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Geologic, geomorphic and hydrologic framework and evolution of the Bengal basin, India and Bangladesh

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A B S T R A C T

The Bengal basin, the largest fluvio-deltaic sedimentary system on Earth, is located in Bangladesh and three eastern states of India. Sediment accumulates in the basin from the Ganges, Brahmaputra, and Meghna (GBM) river systems and is dispersed into the Bay of Bengal, forming the largest submarine fan in the world. The basin is located in the Himalayan foreland at the junction of the Indian, Eurasian, and Burmese plates. The basin is bounded by the Indian craton on the west and the Indo-Burmese fold belts on the east. It can be broadly divided into a stable shelf and a foredeep separated by a deep seismic hinge zone. Basin sediments overlie Gondwanan basement and vary in thickness from a few kilometers on the stable shelf to more than 16 km in the foredeep. The basin was initiated at the breakup of Gondwanaland in the late Mesozoic and evolved through the formation of the proto-GBM delta to the present delta starting around 10.5 Ma. The stratigraphy of the different parts of the basin differs considerably, because of contrast in depositional history within the several sub-basins that were produced by intra-plate tectonic activities associated with ongoing Himalayan orogeny. The present-day geomorphology is dominated by the extensive Holocene GBM floodplain and delta. The vertical succession of the deltaic plain can be classified into five units on the basis of differences in grain size, which reflect differing depositional environments. The initiation of the modern GBM delta at the onset of the Pleistocene glacial maximum and its evolution to the present configuration are intricately related to Holocene fluvio-dynamic processes, eustatic sea-level changes, and tectonic movements.

The sedimentology and mineralogy of the different parts of the basin reflect differences in sediment provenance. The mineralogy is dominated by detrital quartz, some feldspar, and minor amounts of carbonates; illite and kaolinite are the main clay minerals. The basin has profuse groundwater resources, but the architecture of the aquifers is not yet well resolved. Different classification schemes have been proposed on the basis of lithology. Regional groundwater flow follows a low hydraulic gradient from north to south, but pumping for irrigation during the past several decades appears to have severely distorted regional flow. Recharge occurs primarily during the monsoon season. Groundwater chemistry is dominated by anoxic, Ca–HCO_3-type water with relatively high concentrations of Fe, Mn, and As. Carbonate dissolution, silicate weathering, FeOOH reduction, and mixing with saline water are the primary processes controlling hydrochemistry.

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1. Introduction

Of the more than 6 billion people worldwide, more than 2% (120 million) live in an area of ~200,000 km^2 (Alam et al., 2003) covering most of Bangladesh and parts of three eastern Indian states (mostly West Bengal, and some of Assam and Tripura). This includes two of the world's largest metropolitan areas: Calcutta, India (now Kolkata; estimated population 15.7 million, rank 12th), and Dhaka, Bangladesh (estimated population 12.6 million, rank 18th) (sources: Office of Registrar General and Census Commissioner, Government of India; Bureau of Statistics, Government of Bangladesh; Th. Brinkhoff, The Principal Agglomerations of the World, www.citypopulation.de, September 2007). This area, known as the Bengal basin, is the world's largest fluvio-deltaic system (Coleman, 1981; Alam et al., 2003).

The Bengal basin is drained by the rivers Ganges, Brahmaputra (also known as the Jamuna in Bangladesh), and Meghna, along with numerous tributaries and distributaries. Hence, the region is also known as the Ganges–Brahmaputra–Meghna (GBM) delta or basin. By discharge, the Brahmaputra and Ganges are the fourth and fifth largest rivers on Earth, respectively (www.waterencyclopedia.com, September 2006). The average discharge (1949–1973) of the River Ganges near the entrance to the Bengal basin (Farakka) was 12,037 m^3/s, while the average discharge (1969–1975) of the Brahmaputra in Bangladesh (Bahadurabad) was 19,673 m^3/s (www.sage.wisc.edu, September 2006). Cumulative riverine discharge through the Bengal basin to the ocean is the fourth largest in the world (Milliman and Meade, 1983). The Bengal basin also represents the world's largest sediment dispersal system (Kuehl et al., 1989; Milliman et al., 1995; Goodbred et al., 2003), with passage of an estimated 1060 million tons of sediment per year to the Bay of Bengal through a delta front of 380 km (Allison, 1998). Thus has formed the world's biggest submarine fan, the Bengal fan (Kuehl et al., 1989; Rea, 1992), with an area of 3×10^6 km^2.

The Ganges enters the basin from the northwest after draining the Himalayas and most of north India for about 2500 km (Fig. 1). The Ganges divides downstream into two distributaries. The main stem (River Padma) flows southeast toward the confluence with the River Brahmaputra in Bangladesh. The other part flows due south through West Bengal as the River Bhagirathi–Hoogly. For simplicity, both these distributaries are termed as the original stream, i.e., Ganges. The Ganges flows along a meandering course with very few braided reaches. The river channel is avulsing eastward for last ~250 years (Brammer, 1996). The Brahmaputra enters the basin from the northeast (Fig. 1) after draining Tibet and northeast India for about 2900 km. It has a paleochannel that bifurcated along the eastern edge of the Madhupur forest. In general, the Brahmaputra is a braided stream characterized by multiple thalwegs, mid-channel bars, and vegetated river islands. The channel belt shows a rapid lateral migration of as much as 800 m/year (Allison, 1998). The Meghna drains the Sylhet basin and part of the Tripura hills before flowing into the Brahmaputra (Fig. 1).

2. Boundaries of the basin

The Bengal basin is bounded (Figs. 1 and 2) on the west and northwest by the Rajmahal Hills (Trap), which are composed of lower Jurassic to Cretaceous trap basalts of the Upper Gondwana system (Ball, 1877). The northeast is bounded by the Garo, Khasi and Jayantia hills (west to east), which stretch for about 97 km from north to south and 240 km from east to west (Morgan and McIntire, 1959). In the far northeast, Shillong or Assam plateau acts as a boundary (Fig. 2). The hills and the plateaus are composed of intensely stressed Precambrian and early Paleozoic granite, gneiss, schist and quartzite overlain by the Eocene Nummilitic limestone (Wadia, 1949). The eastern limit of the Bengal basin is marked by the Tripura hills and Indo-Burmese fold belts to the north and Chittagong hills to the south (Fig. 2), which are composed of Paleocene–Pliocene age sediments of the Siwalik system (the Himalayan foredeep basin sediment system) (West, 1949). The Tripura hills include a train of plunging anticlines (Fig. 2), which die out under overlapping recent sediments of the Sylhet basin (Morgan and McIntire, 1959). The Bangladesh–India border follows the base of the hills.

3. Geologic framework and history

The Bengal basin is a classic example of a peripheral foreland basin formed via continent–continent collision. The basin is a result of the subduction of the Indian plate below the Eurasian (Tibetan) and Burmese plates. Although the direction of subsidence below the Eurasian plate is almost north–south, subduction occurs along a northeast–southwest trend below the Burmese plate (the Burmese–Andaman arc). The Moho has been estimated to be at a depth of about 15 km near the Bay of Bengal, and it deepens to about 36 km below the northern edge of the Bengal basin. Lithospheric flexure and subsidence of the basin are occurring at a rate of 2–4 mm/year (Goodbred et al., 2003). Recent seismic studies suggest that subduction has stopped below the Himalayan arc and is only partially continuing below the Burmese–Andaman arc (Biswas and Das Gupta, 1989; Biswas, 1991; Biswas et al., 1992; Biswas and Majumdar, 1997). The Cenozoic evolution of the eastern parts of the Bengal basin is related more to northeastward oblique subduction of the Indian plate beneath the Burmese plate, along with westward migration of accretionary prism complexes (Dasgupta and Nandy, 1995; Gani and Alam, 1999; Alam et al., 2003). As a result of the resistance to subduction below the Eurasian plate and plate convergence, intense deformation and seismic activity occur in the Indian intraplate region, including on the stable shelf in the western part of the Bengal basin (Fig. 2), resulting in folding of strata and brittle deformation via high-angle basement faults (Biswas and Majumdar, 1997). Tectonic loading to the north–northeast is accommodated along the Dauki fault zone (Alam et al., 2003), which consists of a set of near-vertical, deep-seated reverse faults.

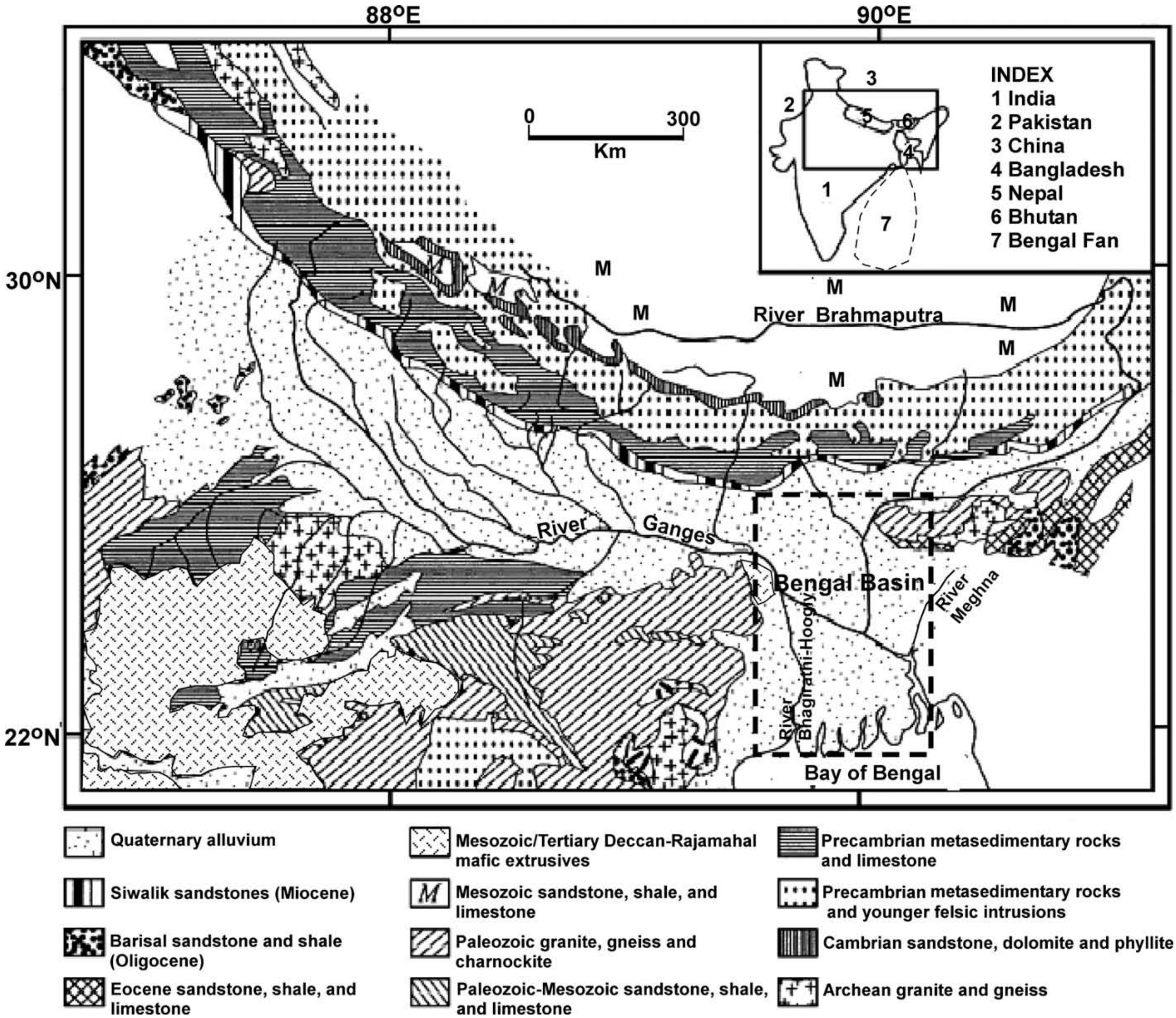

Fig. 1. Geologic map of the Indian subcontinent along with location of the Bengal basin (adapted from Heroy et al., 2003).

