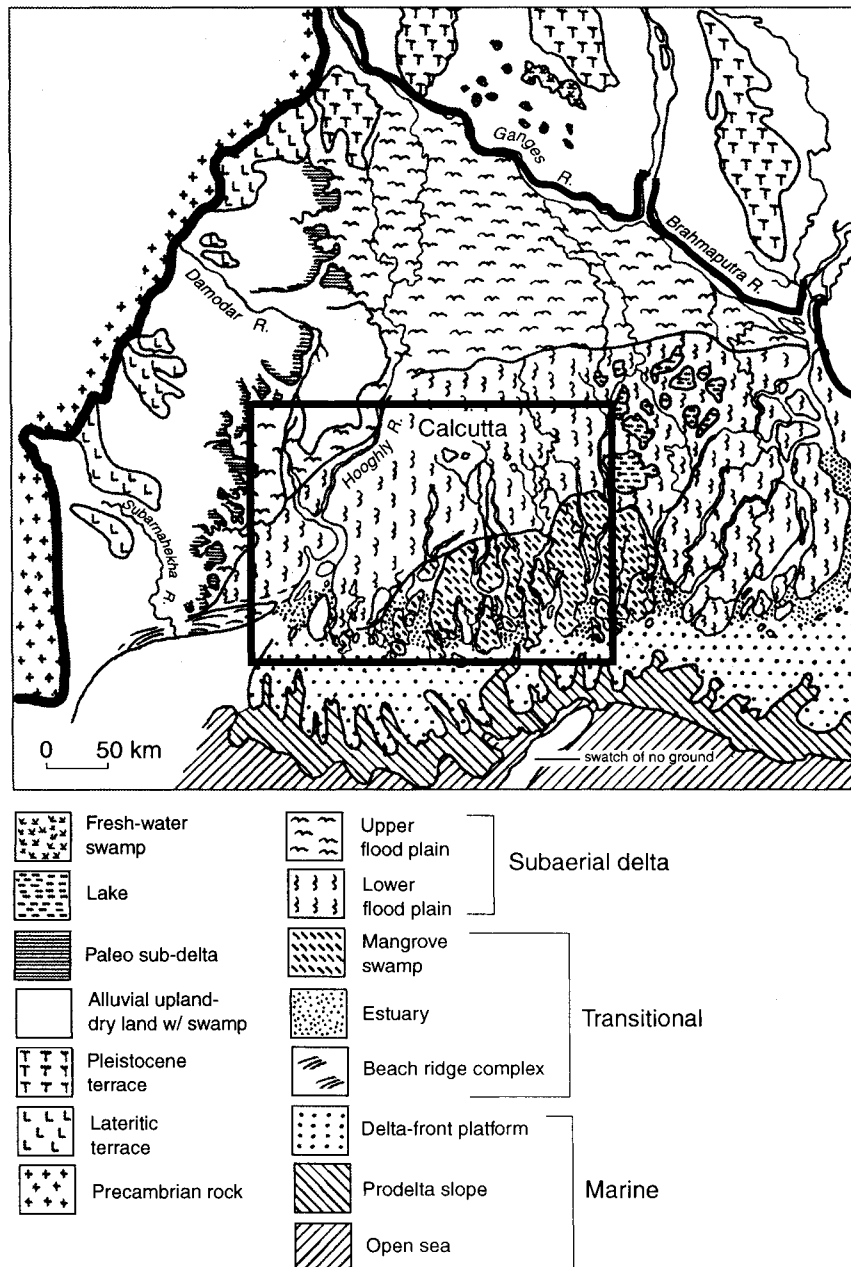


Figure 2. Distribution of depositional environments in the Ganges-Brahmaputra delta (area within heavy line), and pre-Holocene terrains in the contiguous region (modified AGARWAL and MITRA, 1991). The rectangular area denotes the sector of core recovery in this study (Figure 3).

the Sundarbans, the complex of mangrove-covered islands and associated tidal creeks and estuaries on the SW delta margin.

METHODS

Fourteen cores, collected for paleoenvironmental analysis, are used for the present investigation. These borings, distributed across the western Ganges-Brahmaputra delta (Figure 3), range in length from 20 to 50 m (Table 1). The lithological

facies were initially defined by visual observation of split cores and petrologic description of core samples. More than 1500 samples were selected down-core at about 20 to 50 cm intervals for palynological, micropaleontological and sedimentological analyses. In addition, a number of representative samples were selected for general lithological study and more specific analyses, including grain size, heavy mineral, spore and pollen, foraminifera and radiocarbon dating (CHANDA *et al.*, 1996). This information, and many of the core

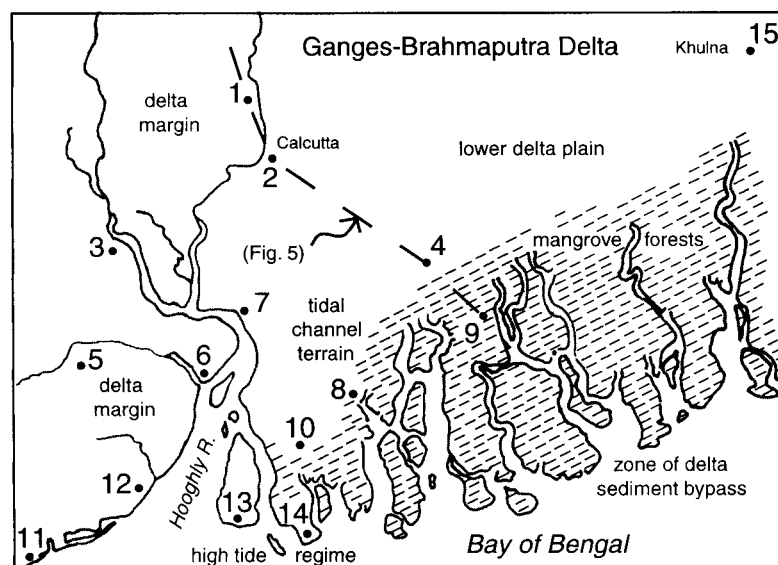


Figure 3. Position of the 15 cores used in the present study (locality names and other details pertaining to borings are given in Table 1). The NW-SE transect of cores is shown in Figure 5.

logs, are available elsewhere (HAIT *et al.*, 1994a,b; CHANDA and HAIT, 1996; DAS, 1996; HAIT *et al.*, 1996a,b).