The Bengal basin is bounded on the west by the peninsular shield of India, which has a Precambrian basement of metasedimentary rocks with granitic, granophyric, and doleritic intrusions. These are covered by scattered, east–west trending intracratonic Gondwana deposits, such as in the Damodar basin with the Raniganj and Jharia coal basins, and some Tertiary deposits, such as the Baripada and Durgapur beds, as well as Mesozoic volcanics of the Rajmahal trap. On the east, the Naga–Lushai orogenic belt (Sengupta, 1966), also known as the Naga–Halflong–Disang thrust zone (Alam et al., 2003), bounds the basin. This belt consists of highly deformed Cretaceous-Tertiary strata and is bordered on the north and northeast by the Dauki fault zone (Evans, 1964) and on the east by the Naga thrust (Sengupta, 1966). The Shillong Plateau, which borders the basin on the north–northeast, is most probably the continuation of the Indian shield through the Garo–Rajmahal gap (Sengupta, 1966), which is a large depression with younger sedimentary fill between the Rajmahal and Garo hills. The boundary of the Indian plate below the Bengal basin is interpreted to be the Calcutta–Mymensingha hinge zone (CMHZ, discussed later) (Fig. 2), which also acts as a transitional zone between the stable shelf and Bengal foredeep (Alam, 1989). The shelf area in Bangladesh consists of three major features, the Dinajpur slope, Rangpur saddle, and Bogra slope, whereas the foredeep is formed by the Sylhet trough, Faridpur trough, and Hatia trough. About 1–8 km of Permian to Holocene clastic sediments rest on the stable shelf in the western part of the basin (Imam and Shaw, 1985), and as much as 16 km of Tertiary to Quaternary alluvial sediment fills the foredeep of the basin, which at present lies at the mouth of the Ganges and Brahmaputra rivers (Allison, 1998) (Fig. 2). The basin became a huge sink of the sediments eroded from the rising mountain range (Allison, 1998) by the mid-Miocene (Curray et al., 1982).

The ongoing orogeny along the Himalayan and Burmese front has kept the basin tectonically active, generating vertically displaced regional sedimentary blocks in the foredeep, and dividing the basin into numerous poorly connected sub-basins (e.g., Faridpur trough, Sylhet trough) (Goodbred et al., 2003). Also, sediment supply to the basin has varied over time (Fig. 2), including major provenances in the Indian shield, Himalayan foreland, and Burmese arc (Alam et al., 2003), thus causing conspicuous differences

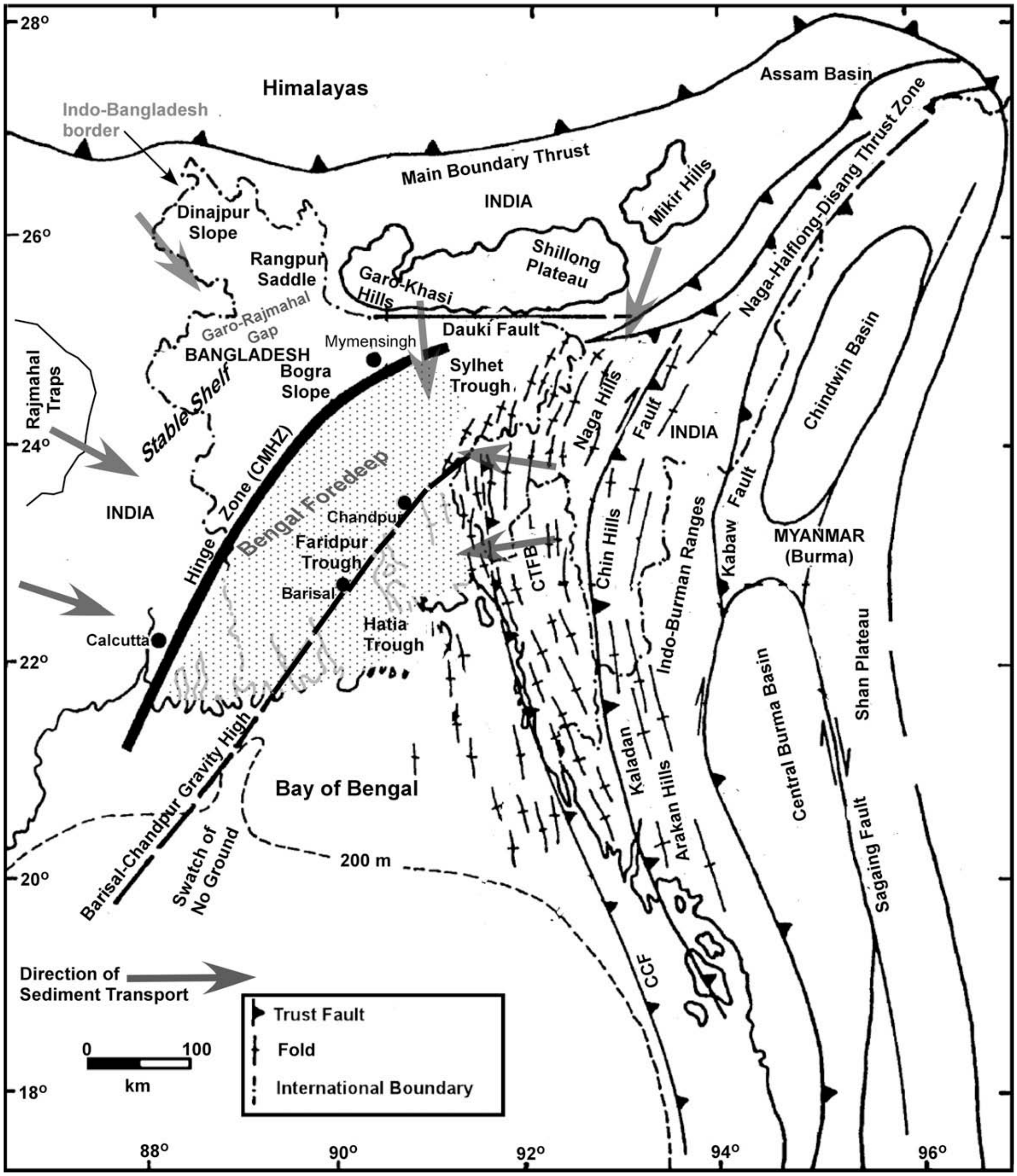

Fig. 2. Tectonic map of the Bengal basin and surrounding areas, showing the directions of sediment transport (modified from Uddin and Lundberg, 1999, and Alam et al., 2003). CCF: Chittagong-Cox Bazar fault; CTFB: Chittagong-Tripura fold belt.

in sedimentary environments, history, and lithology within the different parts of the basin (Goodbred et al., 2003). The basin has been viewed as divided into eastern (mostly foredeep) and western (mostly stable shelf) parts, which are separated by the CMHZ, as discussed earlier (Sengupta, 1966).

Stratigraphic comparison of the different areas of the Bengal basin shows that from the Cretaceous through the mid-Eocene, sedimentation patterns were similar throughout the basin (Fig. 3). The succession starts with the Gondwana sediments and volcanics, followed by a thick sequence of shallow-marine clastic and carbonate sediments in both the eastern and the western sub-basins. Arenaceous sediments dominate the clastic facies in both areas. A carbonate deposit, known as the nummilitic Sylhet Limestone, is found extensively throughout the basin. As a result of the basin configuration and nature of the submergence, the succession is thinner in the western sub-basin. After the deposition of the Sylhet Limestone, the sedimentation pattern of the basin changed to become more clay rich, as marked by the Kopili Formation. After deposition of the Kopili, some significant movement of the basin-basement and basin-margin fault systems led to completely different sets of depositional environments and stratigraphic successions in the two parts of the basin. Thick marine sediments continued to be deposited in the deeper eastern sub-basins (both stable shelf and Bengal foredeep), successively resulting in deposition of the Bogra or Barail, Jamalganj or Surma, and Tipam groups. In the western sub-basin representing the stable shelf, the Bhagirathi Group [consisting of the Memari–Burdwan, Pandua–Matla, and Debagram–Ranaghat formations (Biswas, 1963)] was deposited in

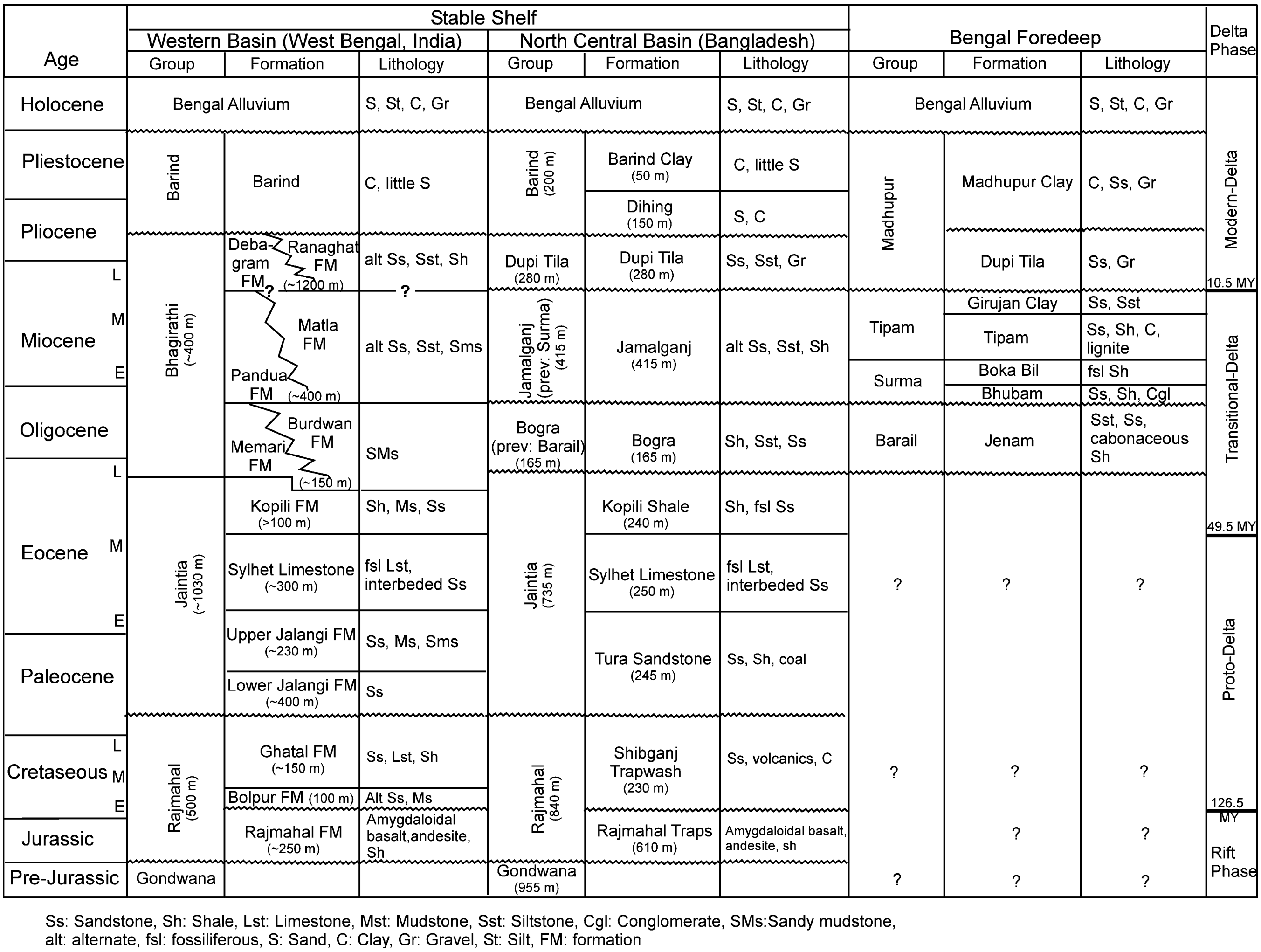

Fig. 3. Stratigraphic correlation diagram of the different parts of the Bengal basin. The stable-shelf succession has been further subdivided within Bangladesh and West Bengal (compiled from Biswas, 1963; Zaher and Rahman, 1980; Alam, 1989, 1997; Alam et al., 1990, 2003; Khan, 1991; Lindsay et al., 1991; Reimann, 1993; BOGMC, 1986).