A preliminary compilation of existing conventional radiocarbon dated sections from excavations and cores in the delta are published by CHANDA and HAIT (1996), HAIT *et al.* (1996a) and UMITSU (1993). For the present study, an additional 5 conventional and 21 AMS dates were obtained from core sections. The 48 core sample dates (given here in years before present, yrs B.P.; corrected for isotopic fractionation, but not calibrated) available from the Ganges-Brahmaputra delta, along with core sample depth and nature of dated material, are presented in Table 2. This listing also includes published dates from a core at Khulna in the central delta (UMITSU, 1993).

These radiometric data are used to determine the *annual mean rate of Holocene sediment accumulation* in each core by

dividing the length of Holocene section by the radiometric data obtained at or near the base of the Holocene unit. For example, a 7 m-long Holocene unit that began to accumulate 7000 years ago records an annual mean accumulation rate of 0.1 cm.

The *annual mean rate of Holocene land subsidence* is determined by the formula, $[a - (b + c + d)]/e$. Parameter *a* is the total thickness of the Holocene section. From this thickness, three values are subtracted: *b* = depth of former sea level at the time when the basal Holocene muds were deposited (in m below present msl), as derived from frequently used world curves (CHAPPEL and SHACKLETON, 1986; FAIRBANKS, 1989); *c* = surface spot elevation on the delta plain at which the core was drilled above present msl; and *d* = the approximate water depth at which the basal Holocene sediment was deposited (this value ranges from near sea level in the case of dated mangrove material to -5 m below sea level

Table 1. Information pertaining to fourteen cores recovered in the western Ganges-Brahmaputra delta (see Fig. 1).

Core Code No.	Core Location	Geographical Coordinates		Spot Height (in m above m.s.l.)	Total Core Length (in m)	Length of Holocene Unit (in m)	% Mud in Holocene Unit	% Sand in Holocene Unit
		N	E					
1	Dankuni	22°05'	88°01'	6.0	30.0	11.5	91.7	8.3
2	Salt Lake	22°34'	88°28'	5.8	32.5	11.3	87.2	12.8
3	Kolaghat	22°27'	87°55'	5.5	30.0	11.0	100	0
4	Canning	22°10'	88°38'	1.6	48.0	43.5	14	86
5	Bhagawanpur	22°05'55"	87°45'10"	2.0	20.0	3.9	87.9	12.1
6	Haldia	22°03'	87°59'	4.3	30.5	>30.5	77	23
7	Diamond Harbour	22°13'	88°10'	6.5	33.0	26.5	100	0
8	Raidighi	22°00'	88°26'14"	2.4	48.1	25.0	31.2	68.8
9	Pakhirayala	22°14'	88°47'	2.0	50.0	>50	43	57
10	Bishalakhshampur	21°50'	88°13'52"	2.7	35.8	>35.8	43.2	56.8
11	Digha	21°37'	87°32'	1.0	30.5	13.2	100	0
12	Junput	21°43'	87°49'	1.0	39.3	16.5	74.6	25.4
13	Sagar Island	21°39'8"	88°5'5"	3.1	49.4	23.0	80.8	19.2
14	Bakkhali	21°37'	88°18'	2.6	42.5	>42.5	55.7	44.3

Table 2. Radiocarbon dates obtained from 14 cores recovered in the western delta, and from 1 core (Khulna) in the central Ganges-Brahmaputra delta.

Code No.	Sampled Core	Depth in m from core top	Age	Laboratory Reference No.	Material Used for Dating
1a	Dankuni	4.40	4500 ± 35	*OS 17646	peat
1b		7.60	6030 ± 140	□BS 1158	peat
2a	Salt Lake	4.25	3990 ± 70	□PRL 1776	peat
2b		13.20	24,200 ± 580	□BS 1235	organic-rich mud
2c		15.85	3860 ± 30	*OS 17059	wood fragments
3a	Kolaghat	7.00	6900 ± 70	□PRL 1781	peat
3b		8.50	7710 ± 50	*OS 17288	wood fragments
3c		26.60	31,750 ± 2030	□BS 1192	organic-rich mud
4	Canning	31.68	6250 ± 140	□BS 1160	wood fragments
5	Bhagwanpur	3.40	5360 ± 30	*OS 17284	wood fragments
6a	Haldia	13.30	7220 ± 50	*OS 16357	wood fragments
6b		24.3	7350 ± 55	*OS 17644	wood fragments
6c		30.00	7800 ± 410	□BS 1179	organic-rich mud
7a	Diamond Harbour	15.25	7030 ± 30	*OS 17285	wood fragments
7b		28.00	14,460 ± 350/320	□PRL 1779	organic-rich mud
8a	Raidighi	21.73	7260 ± 50	*OS 17063	wood fragments
8b		23.40	7960 ± 170	□BS 1394	organic-rich mud
8c		23.50	9420 ± 235	□BS 1389	organic-rich mud
8d		27.00	7430 ± 45	*OS 17283	wood fragments
9a	Pakhiralaya	4.90	4250 ± 40	*OS 17287	wood fragments
9b		22.30	7530 ± 100	□BS 1156	wood fragments
9c		41.30	8250 ± 60	*OS 17064	wood fragments
9d		49.80	8800 ± 135	□BS 1190	organic-rich mud
10a	Bishalakshnipur	3.20	450 ± 25	*OS 17061	wood fragments
10b		27.25	7650 ± 35	*OS 17286	wood fragments
10c		31.75	7460 ± 35	*OS 17060	wood fragments
10d		35.60	7790 ± 50	*OS 17062	wood fragments
11a	Digha	11.80	9150 ± 400	□BS 1236	shell fragments
11b		24.50	22,360 ± 450/420	□PRL 1777	organic-rich mud
12	Junput	13.88	5910 ± 129	□BS 1401	organic-rich mud
13a	Sagar Island	23.65	24,160 ± 520	□BS 1399	organic-rich mud
13b		42.20	52,000 ± 1110	*OS 16360	shell fragments
13c		47.70	42,300 ± 1110	*OS 16695	shell fragments
13d		48.80	38,900 ± 240	*OS 16696	shell fragments
14a	Bakkhali	8.38	4710 ± 120	□BS 1159	wood fragments
14b		12.20	4790 ± 30	*OS 19420	wood fragments
14c		23.40	6040 ± 35	*OS 16697	shell fragments
14d		28.40	5690 ± 35	*OS 16408	shell fragments
14e		41.00	6165 ± 190	□BS 1191	organic-rich mud
15a	Khulna	5.0	3230 ± 110	GaK 12952	peat
15b		13.0	6880 ± 130	GaK-12953	wood fragments
15c		16.0	6490 ± 100	NUTA-342	wood fragments
15d		20.0	7060 ± 120	NUTA-1342	shell fragments
15e		27.0	7640 ± 100	NUTA-343	wood fragments
15f		30.0	10,190 ± 210	GaK-12954	plant material
15g		34.0	8890 ± 150	NUTA-344	plant material
15h		35.0	8910 ± 150	NUTA-1345	shell fragments
15i		48.0	12,320 ± 240	NUTA-345	plant fragments