a more near-shore environment. From the middle of the Pliocene, a similar style of sedimentation resumed throughout the basin, thereby depositing the Barind/Madhupur clay followed by the voluminous and extensive Bengal alluvium over all the previous lithotypes.

Sequence-stratigraphic and seismic studies have established that there is a narrow zone of flexure (the CHMZ) above the Sylhet Limestone in the southeastern part of the western basin. Because of bed instability and adjustment of movement, the post-Sylhet deposits have a broad synformal shape (Sengupta, 1966). The CMHZ acts as a seismic reflector and has been interpreted as a hinge zone or a zone of faults, which may be a shallow manifestation of a much more intense fault zone in the basement (Sengupta, 1966). The CMHZ passes from east of Calcutta (Fig. 2), where it is at a depth of about 4700 m, to the town of Mymensinhga in northern Bangladesh along a trend of N 30°E (Sengupta, 1966). Across this hinge zone, which can be visualized as an imaginary straight line drawn between Calcutta and Ranaghat, the depositional environment sharply changed from stable shelf to deeper-basin conditions (Sengupta, 1966) (Figs. 2–4). The area lying east of this zone has accumulated a great thickness (>8000 m) of argillaceous facies (Sengupta, 1966). The zone can be traced to where it is truncated by the Dauki fault zone in the Naga Hills of Assam (Sengupta, 1966). The location of the CMHZ is confirmed by an alignment of low-magnitude magnetic highs northwest of Calcutta and a steep gravity gradient in the west. Calcutta is flanked by broad gravity highs to the east, indicating the presence of a gravity divide in-between (Sengupta, 1966).

3.1. Basin evolution

The formation of the Bengal basin started with the break-up of Gondwanaland in the late Mesozoic, at about 126 Ma (Lindsay et al., 1991). Extrusion of basalt both in the Rajmahal areas and the south Shillong plateau (Banerjee, 1981) in the late Jurassic to early Cretaceous initiated the process of basin development. This was followed by the slow subsidence of the Bengal shelf in the late Cretaceous, leading to restricted marine transgression from the southeast in the proto-basin. The western part of the basin (mostly in West Bengal) records deposition of lagoonal argillaceous and arenaceous sediments, whereas the Assam front in the eastern and northeastern part was occupied by an open neritic sea (Sengupta, 1966). The proto-GBM delta started forming when sediments were deposited during repeated submergence and transgression over a planar erosional surface, which now is at about 2200 m depth in the central part of the basin, and dips toward the southeast (Lindsay et al., 1991).

During the middle Eocene, basin-wide subsidence initiated by movement along basin-margin faults caused an extensive marine transgression, which resulted in the deposition of the Sylhet

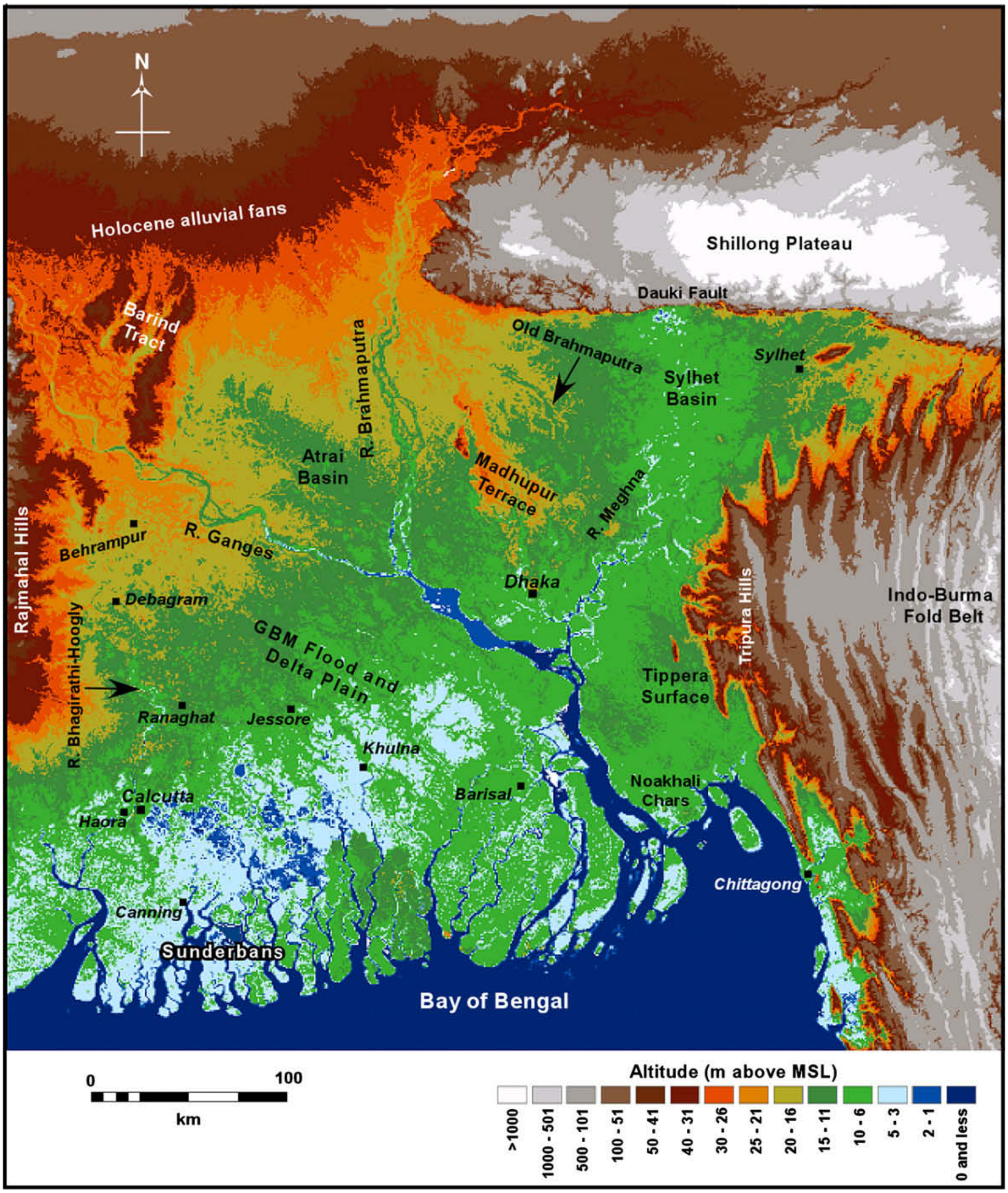

Fig. 4. Geomorphic map of the Bengal basin and surroundings superimposed on the SRTM-90 m digital elevation model (DEM) showing some of the important cities (italicized) and the important physiographic units of the basin: Pleistocene uplands (the Barind and Madhupur terrace) and Recent sediments (Holocene alluvial fans, Tippera surface, Sylhet basin, and GBM flood and delta plain).

Limestone. Basement fault movement probably imprinted the CMHZ on this limestone (Sengupta, 1966). This led to the beginning of separate evolutionary histories for the eastern and the western parts of the basin. Subsequently, the sea began receding from the Bengal basin. At about 49.5 Ma, a major shift in the sedimentation pattern began. The carbonate-clastic platform sedimentary sequence was replaced by a predominantly clastic deposit (Lindsay et al., 1991). The process became conspicuous at about 40 Ma, when the basin became dominated by fluvial clastic sediments and the transitional delta prograded rapidly with frequent lobe switching. The abrupt change in deltaic sedimentation and morphology was probably a manifestation of the collision of the Indian plate with the Eurasian plate and rising of the Himalayas. Comparison of stratigraphic records from the eastern and western parts of the basin shows a subsequent divergence in the sedimentary depositional history as a result of differential subsidence rate, tectonic movements, and eustatic sea-level changes. From the late Eocene–early Oligocene onward, the eastern part of the basin continued to experience marine conditions as marked by a thick arenaceous/argillaceous sequence, while the western part was under fresh water to estuarine conditions, leading to a thinner succession of dominantly argillaceous sediment (Sengupta, 1966). At about 10.5 Ma (Lindsay et al., 1991), in the middle to late Miocene, intense tectonic activity started along the Dauki fault zone and Naga thrust. The activity became more intense in the Pliocene (Sengupta, 1966). The result was basin-wide regression with a major eustatic low. Thus all parts of the basin, including the eastern part, saw a shift from a marine-estuarine environment to a predominantly fluvial–tidal environment, which continues to the present. Deposition of the modern deltaic basin was thus initiated (Lindsay et al., 1991).

4. Physiography and Quaternary geomorphology

Physiographically, the Bengal basin can be divided into two major units, the Pleistocene uplands and deltaic lowlands (Morgan and McIntire, 1959). The divisions may be described as follows (Fig. 4).

4.1. Pleistocene uplands

The whole basin contains several Pleistocene units. There are four major terraces along with several small outliers (Morgan and McIntire, 1959). Two of these terraces flank the basin: east of the Cretaceous Rajmahal hills, and west of the early Tertiary Tripura Hills. The other two, Barind and Madhupur Jungle, lie within the basin.

These Pleistocene uplands are interpreted to be paleo-flood-plains of the earlier GBM system. In terms of sediment characteristics and mineralogy, these deposits are very similar to their Holocene counterpart (Morgan and McIntire, 1959). For example, they have moderately well-sorted sand-size sediments. However, despite the similarities, there are some conspicuous differences. In contrast to the dark, loosely compacted, moist and organic-rich Holocene sediments, the Pleistocene sediments are reddish, brown or tan, mottled, ferruginous or calcareous-nodule rich, relatively dry and organic-poor (Morgan and McIntire, 1959). Moreover, there is a conspicuous difference in the geomorphic features formed by the Pleistocene and the Holocene sediments. The Pleistocene sediments form highlands, which are the manifestation of differential structural displacement between them and the Holocene deposits and also seaward subsidence and of lower areas' entrenchment during low-stand Pleistocene glaciation. Also, the upland is characterized by only a few prominent drainage systems, which flow through deeply scoured, well-defined meanders.

The Barind is the largest Pleistocene unit within the Bengal basin, with an areal extent of about 9400 km^2. It has been dissected into four separate units by recent fluvial systems, which include the north Bengal tributaries of the Ganges and Brahmaputra, namely the Mahananda, Karatoya, Atrai, Jamuna, and Purnabhaba. The area is actively affected by orogenic movements, which are indicated by earthquakes, tilting of the eastern part, river course switching, and visible major fault scarps.

The 4100 km^2 of the Madhupur terrace north of the city of Dhaka is the other important Pleistocene landform of the Bengal basin. The elevation of the upland rises from 6 m above mean sea-level (MSL) in the south to more than 30 m above MSL in the north. The western side has a higher average elevation, whereas the whole upland slopes toward the east, ultimately to be concealed under the thick Holocene alluvium. The western margin marks an abrupt separation between the low-lying, flat, Holocene flood plain in the west and the highly dissected older upland. The boundary is marked by six en-echelon faults ranging from 10 to 21 km in length and with the eastern side up-thrown by at least 6–18 m. It is thought by some workers that at least part of the uplift of the Madhupur terrace occurred during the 1762 catastrophic earthquake (Fergusson, 1863). The diversion of the Brahmaputra from its old course can be possibly attributed to the sudden uplift of the Madhupur terrace and gradual tilting toward the east, which also may have caused the sudden diversion of the Tista from being a tributary of the Ganges to that of the Brahmaputra in 1787. Moreover, the lowland between the en-echelon fault system of the Madhupur and the Karatoya River fault system (not shown in Fig. 4) of the northeast Barind indicates ongoing subsidence/uplift.

4.2. Holocene sediments

The other main physiographic division of the Bengal basin is the Holocene alluvial plain and delta of the GBM system (Morgan and McIntire, 1959), also known as the Holocene alluvial lowland of Bengal (Umitsu, 1987, 1993). These alluvial deposits are the most extensive part of the Bengal basin and cover almost the whole of the basin except the Pleistocene highlands.

Different workers have tried to classify this huge sedimentary basin in various ways. The classification described here is a combination of the two proposed by Morgan and McIntire (1959) and Umitsu (1987). According to this joint scheme, there are four physiographic subdivisions:

(a) *The alluvial fans:* These piedmont alluvial plains are in the foothills of the eastern Himalayas and are formed by deposition from the north Bengal tributaries of the Ganges and Brahmaputra such as the Tista, Atrai, Mahananda, and Purbabhaga (not shown in Fig. 4). These rivers also have dissected the Pleistocene upland of the Barind, as mentioned earlier. Coarse-grained sediments like cobbles and sand dominate these fans.

(b) *Tippera surface:* This 7800-km^2 area in the easternmost part of the basin, near the Tripura hills in the Tippera district, has been classified as a different subdivision on the basis of a characteristic drainage system (Morgan and McIntire, 1959). It is sometimes considered as a part of the GBM flood–delta plain (described later) (Umitsu, 1987). The rivers in this unit show a very well-defined rectangular pattern in contrast to the general braided or meandering pattern of the alluvial plains. The extent to which this distinct pattern has resulted from anthropogenic influence is debatable. The surface is delineated on the north by a northeast–southwest trending fault. The sedimentological characteristics of the deposit are very similar to those of other recent alluvial deposits except slightly more compacted and oxidized, but not as much as the strata in the Pleistocene uplands.

(c) *Sylhet basin:* This small basin is located in the extreme northeastern part of the main basin, surrounded by the Shillong plateau, Tripura hills, and the Madhupur terrace Pleistocene uplands. The south boundary is a major fault scarp. The basin has an average altitude of about 4.5 m above MSL at its center. It was earlier considered as a part of the Ganges–Brahmaputra delta. The Old Brahmaputra River (the original channel of the Brahmaputra) passes through the westernmost part. The present Brahmaputra course has an elevation of about 15 m above MSL, which shows that the Sylhet basin has subsided about 10.5–12 m during the last couple of hundred years. The cause is certainly tectonic, associated with movements of the fault systems. Holocene fossil wood fragments have been found at depths of 15–18 m below surface. The surface is inundated every year during monsoon season. The basin can be classified geomorphologically as having natural, continuously meandering levees with dendritic drainage (Umitsu, 1985). The sediment composition of the basin grades from sandy or silty near the surface to fine sand at a depth of about 12 m.

(d) *Ganges–Brahmaputra–Meghna flood and delta plain:* This is the principal unit of the Bengal basin. This unit is so vast that many studies, including this paper, refer to the Bengal basin as virtually synonymous with the plain. It covers more than 10^5 km^2 of both Bangladesh and West Bengal, India, excluding the units that have already been mentioned.

The plain is bounded by the Pleistocene terraces on the west, the Barind and Madhupur terrace on the north, the Tippera surface on the east (Morgan and McIntire, 1959), and the Bay of Bengal in the south. Like many of the large alluvial systems of the world, the GBM plain is formed by overlapping of a number of sub-deltas (Morgan and McIntire, 1959) and alluvial flood plains. Moreover, avulsion of the major streams in the area within a time scale of 100 years has resulted in a Holocene sediment succession of about 100 m of overbank silts and clays incised by channel sands (Coleman, 1969; Umitsu, 1987; Goodbred and Kuehl, 2000; Allison et al., 2003). Evidence of subsidence of the Holocene sediments to accommodate depositional space has been reported (East, 1818; Smith, 1841; Hunter, 1875; Curtis, 1933; Morgan and McIntire, 1959) from various places, including Calcutta (as much as 12 m), Canning (∼3 m), Khulna (∼6 m) and the Sunderbans, which is the world's largest mangrove forest (as much as 9 m). The active delta area in the southernmost part of the plain, which supports the Sunderbans, can be demarcated from the flood plain by the farthest inland extent of water from the Bay of Bengal during the dry season of October to April (Allison et al., 2003).

The altitude of the GBM alluvial plain is about 15 to 20 m above MSL in the northwest, and decreases to 1 to 2 m above MSL to the south near the coast. According to physiographic characteristics, the plain can be divided into five distinct regions (Umitsu, 1987). These include (a) the area in and around the city of Calcutta; (b) the area of broad and indistinct natural levees (Umitsu, 1985) in the northwest part, also known as the moribund delta (Bagchi, 1944); (c) the central part of the plain, which includes areas with natural levees with dendritic distributary channels near the city of Khulna (Umitsu, 1985), along with meandering and distinct natural levees; (d) the Sunderbans; and (e) the mouth of the river Meghna (Umitsu, 1987).

The oldest surface sediments in the GBM flood plain are identified near Calcutta and near Commila in northeastern Bangladesh, very near the Tippera surface, whereas the youngest sediments are all located in the active floodplain and the delta. The sediments in all places are of Holocene age. The Ganges alluvial deposits are divided into an upper silty or clayey part and a lower sandy part to a depth of about 50 m. In the northwestern part of the plain, near the Tippera surface, the sediments in the upper horizons are slightly oxidized and light gray in color. In the central and southern parts of the plain, organic and peaty materials are locally visible in near-surface horizons. In the southernmost part, in and near the active delta region, silt and sand alternate within an upward fining sequence (Umitsu, 1987). The Brahmaputra-dominated alluvial plain extends between the Barind and the Madhupur terrace. This plain has a distinct basal gravel horizon overlain by a sequence of sandy sediments.

Umitsu (1987, 1993) classified the vertical sequence of the Holocene formations of the GBM plain into five units (lowest, lower, middle, upper, and uppermost). Each of these units is separated from the succeeding units by a difference in grain size, which is certainly a manifestation of differing depositional environments. The individual units can be differentiated as follows, after Umitsu (1987). The lowest unit, which has a thickness of about 10 m, is composed predominantly of gravel. In the northern part of the plain, the bed is at a depth of more than 70 m below the surface, indicating that sea-level at the time of deposition must have been about 100 m below the present level. Sediments from the Brahmaputra plain basal gravel at a depth of 101 m below MSL, in the south of the Barind, yield an approximate age of 28,320 ± 1550 years BP (Umitsu, 1987). The lower unit is dominated by sand-sized sediments with sparse gravel. The unit contains two relatively coarse zones near the middle and the top, reflecting a change in sediment size deposited by the rivers. Organic remains in the lower unit of the central GBM plain near the city of Khulna (Bangladesh), at a depth of 46 m below MSL, yield an age of 12,320 ± 240 years before present (BP) (Umitsu, 1993). Peat layers from the far western GBM plain (West Bengal, India) have been dated ∼7100 to 9100 years BP at depths of 20 to 50 m in the coastal area (Hait et al., 1996). Sylhet basin organic materials at depths of 36.6 to 55 m below MSL yield ages of 6320 ± 70 years BP and 9390 ± 60 years BP, respectively (Goodbred and Kuehl, 2000). An unconformity, probably caused by temporary sea-level fall, separates the lower and the middle units; this is indicated by weathered and oxidized horizons at the top of the lower unit. The lower unit in some locations, mostly in the central plain, has sediments with some peat and organic material, indicating a swampy environment of deposition. The middle unit shows a coarsening upward sequence. Shell fragments and wood remains from the middle unit, at depths of 25–33 m below MSL, range from 7640 ± 100 to 8910 ± 150 years BP (Umitsu, 1993). At the active delta area near the main mouth of the GBM, radiocarbon dating of sediments from a depth of 25 to 30 m below surface records an age of 8400 years BP (Goodbred and Kuehl, 2000). Muddy sand about 50 m west of the aforementioned location and at a depth of 35 m below surface yields an age in the range of 7500–8000 years BP (Goodbred and Kuehl, 2000). The upper unit has a coarse-grained middle part, sandwiched between fine-grained upper and lower parts. This oscillation of sedimentation pattern is interpreted to have been caused by eustatic sea-level changes. Peat layer ages from the upper unit are 7060 ± 120 years BP at 18 m below MSL and 6490 ± 130 year BP at 14 m below MSL (Umitsu, 1993). Clay- and silt-sized sediments are characteristic of most of uppermost horizon, with some peaty sediments. The peaty materials in all these units are interpreted to have been deposited in mangrove swamps, which developed in the prograding delta over time (Vishnu-Mittre and Gupta, 1979; Umitsu, 1987; Islam and Tooley, 1999). Mangrove remains from Calcutta have been dated at ∼7000 years BP (Sen and Banerjee, 1990). Peat fragments recovered in the older delta of the western basin yielded ages of 6500 to 7500 years BP at depths of 6 to 12 m and 2000 to 5000 years BP at depths <5 m (Banerjee and Sen, 1987). The sediments from a location near Calcutta have been dated as 5810 ± 120 years BP at 6.25 m below land surface to 2615 ± 100 years BP at 1.37 m below land surface (Vishnu-Mittre and Gupta, 1979). More dates from the basin are tabulated in Table 1.