Notes: * OS = this study, AMS analysis from Woods Hole AMS Facility. □ = this study, conventional ¹⁴C analysis, from BS = Birbal Sahni Institute of Palaeobotany, Lucknow, India and PRL = Physical Research Laboratory, Ahmedabad, India; GaK and NUTA = Khulna core, conventional ¹⁴C age analysis age and core depth data from UMITSU (1993).

in the case of dated marine shells). This numerator is divided by parameter **e**, the amount of time during which the Holocene section in that core was deposited (*i.e.* from the radiocarbon date at or near the base of the Holocene section).

As an example of mean subsidence rate calculation, the following values are considered: **a** = a 20 m-long Holocene core section is recovered; **b** = an original depth of 12 m below present msl is assigned to the base of the section dated at 7500 yrs B.P.; **c** = drilling was made at a surface elevation of +2 m above msl; **d** = the radiocarbon date was obtained from mangrove plant material that accumulated near sea level, and

thus a value of 0 is used; and **e** = the Holocene section began to accumulate ~7500 years ago. Using the above formula, an annual mean subsidence rate of 0.08 cm/yr is determined.

DIAGNOSTIC ATTRIBUTES OF HOLOCENE AND PLEISTOCENE UNITS IN CORES

Holocene and Pleistocene lithofacies have been distinguished in exposed Quaternary sections of the Bengal basin (MORGAN and McINTIRE, 1959; PODDAR *et al.*, 1992; ROY and CHATTOPADHYAY, 1997; SINGH *et al.*, 1998). However, only a

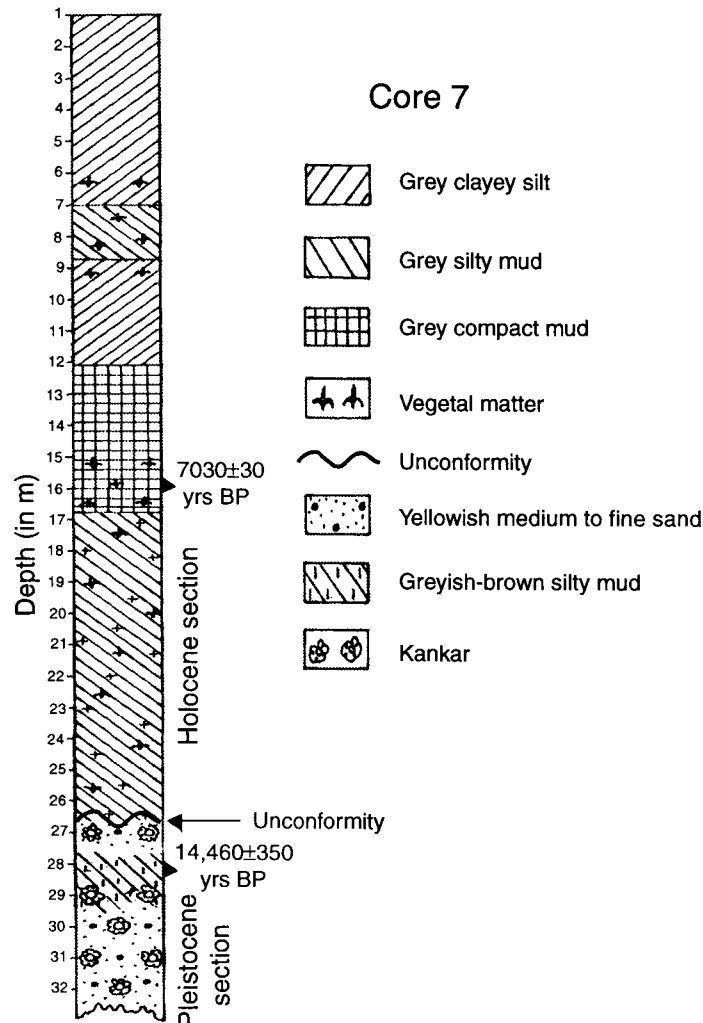


Figure 4. Lithologic log of core 7 recovered at Diamond Harbour, showing radiocarbon dates and distinct Holocene and Pleistocene sediment facies separated by an unconformity.

limited number of these latest Pleistocene and Holocene surface exposures have been radiocarbon dated. Moreover, the chronostratigraphy of late Quaternary formations in the subsurface has remained poorly defined. The radiocarbon-dated borings of the present study serve to refine the late Quaternary stratigraphy of the western Ganges-Brahmaputra delta. Core facies analysis that includes both ^{14}C and lithological data (example in Figure 4) clearly distinguishes the late Pleistocene section from the overlying Holocene deposits in this delta.

Diagnostic features of the *late Pleistocene sequence* include the following:

- Muds are significantly harder (termed stiff) than those of Holocene age, and record effects of laterisation with attributes that include highly weathered oxidized coloration (yellow, brown, tan, mottled and rust).
- Some muds display rust stained (iron oxide) spots, while

others comprise calcareous and/or iron concretions, and these are termed *kankar* (cf. COULSON, 1940).

- Sand is generally poorly sorted and somewhat coarser (medium grained) than those of Holocene age; in the case of one boring (core 11), granules and pebbles are present.
- Sand and silt facies are tan and yellow, and in some cases with rust (iron oxide) stains.
- The late Pleistocene also can generally be distinguished by a lower amount of dispersed plant matter in both muds and sands, and by absence of interbedded peat layers.
- The sand-size fraction of most Pleistocene layers is also characterized by large proportions of fully iron-stained (~19%) and partially iron-stained (~27%) quartz grains based on counts of 300 quartz grains in each sample (Table 3).
- Compositional counts of the sand-size fraction (based on counts of an additional 300 grains in each sample; Table

Table 3. Sand-size fraction analyses: proportions of non-stained, partially iron-stained and fully iron-stained quartz grains (300 grains counted per sample); and proportions of major compositional components (additional 300 grains counted per sample).

Core Location	Stratigraphy	Staining (300 grains counted)			Composition (300 grains counted)						
		Non-stained Quartz	Partially Stained Quartz	Fully Stained Quartz	Light Minerals	Heavy Minerals	Mica	Lithic Fragments	Aggregates	Plant Matter	Shell Fragments
Canning (Core 5)	Holocene (n = 19)	89.6	6.5	3.4	66.1	2.0	10.8	21.0	0	0.1	0
	Pleistocene (n = 3)	48.9	29.6	21.3	69.2	0.7	5.1	13.8	11.1	0	0
Sagar Island (Core 10)	Holocene (n = 47)	89.7	8.0	2.2	62.9	1.5	23.3	0.03	5.5	3.2	1.9
	Pleistocene (n = 29)	56.2	31.6	12.0	56.3	1.5	18.2	0.01	20.3	2.8	0.5
Raidighi (Core 14)	Holocene (n = 29)	83.9	11.9	4.2	64.3	1.7	16.5	11.9	3.3	1.5	0.02
	Pleistocene (n = 27)	54.3	21.2	22.7	57.7	0.7	20.7	12.1	9.4	0.1	0.2
Overall Average	Holocene (n = 95)	87.7	8.8	3.3	64.4	1.7	16.9	11.0	2.9	1.6	0.6
	Pleistocene (n = 59)	53.1	27.5	18.7	61.1	1.0	14.7	8.6	13.6	1.0	0.2

3) record important proportions of aggregate grains (~14%; sand-sized grains formed of partially-cemented silt particles), and by low amounts of plant matter (~1%) and foraminiferal fragments (to 0.2%) that are usually weathered and poorly preserved.

With the exception of some weathered sections near core tops, *Holocene mud and sand facies* are generally characterized as follows:

- Deposits do not display the typical signature of oxidation (yellow, orange, reddish, and brown colors), nor do they include hardened (stiff) muds with calcareous and/or iron concretions.
- In marked contrast to the Pleistocene, Holocene muds are very soft to moderately compact, grey to dark olive grey and black.
- Muds have a high organic matter content, and locally may include abundant plant matter.
- Layers of peat, ranging in thickness from a few millimeters to 50 cm, are commonly interbedded in grey Holocene muds.
- Sands and silts tend to be finer grained than in Pleistocene sections, are usually grey, and commonly include dispersed plant matter and shell fragments.
- Proportions of clear unstained quartz (average to ~88% of all quartz grains), plant debris (to 1.6%), and well-to-moderately preserved foraminiferal tests (to 0.6%) in the sand-size fraction are generally higher than in Pleistocene sands, while aggregate grains (<3%) are present in lower proportions.

Averaged proportions of sand-size components in Holocene and Pleistocene deposits analyzed in selected western delta cores are presented in Table 3. The dated base of the Holocene deltaic section in 9 of 15 cores is within the range of 6500 to 8500 yrs B.P.

In some sections (including those of core site 9, Pakhiralaya), the deltaic unit is underlain by somewhat older Holocene grey mud. This mud stratum tends to be more compact

than the overlying soft Holocene deltaic muds, is somewhat more tan and light yellowish-grey, and commonly contains mangrove palynomorphs and other vegetal matter. Such deposits beneath the typical Holocene deltaic unit, but above the Pleistocene section, is interpreted here as a transgressive unit (*cf.* STANLEY and CHEN, 1993; STANLEY and WARNE, 1993), and are typically >8500 yrs B.P. in age.

The upper part of the oxidized late Pleistocene section below Holocene deltaic and transgressive units is >10,000 yrs B.P. This much older age indicates that an unconformity (minimal hiatus of 1500 years) generally separates the early Holocene from the upper Pleistocene units at most core localities. The log of the boring recovered at Diamond Harbour (core 7 in Figure 3) shows many of the lithostratigraphic characteristics, including the Holocene-upper Pleistocene discontinuity discussed above (Figure 4). The fourteen cores recovered in the western delta, plus the radiocarbon-dated core collected in the central delta at Khulna, Bangladesh (UMITSU, 1993, his Figure 7) can now be stratigraphically correlated across the study area (Figure 5). Logs of other long borings in the study area that are not shown here are available from the authors.

REGIONAL DISTRIBUTION OF HOLOCENE DELTA DEPOSITS

The thickness of Holocene sections in cores ranges from 2.5 to >50 m, with a marked thickening in a southeasterly direction in the study area (Figure 5). An isopach map showing the Holocene thickness pattern (Figure 6A) is compiled on the basis of deltaic deposits in the fifteen delta cores (Table 1). Contours record a distinct NE-SW trend, with thicknesses increasing from <30 to >50 m southeast of a line from Canning (core 4) to Sagar Island (core 13). A less marked NW-SE trend occurs in the Haldia-Raidighi-Bishalakhshampur (cores 6, 8, 10) sector.

The approximate mean annual sediment accumulation

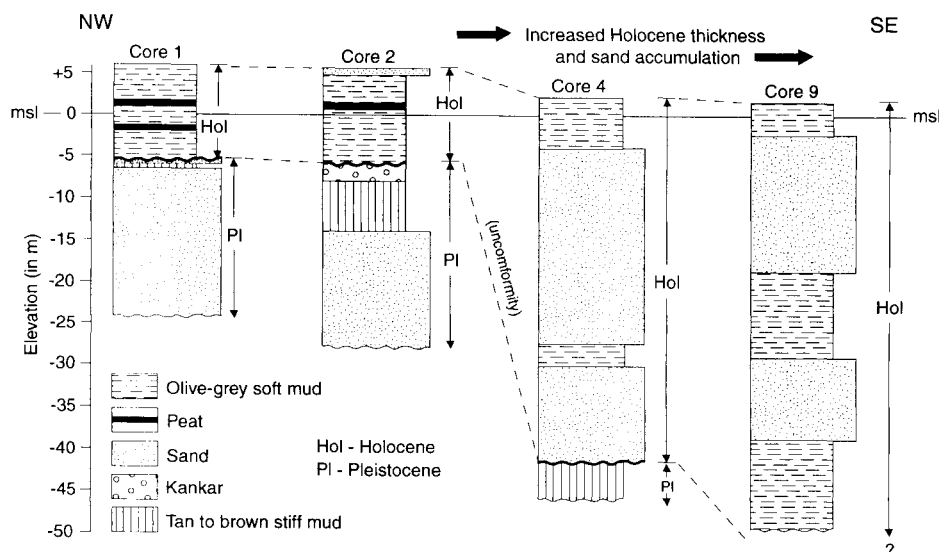


Figure 5. Stratigraphic correlation of 4 cores along a NW to SE transect in the western delta (actual spacing between the cores is shown in Figure 3). This diagram reveals substantial thickening of the Holocene section toward the coast, and the marked increase in proportion of sand in core 4.