5. Holocene landform evolution

As noted earlier, the main surficial lithostratigraphic and geomorphic units of the Bengal basin are mostly of Holocene age (Fig. 5). Hence understanding the Holocene fluvio-dynamic processes along with the effects of eustatic sea-level changes and tectonic impacts in this basin is critical for the study of present-day basin evolution. In the northeastern part of the basin, where tectonic processes are most active, fine-grained sediments dominate the stratigraphy. In the western part of the basin, near the stable shelf, the strong fluvio-dynamic processes have resulted in formation of extensive flood plains with a dominance of coarser grained sediments. The coastal region in the south has a mixture of fine-grained sand and mud deposits with peat layers, which have resulted from eustatic influence (Goodbred et al., 2003).

Deposition of the lowest unit of the modern GBM delta began at the onset of the Pleistocene glacial maximum in this part of the world (Fig. 6) (Islam and Tooley, 1999). This is documented by the fact that the lowest unit was deposited at a depth that is

Table 1
Reports of absolute age of sediments and peat layers from various locations of Bengal basin (after Uddin and Abdullah, 2003)

Location	Sample type	Depth (m bgl)	Age (years BP)	Source
Sirajganj	Wood fragments	NA	28,300	JICA (1976)
Between Madhupur and Barind	Upper coarse sand and micaceous silt	26	6400	Davies and Exley (1992)
		32	6290	
		62	>48,500	
Eastern Dhaka	Peat (from Bashabo formation)	NA	4040 ± 70–1270 ± 140	Monsur and Paepe (1994)
Fardipur	Micaceous silt	6.2	106.6 ± 0.58	BGS/DPHE (2001)
	Fine sand	9.8	960 ± 45	
	Fine sand	10.2	855 ± 45	
	Clay with peat	44.5	8260 ± 75	
	Medium sand	55.2	11,890 ± 80	
	Coarse sand	73.2	18,560 ± 130	
	Gravel	91.4	22,690 ± 190	
Laxmipur	Micaceous silt with peat	10.7	110 ± 0.58	BGS/DPHE (2001)
	Fine and medium sand	35	6920 ± 50	
	Sand	38.7	10,020 ± 85	
	Sand	46.3	9155 ± 70	
	Sand	73.2	8855 ± 70	
	Sand	91.7	11,320 ± 75	
	Sand with silt	137.5	12,585 ± 95	
Kharampur (Chandina deltaic plain)	Peat (top of bed) Peat (bottom of bed)	1–2	5580 ± 75	Uddin and Abdullah (2003)
			5620 ± 75	
Kachpur (Dhaka)	Peat	4	6390 ± 80	Uddin and Abdullah (2003)

now about 70 m below the present land surface, indicating that the glacial maximum sea-level and the base level of land erosion must have been at least 100 m below present MSL. Thus the rivers draining the plain during that time must have scoured through the earlier plains (Fig. 6A) and deposited the basal gravel at a depth analogous to the sea-level at that time (Umitsu, 1993). At that time, the "Swatch of no ground" submarine canyon (Fig. 2) now in the center of the Bay of Bengal most probably was the estuary of the GBM plain (Chowdhury et al., 1985). If this hypothesis is true, then most of the northern part of the Bay of Bengal was dry land during the Pleistocene glaciation (Islam and Tooley, 1999). The sediment supply at this time was low compared to the present (Milliman et al., 1995), and sediment inflow was low until the late Pleistocene, about 15,000 years BP (Weber et al., 1997).

Around 12,000–11,500 years BP, at the beginning of the Holocene, the southwest monsoon, which determines the climate-controlled processes in southeast Asia, became stronger than at present (Gasse et al., 1991), which led to a simultaneous increase in discharge and fluvial sedimentation. The sediment discharge has been estimated to be on the order of 2.5×10^9 t/year (Goodbred and Kuehl, 2000). The lower unit of the GBM plain was probably deposited at this time as an extensive flood plain in the central region (Umitsu, 1993). The coarsening upward of the lower unit may be correlated with increased discharge and aggravated erosion along the upper reaches of the main rivers.

The sedimentary record of 11,000–10,000 years BP contains both dissected flood plains (Umitsu, 1993) caused by fluvial erosion and also drastic fining of sediments and deposition of lower delta mud over lowstand oxidized sand units (Fig. 6B), which suggests sea-level rise (Goodbred and Kuehl, 2000). It has been hypothesized that the eustatic sea-level rose to about 45 m below present MSL (Fairbanks, 1989; Blanchon and Shaw, 1995), which caused extensive back-flooding and sedimentation (Goodbred and Kuehl, 2000) along with a temporary sea-level fall forming shallow valley plains (Umitsu, 1993). Various workers agree that the present GBM delta began to prograde into the Bay of Bengal at this time (Lindsay et al., 1991; Goodbred and Kuehl, 2000). The sharp decrease of sediment input to the submarine fan at this time (Weber et al., 1997) could be a manifestation of enhanced sediment trapping in the delta-plain system. The fine sediment thus deposited would constitute the middle unit of the GBM plain (Umitsu, 1993). Hence, most probably there was a short-lived but effective sea-level fall followed by a sea-level rise, which cumulatively initiated the modern delta-forming processes.

From about 10,000 to about 7000 years BP, in the mid-Holocene, a major and rapid transgression (Umitsu, 1993; Islam and Tooley, 1999; Goodbred and Kuehl, 2000) occurred probably as a result of glacial ice melting. Sea-level rise resulted in the deposition of fine sediments (the upper unit of the GBM plain) even in the north-central part of the basin (Fig. 6C). The coastline at that time transgressed up to the central delta north of Khulna (Umitsu, 1993). This continued transgression might also have included some short-lived regressions, which are indicated by increased fluvial activity (Islam and Tooley, 1999). During the latter part of this general transgression, the coastline probably receded slightly toward the south, causing the coarsening of the upper horizons of the upper unit. At this time, mangrove vegetation (Vishnu-Mittre and Gupta, 1979) spread over the central GBM plain and caused extensive deposition of peat.

After about 7000 years BP, the gradient of the sea-level rise curve decreased (Umitsu, 1993; Islam and Tooley, 1999; Goodbred and Kuehl, 2000). Nonetheless, the general trend of the eustatic sea-level curve shows continuous sea-level rise from the mid-Holocene onward (Fig. 7). The decreased rate of sea-level rise since 7000 years BP led to the deposition of the uppermost unit of the GBM plain, which contains clay, silt, and organic-rich layers throughout the southern Bengal basin (Fig. 6D). At about 5000 years BP (Fig. 6E), the main channels of both Ganges and Brahmaputra started draining the eastern part of the basin (Goodbred and Kuehl, 2000). The continuation of these processes resulted in the progradation of the active delta in the present-day configuration around 3500 to 3000 years BP (Goodbred and Kuehl, 2000) and the growth of the mangrove forests in the Sunderbans region (Fig. 6F).

Extensive peat layers in the upper and uppermost units throughout the southern Bengal basin have been reported by various workers, including Vishnu-Mittre and Gupta (1979), Sen and Banerjee (1990), Barui and Chanda (1992), Umitsu (1987, 1993) and Islam and Tooley (1999), who referred to the layers as the Bengal peat. Civil construction in Calcutta in the recent past, even at shallow depths, has yielded remnants of peaty material. The above-mentioned authors have claimed the peat as in-situ in origin and mostly formed from mangrove (or mangal) vegetation. Studies near the city of Khulna have yielded five well-developed and

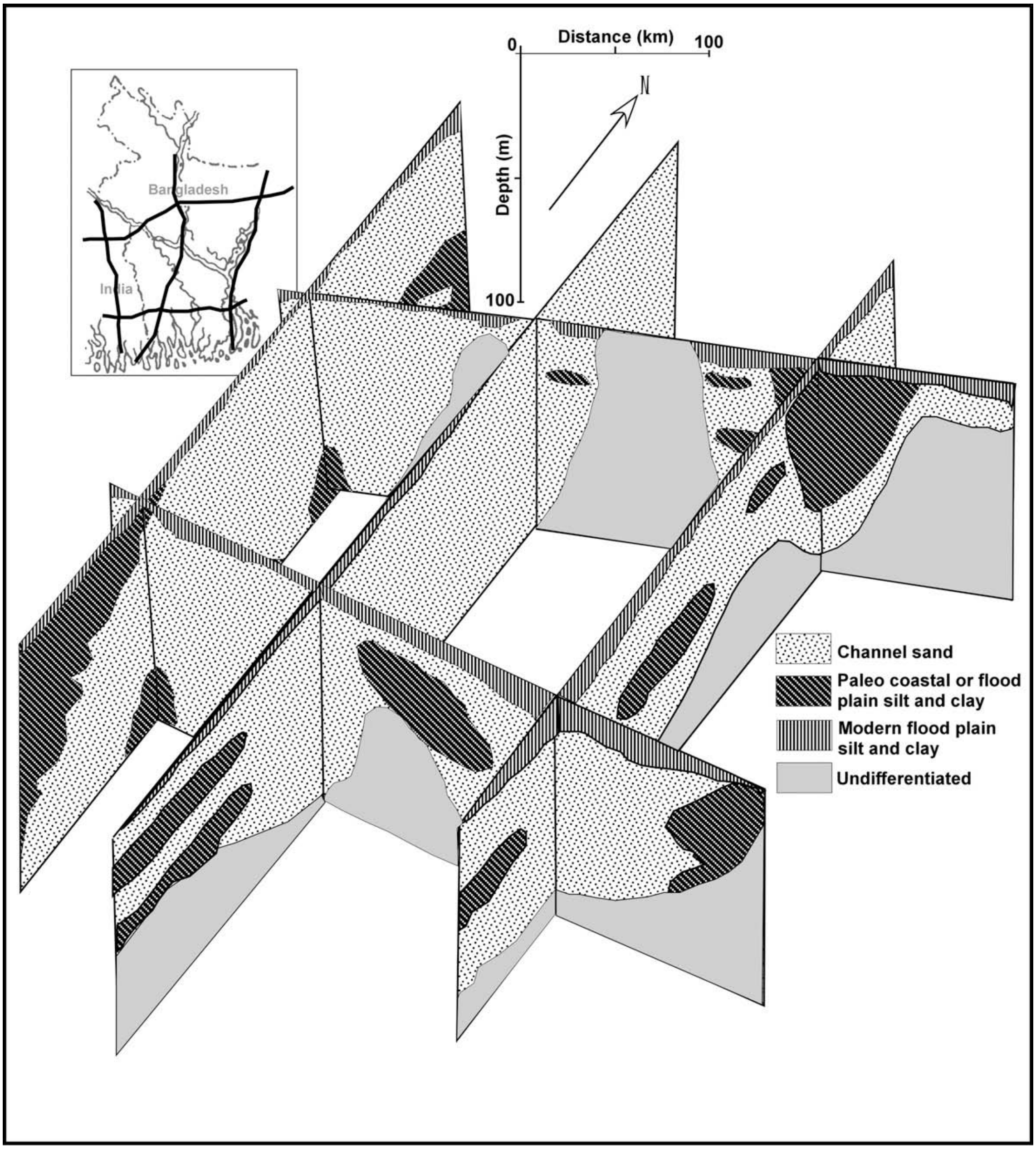

Fig. 5. Lithologic fence diagram of the most recent sediments in the Bengal basin (adapted from Goodbred et al., 2003, and Mukherjee, 2006).

generally thick layers of peat, each separated by inorganic layers (Islam and Tooley, 1999). The lowermost peat layer has been dated at 7000 to 6650 years old and contains remains of mangrove plants like *Acrostichum aureum*, *Heritiera* spp., and *Avicennia* spp. Parts of the uppermost layer have been dated at 5000–2000 years old and contain abundant remains of freshwater peat-forming plants. The intercalation of mangrove and fresh-water plants with mineral-rich layers has been interpreted to indicate deposition in a basin that was inundated by sea-level rise with intermediate temporary sea-level falls (Islam and Tooley, 1999).