rates are calculated using a base-of-core Holocene date of 7500 yrs B.P. (derived from the recorded 6500 to 8500 yrs B.P. dates): for a 10 m-long section, the rate is 0.13 cm/yr.; for a 20 m section, the rate is 0.27 cm/yr.; for a 30 m section, the rate is 0.4 cm/yr.; for a 40 m section, the rate is 0.53 cm/yr.; and for 50 m section, the rate is 0.67 cm/yr. Mean sediment accumulation rates increase toward the south and southeast. The rates of mean vertical motion are lowest in the NW sector of the cored study area (slight uplift to <0.2 cm/yr), while subsidence increases substantially toward the SE. The highest subsidence rate (to ~0.5 cm/yr) is recorded at Pakhiralaya (core 9).

The total proportions of mud (clay and mixed silt and clay) and of sandy facies (clean coarse silt, mixed silt and sand, mixed sand and coarser-grain sediment) that form the Holocene section are measured for each core (Table 1). These data provide general information on sediment dispersal. The map depicting the regional distribution of total sand percentage (range from 0 to 86%) indicates that sand is preferentially distributed along the NE-SW trend, *i.e.* parallel to Holocene thickening (Figure 6B), from Canning (core 4) toward Bishalakshampur (core 10). A less distinct trend is also noted from Bhagwanpur (core 5) in the NW to Bishalakshampur (core 10) in the SE. The linear area covered by high (>60%) sand proportions is narrow, with values decreasing from 80% in a direction to the SW of Canning (core 4). A tighter net of cores is needed to further refine dispersal patterns.

The map showing the total proportion of mud (14 to 100%) in Holocene core sections reveals that highest values are concentrated in the broad NW sector of the study area (Figure 6C), in marked contrast to the NE-SW trending sand-rich belt. A secondary, less obvious, zone comprising high proportions of mud occurs in the Sagar Island-Junput-Haldia sector (cores 13, 12, 6). It is of note that peat layers most commonly

occur in the NW delta sector where the Holocene section is generally thin and proportions of mud layers are highest (Figure 6C).

NEOTECTONICS AS ONE OF THE CONTROLS OF DELTA DEPOSITION

The natural factors that resulted in formation of the Holocene Ganges-Brahmaputra delta is, in a number of respects, similar to those that develop other geologically recent world deltas. The modern depocenter began to accumulate in the early Holocene (*cf.* BANERJEE and SEN, 1987; STANLEY and WARNE, 1994) and, as in other deltas, there are marked petrologic distinctions between Holocene and underlying Pleistocene lithofacies (*cf.* COLEMAN and ROBERTS, 1988; CHEN and STANLEY, 1993; STANLEY *et al.*, 1996a, b). Moreover, mean rates of sediment accumulation (ranging from 0.1 to 0.7 cm/yr) and mean rates of subsidence (ranging to 0.5 cm/yr) are similar to those recorded for deltas forming in quite different tectonic settings, such as the Yangtze (STANLEY and CHEN, 1993), Nile (STANLEY and WARNE, 1993) and other Mediterranean deltas (STANLEY, 1997).

Coring and high-resolution subbottom profiling in many world deltas show that late Quaternary deposits thicken gradually from delta axes towards lower delta plains, and then rapidly become thicker at, or close to, the land-sea interface of such depocenters (COLEMAN, 1982; CHEN and STANLEY, 1993; STANLEY and WARNE, 1993; TORNVIST, 1993). Most often, Holocene thickness isopachs tend to parallel delta coasts (COLEMAN, 1982; ZHENG *et al.*, 1994). However, temporal and spatial variations of both Holocene sediment thickness and lithology in the study area are not coast parallel (E-W), but rather trend diagonally (NE-SW) across the southwestern and central delta plain (Figure 6A-C). This

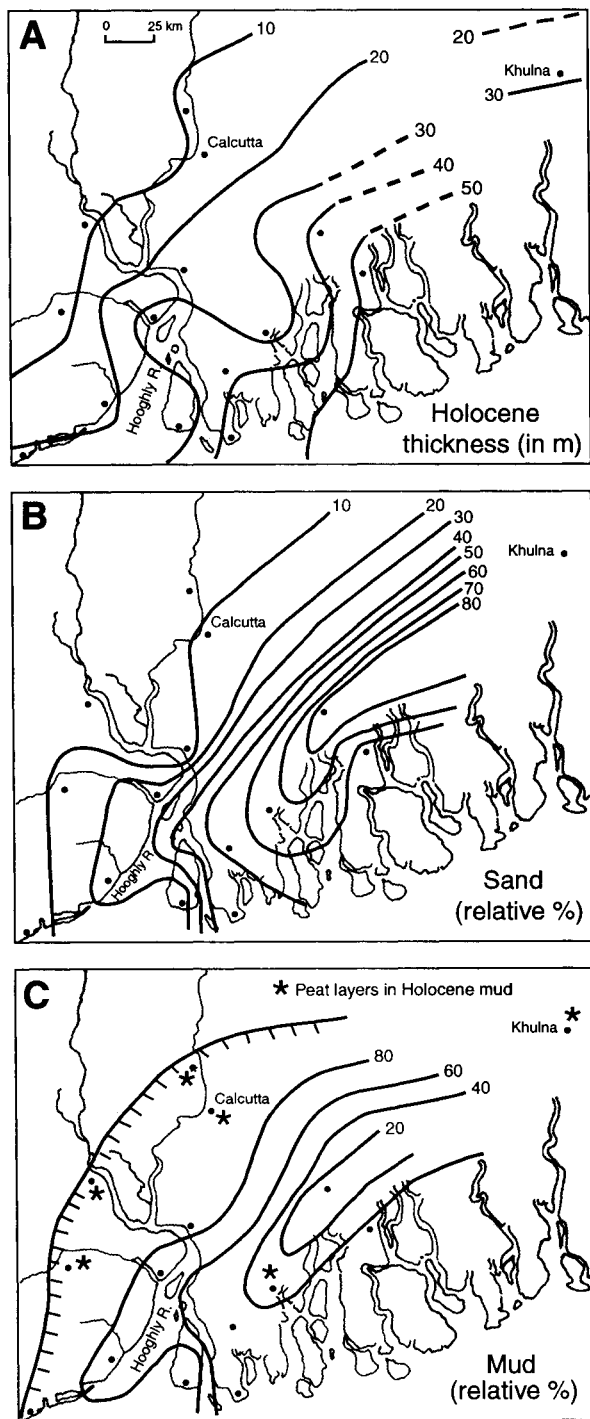


Figure 6. A, Holocene thickness variability in the delta study area. B, proportion of sand in the Holocene sequence. C, preferential distribution of Holocene peat layers in mud-rich sections of reduced thickness.

finding reveals that, some controlling factors in addition to sea-level rise, seaward-directed sediment input and progradation of the delta margin have dominated sedimentation processes.

Depositional patterns indicate that enhanced subsidence, which created accommodation space along a NE-SW trend, had to develop in this area in order to receive >50 m of sediment during the past ~7500 years (Figure 5). A zone of subsidence oriented diagonally across the depocenter, has been a key factor controlling the regional pattern of Holocene deposition. Information on this particular evolution is provided by tectonic, stratigraphic, and morphologic criteria in the delta, all of which show predominant NE-SW trends and are discussed below.

A deep-lying NE-SW hinge zone, defined on tectonic and stratigraphic criteria, extends from the Bay of Bengal to beneath the delta proper (Figure 7A), *i.e.* from at least Mahanadi, offshore India to Mymensingh, Bangladesh. This feature has been identified by deep drilling and geophysical surveys for hydrocarbon exploration (ROYBARMAN, 1983, 1992; LINDSAY *et al.*, 1991; ALAM, 1996; MUKHERJEA and HAZRA, 1997). Development of the hinge zone, the boundary between two separate tectonic blocks, is related to isostatic adjustment of the crust and differential movement of structural blocks that underlie the delta, phenomena related to rise of the Himalayas and sediment loading on the lower Bengal basin. The hinge zone dates back at least to the Eocene, and displacement along the structure continued through Tertiary time. Although the trend of this structure is well defined in deep geophysical surveys, seismic profiles across this feature are insufficiently defined at shallow depths to clearly show the latest Quaternary depositional and neotectonic trends near the delta plain surface (LINDSAY *et al.*, 1991).

In a separate study, morphologic lineaments on the lower Ganges-Brahmaputra delta plain are identified on the basis of tonal change in satellite images. The prominent NE-SW oriented Kakdwip-Khulna-Dacca lineament (AGARWAL and MITRA, 1991), is of interest here. This feature is subparallel with and trends to SE of the deep Tertiary hinge zone described above (Figure 7B), and is partially superposed above the hinge zone in the western delta. This suggests that displacement has continued to offset the delta plain near the boundary between the two separate tectonic blocks described above.

A third observation pertains to surface elevation contours (1.0 to 5.0 m above m.s.l.) in the low-lying southwestern and central delta (Figure 7C). Contours trend from ENE to WSW (DELFT HYDRAULICS, 1989; MILLIMAN *et al.*, 1989; JELGERSMA, 1994; BROADUS, 1996). The 1-m contour line, proximal to and subparallel with the prominent surface lineament feature described above, appears to delineate ongoing offsets oriented diagonally across the delta plain.

We propose that displacement which formed the accommodation space during the Holocene was focused along the hinge zone and the Kakdwip-Khulna-Dacca lineament, both converging in the western delta (Figure 8). Our core analysis indicates that structural activity has continued to present, maintaining the NE to SW trend that crosses the delta diagonally. It is likely that this mobility produced the distinct spatial and temporal Holocene depositional patterns recorded in the present study, especially the well-defined linear sector of subsurface Holocene thickening (Figure 5), distribution of a thin mud section (Figure 6C), and dominant sand dispersal

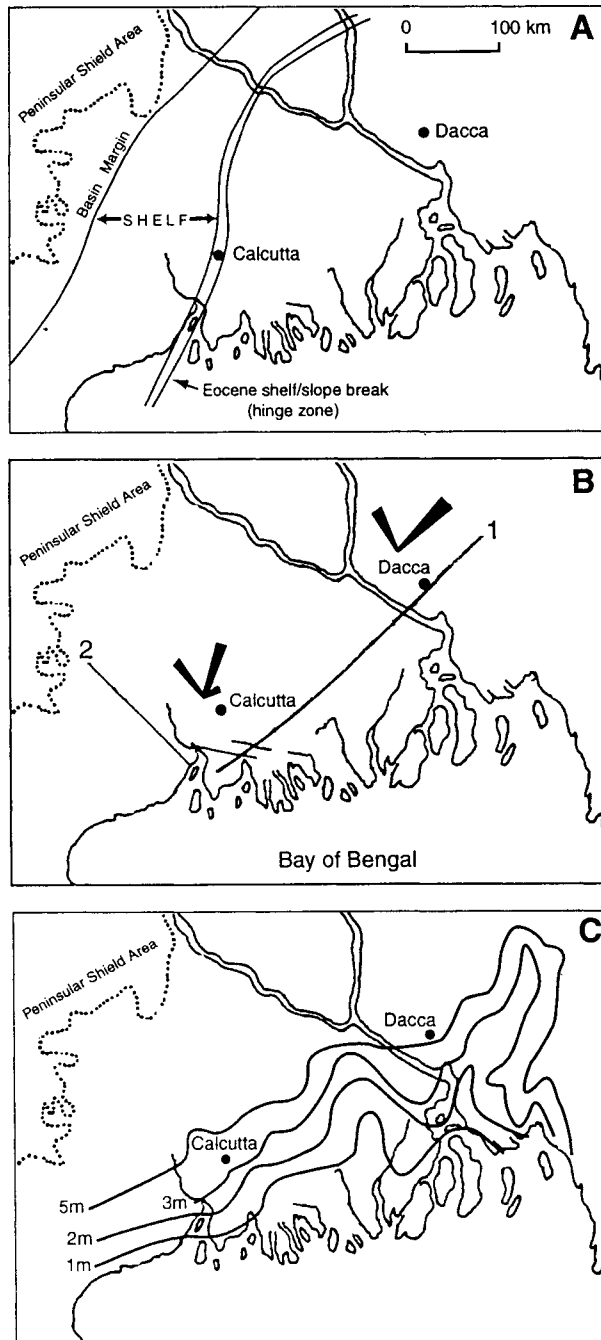


Figure 7. Structural features discussed in text: (A) deep-seated tectonic hinge zone (modified from ROYBARMAN, 1992); (B) delta surface lineaments (1 = Kakdwip-Dacca; 2 = NW-SE structure) and two rose diagrams showing orientation of other delta plain lineaments (modified after AGARWAL and MITRA, 1991); and (C) surface contours in meters above m.s.l.