6. Sedimentology, mineralogy, and elemental distribution

To a large extent, the sedimentology and mineralogy of the Bengal basin depend on the primary types of sediments eroded and transported by the Ganges, the Brahmaputra, and their northern tributaries like the Meghna, Tista, Rangeet, and Mahananda. Bank and floodplain sediments have been designated as major short-term river sediment sources (Meade and Parker, 1985). More than 76% of bed sediments from the GBM river system are fine to very fine sand, with a mean grain size of 2.5–4 Φ (1/6–1/16 mm) (Datta and Subramanian, 1997). The grain size decreases from upper to lower reaches, and 66% of the sediments are moderately to well sorted according to the scale of Folk and Ward (1957) (Datta and Subramanian, 1997). All bed sediments are positively skewed (Goswami, 1985; Datta and Subramanian, 1997), and 95% of the suspended sediments are more than 6Φ (0.01 mm) and are well sorted (Datta and Subramanian, 1997).

Because of differences in sediment provenance, the Brahmaputra and Ganges systems have quite distinctive mineralogies (Heroy et al., 2003). The Brahmaputra flows through various rock types, including Precambrian metamorphic rocks (high-grade schist, gneiss, quartzite, and marble), felsic intrusives, Paleozoic–Mesozoic sandstones, shales and limestones of the Himalayan terrain

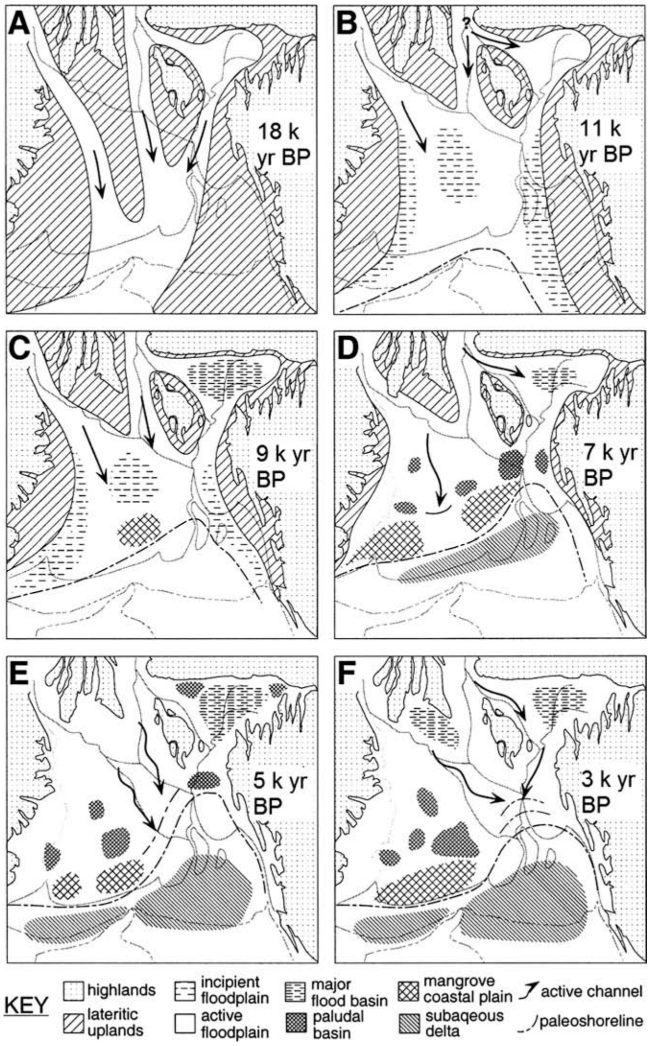

Fig. 6. Stages of Holocene landform evolution of the Bengal basin (see Section 6 of text for description). Reprinted from Sedimentary Geology, vol. 133, nos. 3–4, Goodbred, S.L., Kuehl, S.A., The significance of large sediment supply, active tectonism, and eustasy on margin sequence development: Late Quaternary stratigraphy and evolution of the Ganges–Brahmaputra delta, 227–248, copyright 2000, with permission from Elsevier.

(Huizing, 1971). The Ganges drains terrains with similar kinds of lithologies, but also receives lower course and lowland tributaries, which drain Mesozoic and Tertiary mafic extrusives and the Precambrian–Cambrian shield (Huizing, 1971). The tributaries of the lower Gangetic plain, in the upper reaches from the Bengal basin, produce a saline and alkaline soil, which contains calcareous concretions called "kankar" (Sarin et al., 1989). In contrast, the Brahmaputra alluvium has less calcareous matter than the Ganges (Wadia, 1981), and Brahmaputra and Meghna sediments are characterized typically by noncalcareous, acidic soil (Saheed, 1995).

The Bengal basin sediment mineralogy is dominated by detrital quartz and feldspar grains (Datta and Subramanian, 1997). The higher quartz content relative to feldspar is indicative of low-relief tropical weathering in the basin (Potter, 1978). Among the clay minerals, illite and kaolinite are profuse and are in nearly equal proportions, whereas chlorite and montmorillonite are insignificant (Datta and Subramanian, 1997). High illite and low chlorite content indicates the ongoing neotectonic activity around the basin (Morgan and McIntire, 1959) and the enrichment of the parent rocks in muscovite mica (Griffin et al., 1968). The large amount of kaolinite signifies the intense kaolinization of the parent minerals (e.g., feldspars). The Ganges system has a higher amount of smectite and a lower amount of kaolinite in comparison to the Brahmaputra (Sarin et al., 1989). Several studies have concluded that the kaolinite–smectite assemblage has been derived from the low-temperature alteration of the high-grade crystalline metasediments of the Himalayas by pedogenic processes within the Bengal basin, whereas the illite–chlorite suite has been derived from direct erosion of the Himalayas. Any component of these assemblages derived from the cratonic part of the Indian subcontinent is insignificant (France-Lanord et al., 1993; Heroy et al., 2003).

The heavy mineral assemblages in all three river systems of the Bengal basin are similar (Datta and Subramanian, 1997). Among the heavy minerals, amphibole is most prominent, followed by garnet and epidote. There is a slight enrichment of pyrope garnet in the Ganges system, while epidote and amphibole are slightly higher in the Brahmaputra system (Huizing, 1971; Datta and Subramanian, 1997). Unstable minerals in general dominate the heavy mineral assemblage (e.g., hornblende, garnet, magnetite, and ilmenite), followed by semistable minerals like apatite, epidote, staurolite, and kyanite. Stable and ultrastable heavy minerals are less common (Datta and Subramanian, 1997). The predominance of unstable heavy minerals is possibly a manifestation of lack of significant chemical alteration during transport (Kumar and Singh, 1978). The high-grade metamorphic terrains (see Fig. 1) are the provenance of 40–46% of the heavy minerals, followed by the igneous terrains with 21–29% (Huizing, 1971; Datta and Subramanian, 1997). Pyrite is rare but is found sometimes in the sediments of the basin (BGS/DPHE, 2001). This range of heavy minerals is comparable to that of Miocene and younger sediments eroded from various orogenic sources, including the Himalayas ophiolites (Uddin and Lundberg, 1998; Zheng, 2006).

The distributions of nitrogen and phosphorus in the sediments of the Ganges, Brahmaputra and Meghna river systems are similar and vary within a narrow range. The average total nitrogen (TN) of the three basins ranges from 0.1 to 0.6 mg/g (Datta et al., 1999). The average total phosphorus (TP) is about 0.7 ± 0.1 mg/g in the Meghna basin, 0.9 ± 0.2 mg/g in the Brahmaputra and 1.0 ± 0.4 mg/g in the Ganges (Datta et al., 1999). Total nitrogen in the basin may be controlled both by sources of organic matter and biogeochemical processes (Datta et al., 1999).

The total carbon (TC) content appreciably increases from the Meghna basin to the Ganges. The values are 1.8 ± 0.5 mg/g in the Meghna, 2.0 ± 1.7 mg/g in the Brahmaputra and 8.2 ± 2.8 mg/g in the Ganges (Datta et al., 1999). In the Meghna basin the total carbon consists primarily of TOC and there is little or no total inorganic carbon (TIC), but the Ganges basin contains appreciable amounts of both TIC and TOC. Sarin et al. (1989) reported higher concentrations of Na and Cl in Ganges sediments than in Brahmaputra sediments. In general, in the Bengal basin, there is a very good correlation between TN and total organic carbon (TOC) and between TOC and grain size of the sediments.

Common naturally occurring trace metal contaminants reported in the Bengal basin sediments include lead, arsenic, cadmium, mercury, and selenium (Aswathanarayana, 1995). The concentrations of trace elements like lead, arsenic, and mercury are lower in the Bengal basin than in typical shale and clay (Datta and Subramanian, 1997). The index of geoaccumulation (Müller, 1979) is negative for lead, arsenic, and mercury in the GBM system but is positive for cadmium in the Brahmaputra plains (Datta and Subramanian, 1997).

7. Hydrology

In recent years, groundwater in the Bengal basin has been the subject of attention because of water quality issues. In general,