trends (Figure 6B) between the late Pleistocene units and the delta plain surface. Differential displacement along the NE-SW trend would explain why Holocene depositional patterns so closely parallel the major delta surface lineament and surface elevation contour lines.

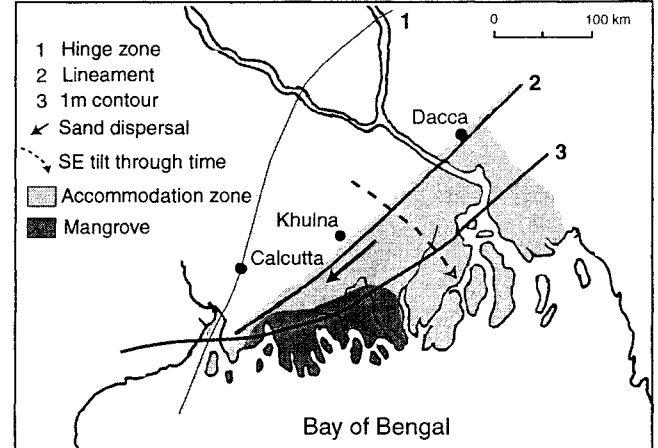


Figure 8. Study of area showing relation among Holocene depositional patterns, distribution of mangroves and neotectonics. Noted is the area underlain by important accommodation space, easterly shift of the delta surface through Holocene time, and SW-directed sand dispersal.

Attention is also called here to the somewhat less prominent NW-SE trend indicated by some Holocene isopachs (Figure 6A) and regional sand and mud distribution patterns (Figure 6B, C). These are parallel to a group of less well-defined NW-SE trending surface lineaments shown in Figure 7B.

Holocene depositional trends, especially those that extend upward all the way to the present delta plain surface, are compatible with the postulate that this western delta study area has been affected by recent fault reactivation (MUKHERJEA and HAZRA, 1997; ROY and CHATTOPADHYAY, 1997; SINGH *et al.*, 1998). Moreover, late Quaternary tectonic displacement that induced tilting of the delta region to the east and altered the course of the Ganges-Brahmaputra-Meghna river system resulted in an eastward shift in delta progradation (SANYAL, 1990; CHAUDHURI and CHOUDHURY, 1994; BLASCO *et al.*, 1996). Indirect evidence of tilting is shown by trend changes through time, *i.e.* progressive shifts to the SE, from the hinge zone through time, *i.e.* progressive shifts to the SE, from the hinge zone direction to that of the lineaments and delta plain surface contours that are not parallel to the coast line (Figures 7,8). As a consequence, the western part of the delta in the late Holocene has experienced a reduction of fresh water flow, decreased progradation rate, increased salt water incursion and some net erosion (ALLISON, 1998b).

Radiocarbon-dated core sections record an incongruous chronostratigraphic sequence of ages upward above the more consistently dated base of cores (Table 2): there appears to be a decreased rate of sediment accumulation from early (to ~ 1.0 cm/yr) to late Holocene (~ 0.1 cm/yr) time. This may be due to sediment reworking in the delta and to sediment that bypassed the delta and accumulated on the shelf and beyond, a phenomenon substantiated by investigation of the shelf seaward of the delta by other workers (KUEHL *et al.*, 1997; ALLISON, 1998b; MICHELS *et al.*, 1998). Those studies indicate that only about 1/3rd of the sediment load of the Ganges-Brahmaputra river system accumulates in the delta proper

(GOODBRED and KUEHL, 1998) while 2/3rds of the load bypasses the delta and is deposited on the continental shelf and deeper environments beyond the shelf-break.

Evidence of ongoing seaward transport of suspended sediment via the delta estuaries is visible on satellite images (AGARWAL and MITRA, 1991; ALLISON, 1998a). This bypassed material is derived from fluvial input and also erosion of the delta, its coast and nearshore shelf areas. Holocene mean sedimentation rates we measure in the delta proper (<0.7 cm/yr) are comparable to modern depositional rates seaward of the coast, on two parts of the modern shelf: in the subaqueous delta topset, at water depths of <20 m; and in the subaqueous bottomset, at >80 m. However, mean sediment accumulation rates in the delta proper are for the most part lower than those presently recorded along a coast-parallel belt at shelf depths between 20 to 80 m, where deposition rates range from 1 to >6 cm/yr (KUEHL *et al.*, 1997; MICHELS *et al.*, 1998). These data, supplemented by high-resolution seismic profiles made on the shelf south of the delta proper, confirm that there has been active seaward progradation of the subaqueous delta in recent time (ALLISON, 1998b).

NATURAL AND ANTHROPOGENIC INFLUENCES ON MODERN SUNDERBANS

Development of the Ganges-Brahmaputra delta resulting from the natural controlling factors described above prevailed prior to the population explosion in this region. Until the last century, there was a direct relationship among Holocene depositional patterns, continued differential structural displacement of this sequence, sediment accumulation rates and regional evolution of peat layers and mangroves. Especially important factors in the regional distribution of both peat and mangrove were sea level, vertical motion of land (subsidence) and creation of accommodation space needed to receive Holocene deposits that thicken toward the SE (Figures 5, 6A).