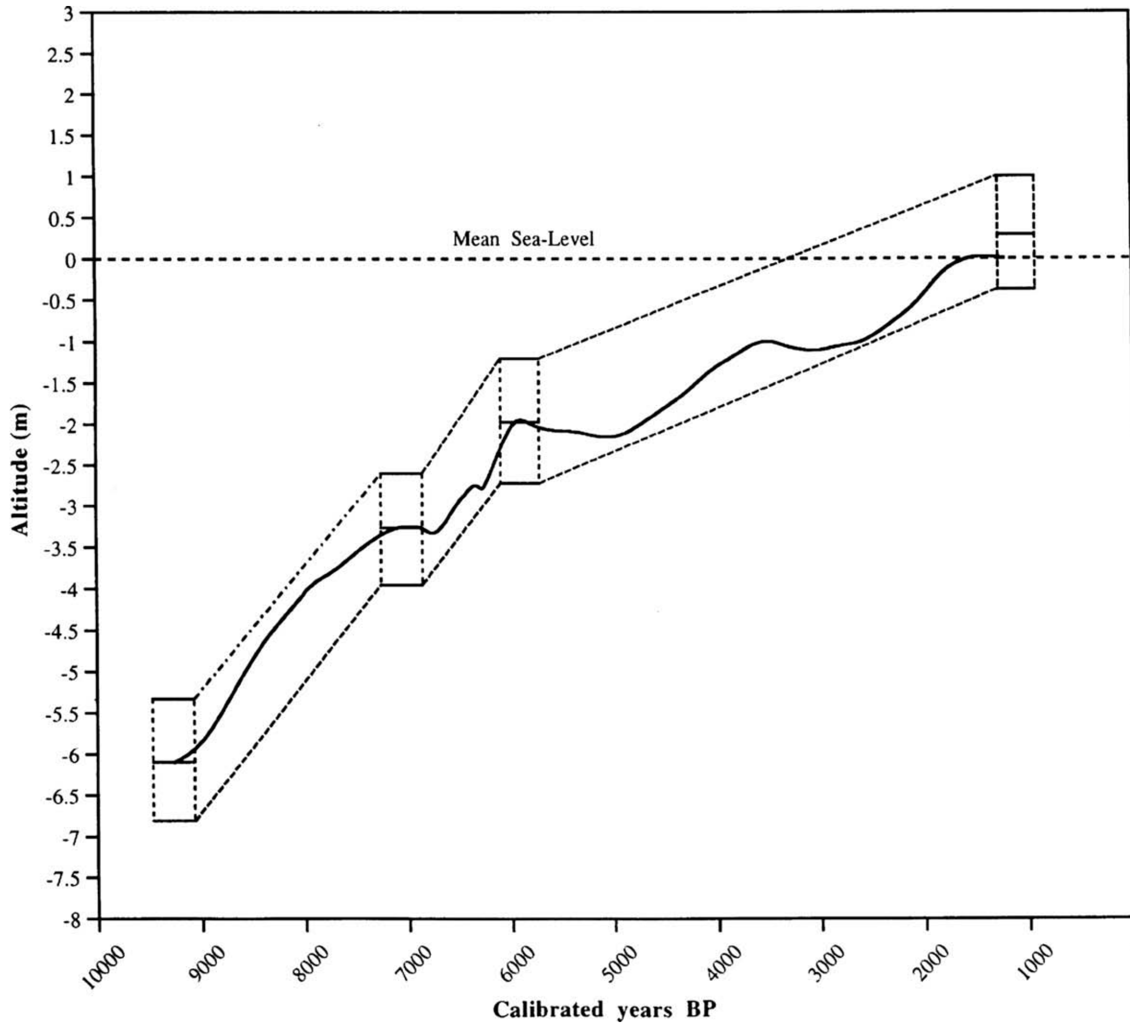

Fig. 7. Holocene sea-level curve (solid line) constructed for the Bengal basin from altitude and radiocarbon dating. The error margins are marked by the dashed lines beside the curve. Reprinted from Quaternary International, vol. 55, no. 1, Islam, M.S., Tooley, M.J., Coastal and sea-level changes during the Holocene in Bangladesh, 61–75, copyright 1999, with permission from Elsevier.

groundwater flow in the basin is strongly influenced by the heavy rainfall caused by the southeast monsoon wind from mid-June to mid-October originating from the Bay of Bengal. Annual rainfall ranges from about 125 cm in the west-central part of the basin to more than 500 cm near the Shillong plateau in the northeast and the Himalayas in the north. In the western Bengal basin, the average pre-monsoon rainfall (January–May) is 16.23% of annual rainfall, monsoon rainfall (June–October) is 82.21%, and post-monsoon (November–December) is 1.57% (Mukherjee et al., 2007a). The average temperature is about 30 °C in the summer and about 15 °C in the winter. Monsoonal rainfall and the water from Himalayan snowmelt carried by the Ganges and Brahmaputra cause extensive, damaging floods in the Bengal lowlands. BGS/DPHE (2001) reported as much as 56.9% of the total area of Bangladesh flooded annually between 1954 and 1988 [based on Miah (1988) and Brammer (1990a,b)].

7.1. Recharge

Everywhere on the delta plain, precipitation exceeds annual potential evapotranspiration (Allison, 1998). Recharge has been estimated to range from 0.3 to 5.5 mm/day (BGS/DPHE, 2001) and average 1.6 mm/day annually (Basu et al., 2001; Dowling et al., 2003) for the Bangladesh part of the basin. JICA (2002) calculated a potential recharge (PR) of 709 mm/year for western Bangladesh. For the West Bengal part, SWID (1998) estimated that absolute recharge is as much as 15% of total precipitation. On the basis of more than 100 years of historical climatological data, Mukherjee et al. (2007a) calculated the mean annual PR for western Bengal basin as 587 mm/year or 1.61 mm/day (range: 384–767 mm/year), which is 39% of the mean annual rainfall. Because of heavy monsoonal rainfall, most of the PR is during monsoon season (mean: 3.67 mm/day, range 2.41–4.86 mm/day), with little to no recharge during the pre-monsoon (mean: 0.18 mm/day, range 0.15–0.25 mm/day) and post-monsoon (mean: 0.06 mm/day, range 0.05–0.08 mm/day). The estimated annual absolute recharge from precipitation is 0.41–0.58 mm/m^2/day. However, a large part of the water that is abstracted for irrigation (annual mean: 1.2 mm/m^2/day) may return to the groundwater as recharge (annual mean: 0.75 mm/m^2/day) (Mukherjee et al., 2007a). Characterization of stable isotopic (δ^{18}O–δ^2H) composition of rainfall shows that the local meteoric water line is very similar to the global meteoric water line (Aggarwal et al., 2000; Mukherjee et al., 2007b); pre-monsoonal rainfall composition is much more isotopically enriched (heavier) than monsoonal rainfall, indicating a local moisture source rather than the Bay of Bengal (Mukherjee et al., 2007b).

7.2. Aquifer framework and groundwater flow

In various attempts to define the aquifer–aquitard structure of the Bengal basin, the aquifer systems have been classified by lithology and depth at the basin scale (e.g., UNDP, 1982; AIP/PHED, 1991, 1995; CGWB, 1994, 1997; SWID, 1998; Acharyya et al., 2000). However, stratigraphy has also sometimes been considered in smaller scale models (Ravenscroft, 2003). The difference in these processes of classification makes aquifer correlation across the basin challenging.

UNDP (1982) classified the aquifers in Bangladesh into three depth zones on the basis of lithological data to a depth of 137 m:

(i) *The shallower, upper aquifers:* These semi-confined aquifers consist of fine sands with thin medium sand interbeds and numerous, discontinuous clay layers below the surface soil. The thickness of these aquifers ranges from <10 m in the northwest of the basin to about 60 m in the south. In the coastal region, these aquifers contain brackish water, with some fresh water pockets.

(ii) *The main aquifers:* These semi-confined to locally unconfined aquifers act as the main drinking water source of the eastern part of the basin. They consist of medium- to coarse-grained sands, in part alternating with gravel layers. They vary in thickness from 5 m in the northwest to more than 75 m in the south, and are at a depth of about 140 to 150 m below ground level (bgl).

(iii) *The deeper aquifers:* These are confined aquifers at depths of 150 m to 200 m bgl, and are separated from the main aquifer by clay layers. They consist of medium to coarse sands with interbeds of silt and clay. These aquifers have very limited interaction with the overlying aquifers.

Besides classifying the aquifers by lithology, recent work has suggested divisions based on the apparent age of the groundwater. Aggarwal et al. (2000) considered groundwater recharged within the past 100 years to reside in the first (shallowest) aquifer (70 to 100 m deep). Groundwater about 3000 years old is inferred to reside in the second aquifer, which extends to 200–300 m bgl, whereas water about 20,000 years old resides in the third aquifer, below 200–300 m bgl. However, Aggarwal et al. (2000) noted that depth cannot be a dependable criterion for this classification of the aquifers.

In one of the most comprehensive groundwater studies of the Bengal basin, BGS/DPHE (2001) proposed five major aquifer systems. These are:

(a) Late Pleistocene to Holocene Tista mega-fanglomerate and Brahmaputra channel basal gravel aquifers composed of coarse sand, gravels, and cobbles.

(b) Late Pleistocene to Holocene Ganges, lower Brahmaputra and Meghna main-channel shallow aquifers composed of braided and meandering river sediments.

(c) Early to middle Pleistocene coastal and moribund Ganges delta deep aquifers composed of stacked, main-channel, medium to coarse sands at depths more than 130 m.

(d) Early to middle Pleistocene Old Brahmaputra and Chandina deep aquifers composed of red–brown medium to fine sands underlying Holocene gray medium to fine sands.

(e) Early to middle Pleistocene Madhupur terrace and Barind aquifers composed of coarse to fine fluvial sands, confined by near-surface clay residuum.

Islam and Udiin (2002) and Uddin and Abdullah (2003) proposed a four-layer, age-based classification of the aquifers, which from bottom to top are:

(1) *The Pliocene aquifers:* These are the Dupi Tila aquifers, composed of light grey to yellowish brown, medium to coarse sand, interbedded with gravels and pebbles.

(2) *The Late Pleistocene–Early Holocene aquifers:* These probably correspond to the deep aquifers of UNDP (1982), the third aquifer of Aggarwal et al. (2000), and the deep aquifer (c) of BGS/DPHE (2001) classification.

(3) *The Middle Holocene aquifers:* These aquifers may correspond to the main aquifer of UNDP (1982), the second aquifer of Aggarwal et al. (2000) or the lower shallow aquifer (b) of BGS/DPHE (2001) classification. These mostly exist in the GBM flood and deltaic plains of Bangladesh, and consist of upward coarsening sand layers, with some silt and peat at the top.

(4) *The Upper Holocene aquifers:* Corresponding to the upper shallow aquifers of UNDP (1982) and BGS/DPHE (2001), and the first aquifer of Aggarwal et al. (2000), these shallow aquifers are present all along the central and southern deltaic region of Bangladesh. They consist of vertically layered, interconnected sands, underlain by interbedded silts and clays.

For the western part of the Bengal basin, descriptions of the aquifers are based mostly on lithology, and few publications are available on the regional aquifer framework. Mukherjee et al. (2007a) delineated the regional hydrostratigraphy (down to 300 m below MSL), identifying a continuous, semi-confined sand aquifer (referred to as the main or *Sonar Bangla* aquifer), underlain by a thick, basal clay aquitard (referred to as the Murshidabad aquitard). The main aquifer thickens from the north (~80 m) toward the east (~150 m) and south (>200 m) (Fig. 8). In the southwestern part of the basin, near the modern delta, there are several intermediate-depth clayey aquitards, which divide the main aquifer into laterally connected, confined aquifers. Some isolated deeper aquifers are confined within the basal aquitards.

Transmissivity (T) values from Bangladesh range from ~3000 to 7000 m^2/day in BGS/DPHE (2001) aquifer systems (a) and (b) and from ~300 to 3000 m^2/day in aquifer systems (c)–(e) (BGS/DPHE, 2001). CGWB (1994) and SWID (1998) estimated T values in West Bengal from 3300 to 7000 m^2/day in Murshidabad, 5000–8800 m^2/day in North 24 Parganas, and 500–3000 m^2/day in South 24 Parganas. The mean T values in the four districts of the western Bengal basin are around 1000 m^2/day (Mukherjee and Fryar, unpublished data). Sikdar et al. (2001) reported a maximum value of 7774 m^2/day in the Sinthi neighborhood of Kolkata. Aquifer storage coefficients have been estimated to be within the range of 1.3×10^{-5}–6.7×10^{-3} for most of the aquifers of Bangladesh (BGS/DPHE, 2001). The hydraulic conductivity (K) of the young gray sediments has been estimated in the range of 0.4–100 m/day. The older red–brown sediments have K on the order of 0.2–50 m/day (BGS/DPHE, 2001).