Peat layers in the subsurface Holocene section (Figure 6C), rich in mangrove and other organic matter and commonly interbedded in dark grey to olive muds, accumulated primarily in the central (UMITSU, 1993) and northwestern delta (CHANDA and MUKHERJEE, 1969; VISHNU-MITRE and GUPTA, 1970; GUPTA, 1981; BARUI *et al.*, 1986; BANERJEE and SEN, 1987, 1988; SEN and BANERJEE, 1990; CHANDA and HAIT, 1996; HAIT *et al.*, 1996b). These are sectors characterized by modest to relatively low subsidence rates (mostly <0.2 cm/yr). In contrast, the reduced proportion of peat in the south and south-central delta may be a function of more mobile substrate conditions that resulted in deeper water conditions, precluding such deposits from forming during the early to mid-Holocene. This resulted from the interplay of relatively high subsidence rate (>0.2 cm/yr) that lowered the delta surface and induced the relatively high rate of relative sea-level rise at that time (CHANDA and HAIT, 1996).

With regards to mangrove forests, most of the Sundarbans (Figures 1,2) are positioned on the low-lying southern delta plain and situated at elevations within 1 m of present m.s.l. (DELFT HYDRAULICS, 1989; MILLIMAN *et al.*, 1989; JELGERSMA, 1994; BROADUS, 1996). The close relationship among

mangrove, sea level and specific intertidal (brackish to saline) habitat requirements results in mangrove ecosystem development that is particularly vulnerable to changes of sea level (ELLISON and STODDART, 1991; ELLISON, 1994). Paleobiological study, including palynological analyses, of core sediment sequences indicates that rapid land subsidence coupled with rapid sea-level rise during the early to mid-Holocene limited mangrove ecosystems on the southernmost plain of the Ganges-Brahmaputra delta (CHANDA and HAIT, 1996; HAIT *et al.*, 1996a). Extensive mangrove forests at that time developed in more stable sectors, positioned to about 80 to 120 km north of the present coastline (CHANDA and MUKHERJEE, 1969; VISHNU-MITRE and GUPTA, 1970; GUPTA, 1981; BARUI *et al.*, 1986; BARUI and CHANDA, 1992; BANERJEE and SEN, 1987, 1988; SEN and BANERJEE, 1990; CHANDA and HAIT, 1996; HAIT *et al.*, 1996b).

From the mid-Holocene onward, mangrove forests spread southeastward. Climatic fluctuation is not viewed as a direct factor of the southward growth trend, since the warm and wet regime has remained fairly constant in this region since the early Holocene (GUPTA, 1981; SEN and BANERJEE, 1988; CHANDA and HAIT, 1996). Rather, this forest development has been a response to altered sedimentation rates as sea-level rise decelerated and increased rate of sediment accumulation came into balance with the rate of subsidence. As a result of these factors, along with high fresh water influx after the mid-Holocene, progressively more luxuriant growth of mangroves began to inhabit the southern and southeastern Sundarban region to along what is now the present coast. Through time, mangroves evolved as a wide NE-SW zone on the lower delta plain (Figure 1), and their northern extension to at least 120 km from the present coast (BANERJEE and SEN, 1987; CHANDA and HAIT, 1996) became generally parallel to the earlier discussed neotectonic trends and zone of Holocene sediment thickening (Figure 8). This broad growth of mangrove is a function of fluvial discharge mixing with marine water across a wide zone by high tide flow through the extensive, primarily N-S oriented estuaries. Until the 1800s, conditions needed for mangrove growth in the delta were maintained, including a balance between sediment accretion and erosion and between fresh and salt water input.

During this century, however, markedly increased growth of human activity has caused significant reduction of the mangrove ecosystem and consequent rapid loss of biological productivity in the Sundarbans. At present, the northern limit of the mangrove is reduced to ~ 50 – 60 km from the coast (Figure 2). Anthropogenic influences include reduced fluvial influx to the delta, increased level of pollutants, and physical removal of mangroves for wood and as part of reclamation for settlement, agriculture and aquaculture (NASKAR, 1985; CHANDA and DATTA, 1986; CHAUDHURI and CHOUDHURY, 1994; GUHA BAKSHI and NASKAR, 1994; HUSSAIN and ACHARYA, 1994; SANTRA, 1994; SANYAL, 1996; SIKDAR and HAIT, 1997; ALAM, 1998). Mapping of specific mangrove vegetation patterns by ground-surface measurement and satellite observation indicates that, in late Holocene, the southwestern and central sectors of the delta have become more saline than the eastern delta. This shift may have resulted in part from natural factors, such as eastward tilting of the

delta (SANYAL, 1990; BLASCO *et al.*, 1996), a phenomenon supported by findings in this study, and also from increased human pressures that include reduced fresh water influx to the west and central sectors.

CONCLUSIONS

Analysis of radiocarbon-dated cores recovered in the western Ganges-Brahmaputra delta, provides the basis for preliminary subsurface mapping of Holocene deltaic sequences and underlying transgressive units and late Pleistocene alluvial deposits. This investigation reveals that neotectonics and subsidence have been among the major controls of late Quaternary depositional patterns. Distribution of peat layers interbedded in Holocene sequences of the western delta and of extensive mangrove forests that form the Sundarbans in the southern and southeastern delta are directly related to Holocene depositional and neotectonic patterns (Figure 7), particularly differential land subsidence and change in relative sea level.

The rapidly growing rural population in Ganges-Brahmaputra delta regions of both India and Bangladesh is heavily dependent on mangrove forests (NASKAR, 1988; CHAUDHURI and CHOUDHURY, 1994; HUSSAIN and ACHARYA, 1994). One effect of intensified human pressure has been increased salinity in both soil and water that is now resulting in decreased agricultural, aquacultural and forest productivity (MILLIMAN *et al.*, 1989; NAZRUL-ISLAM, 1993; ALAM, 1996; ALLISON, 1998a). The present study reveals that increased salinity levels are the result of natural factors, such as delta surface tilting and subsidence, as well as of growing anthropogenic influences, including substantial decrease in river flow.

The mangrove forest acts as a buffer zone which helps reduce the impact of landward-driven tides, storms and cyclones, and protects the hinterland from environmental and economic hazards (CHAUDHURI and CHOUDHURY, 1994). It is evident that anthropogenic activities which directly increase salinity and aggravate the natural effects of subsidence must now be regulated to protect this biologically unique ecosystem. Recovery and multi-disciplinary study of a larger, more evenly distributed suite of radiocarbon-dated cores in the central and eastern Bangladesh sectors of the delta are needed to advance our understanding of the interplay between contemporary Holocene neotectonics, sea level and depositional patterns across the entire depocenter.

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