On the basis of strontium isotope analyses, the groundwater flux to the Bay of Bengal has been estimated on the order of 2×10^{11} m^3/year, which is equal to about 19% of the total surface water flux (1.07×10^{12} m^3/year) (Basu et al., 2001). However, this estimate is controversial because a large groundwater flux is implausible in a flat terrain like the GBM plain, where in a distance of 100 km, the land surface elevation only decreases by about 10 m (Harvey, 2002). The hydraulic gradient decreases from about 1 m/km in the northern Bengal basin to about 0.01 m/km in the southern basin (BGS/DPHE, 2001). In general, the regional groundwater flow is from north to south with local variations in the vicinity of the river systems, which are mostly effluent. Modern continuation of such regional flow has been questioned by Harvey (2002) and Mukherjee (2006) in light of the large amount of

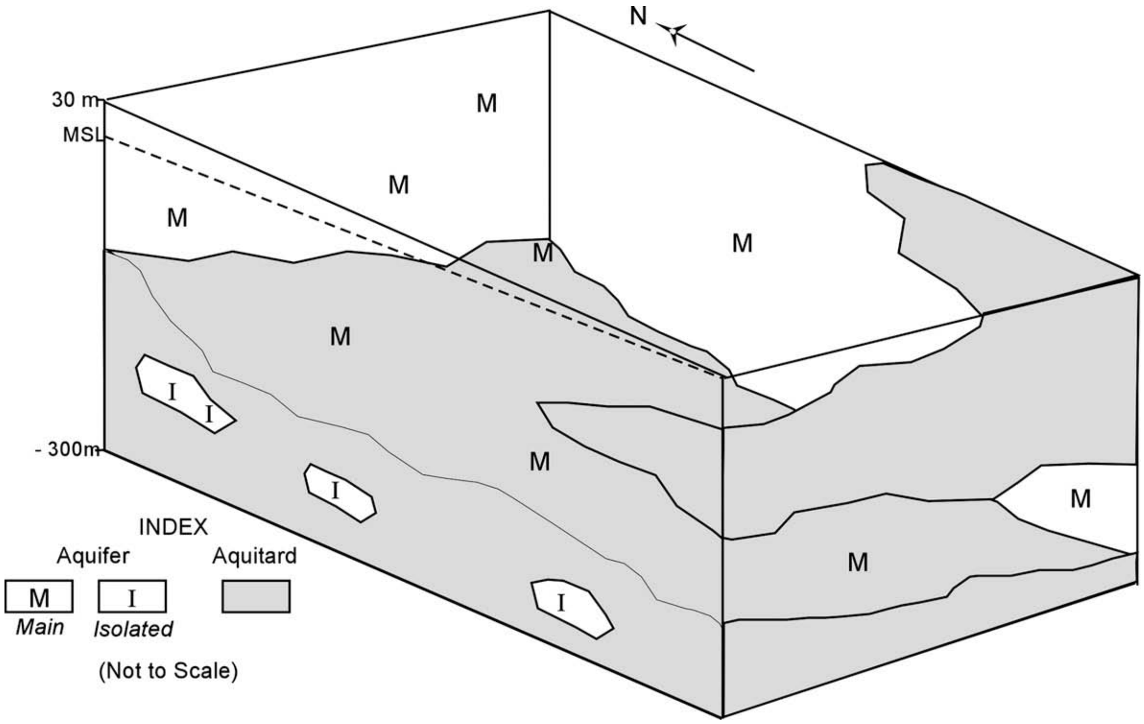

Fig. 8. A simplified, conceptual hydrostratigraphic model of the western part of the Bengal basin (adapted from Mukherjee, 2006). See text for discussion.

pumping, mostly for irrigation, within the basin. Sikdar et al. (2001) showed that there was a north–south regional flow in the vicinity of Calcutta, prior to the 1970s, which has since been disrupted as a consequence of urban pumping.

The low hydraulic gradient has led to a very slow flushing rate, which is thought to have had a significant effect on the chemistry of groundwater in the basin. Estimates show that Brahmaputra and Ganges basin sediments may have been flushed only once, if at all, since they have been deposited (BGS/DPHE, 2001). Using Darcy's law and volumetric calculations, BGS/DPHE (2001) estimated that the lower shallow aquifer would be flushed in ~20 to 71 ka under the present hydraulic gradient and in ~13 to 20 ka under an early Holocene hydraulic gradient. On the basis of ^{4}He accumulation, Dowling et al. (2003) calculated that groundwater at depths >200 m is >1 ka old. Klump et al. (2006) suggested that the groundwater is very young (<5 years) down to a depth of 10 m and may be about 40 years age within a depth of 15 to 30 m.

7.3. Source of groundwater

Using ^{18}O and ^{2}H analyses, Krishnamurthy and Bhattacharya (1991) and Mukherjee et al. (2007b) showed that groundwater of the western Bengal basin is mostly recharged by monsoonal precipitation. Moreover, the stable isotopic composition of groundwater demonstrates an continental depletion effect (Dansgaard, 1964) as the Indian southeastern monsoon wind moves from the Bay of Bengal west–northwest toward central India (Ananthakrishnan, 1977; Rao, 1981) and northward toward the eastern Himalayas. Dray (1983) inferred a lack of rapid interaction between River Ganges water and the groundwater of Bangladesh, while Shivanna et al. (1999) suggested that the depleted stable isotopic values of some shallow groundwater relative to local precipitation in Murshidabad district, West Bengal, are an artifact of interaction with the depleted Ganges water. Aggarwal et al. (2000) concluded that deep groundwater with $\delta^{18}O$ values >3‰ or <6‰ VSMOW represents recharge from precipitation during different climatic regimes from $\sim$ 3 to 30 ka.

7.4. River water chemistry

The Ganges–Brahmaputra–Meghna river system is one of the global leaders in annual solute flux to the tropical seas. The river system contributes about 5% (152×10^{6} t/year) of annual global chemical flux to the world's ocean, which is about 68% of that of the Amazon river system (Datta and Subramanian, 1997b). The river system also contributes large proportions of the global fluxes of trace metals (e.g., F, Sr) (Datta et al., 2000; Basu et al., 2001). The river waters in the basin are circumneutral to slightly alkaline (Datta and Subramanian, 1997b; Mukherjee and Fryar, 2008), indicating chemical evolution associated with mineral weathering (Ollier, 1969). The cation loads are greatest in the Ganges river waters, followed by the Bramhaputra and the Meghna. Inland river waters are mostly $Ca–HCO_3$ type, with solute compositions in the lower range of the groundwater concentrations (Datta and Subramanian, 1997b; Mukherjee and Fryar, 2008). The chemistry suggests dominance of carbonate dissolution, with some input of calcic plagioclase and pyroxene weathering (Datta and Subramanian, 1997b). The weathering rate is two to three times that of the Amazon and Huang Ho river systems and three to four times the global average (Datta and Subramanian, 1997b). The local, groundwater-fed tributaries (e.g., Jalangi, Ichamati) of the major rivers generally have higher solute concentrations and greater ^{2}H and ^{18}O enrichment than the rivers, which originate at relatively high altitudes. The tidally influenced streams near the delta front are essentially Na–Cl type, with $\delta^{2}H$ and $\delta^{18}O$ compositions close to sea water (Mukherjee et al., 2007b; Mukherjee and Fryar, 2008). The river chemistry evolves with weathering during the pre-monsoon and is diluted during the monsoon (Sarin et al., 1989). Trace metal compositions in the river waters are generally much lower than in the adjacent groundwater, with no elevated dissolved As in the Himalayan rivers. However, high concentrations of As have been detected in local tributaries, probably reflecting the composition of base flow (Mukherjee and Fryar, 2008). Most of the As in the river solute load is associated with insoluble phases like crystalline Fe oxides (Stummeyer et al., 2002).

7.5. Groundwater chemistry

Although the chemistry of groundwater in the Bengal basin, like the stratigraphic framework, is heterogeneous, some generalizations can be made. Bengal basin groundwater tends to be Ca–HCO_3 dominated, with some Na–Cl dominated waters, relatively high As, Fe, and Mn, and low or undetectable SO_4 and NO_3 (e.g., Ahmed et al., 1998; BGS/DPHE/MML, 1999; Nickson et al., 1998, 2000; McArthur et al., 2001; Dowling et al., 2002). Mukherjee and Fryar (2008) noted that this description may be further typified in a hydrostratigraphic context in the western Bengal basin, where the main, semi-confined aquifer contains Ca–HCO_3 water and the isolated, deeper confined aquifers contain Na–Cl or HCO_3 waters, similar to descriptions provided by Handa (1972), Ahmed (1994), Sikdar et al. (2001), and Bhattacharya et al. (2002). Mukherjee and Fryar (2008) further noted that the main aquifer water may evolve to form the isolated waters by cation exchange with aquifer sediments and by mixing with connate water in various proportions. However, salinity caused by upward diffusion of connate water from very deep aquifers appears to be unlikely as predicted by geochemical modeling. Sikdar et al. (2001) attributed increasing salinization of groundwater in the Calcutta region, which has accompanied pumping, to mixing of fresh groundwater with modified connate water in low-permeability zones (Handa, 1972). Along the Bay of Bengal, relatively fresh groundwater underlies shallow saline groundwater (BGS/DPHE, 2001).

Galy and France-Lanord (1999) concluded that the water chemistry of the Bengal basin is controlled by the presence of carbonates, the composition of silicates, and the oxidation of sulfides. They suggested that weathering in the basin is dominated by H_2CO_3 liberated by degradation of organic matter in the soil, and <10% of the weathering of the Ganges basin is caused by H_2SO_4 derived from sulfide oxidation. The authors also suggested that, because Ca-plagioclase is not abundant in the Himalayas, weathering of the alkaline Himalayan silicates releases Na and K as the dominant cations. Mg found in the hydrobiotite, vermiculite, and smectite of the sediments derived from the Himalaya (Baumler and Zech, 1994; Grout, 1995) is probably introduced into the system from weathering of biotite, and to a lesser extent from chlorite, pyroxene, and garnet (Galy and France-Lanord, 1999). Dowling et al. (2003) found that the average $(Ca + Mg)/HCO_3$ molar ratio (0.9) and the correlation between Sr and HCO_3 are consistent with dissolution of detrital carbonates in the upper reaches of the river, and thus concluded that the Ganges and Brahmaputra flood plains have been dominated by carbonate weathering. Relatively high Ca and Mg concentrations in southwestern Bangladesh coincide with relatively calcareous sediments deposited by the Ganges (BGS/DPHE, 2001). The deposition of silt-dominated sediments in the foreland basin of the Himalayas (Burbank, 1992), however, probably favors silicate weathering (Derry and France-Lanord, 1996; Galy and France-Lanord, 1999).

Mukherjee and Fryar (2008) showed that groundwater of the western Bengal basin is influenced by both carbonate dissolution and silicate weathering. Hence, Na and K may enter the Bengal basin groundwater from incongruent dissolution of feldspars, micas, and pyroxenes, whereas Ca and Mg can be derived both from silicate and carbonate weathering. Other than carbonate and silicate weathering, HCO_3 in groundwater can originate from biogenic CO_2 gas dissolution in the vadose zone (Garrels, 1967).

Groundwater in the Bengal basin has been found to be anoxic (Mehta and Bhattacharya, 2000; Harvey et al., 2002; Swartz et al., 2004), with abundant detections of sulfide and CH_4 (e.g., Ahmed et al., 1998; Gavrieli et al., 2000; Nickson et al., 2000; McArthur et al., 2001, 2004) and very little dissolved O_2. Throughout Bangladesh, SO_4 concentrations are relatively low (median <1 mg/L) and Fe and Mn concentrations are relatively high, consistent with strongly reducing conditions (BGS/DPHE, 2001). Anomalously high SO_4 and NO_3 concentrations in Dhaka provide evidence of ground-water pollution by sewage (Ahmed et al., 1998). In West Bengal, SO_4 concentrations as high as 39.6 mg/L have been documented by Mukherjee and Fryar (2008), and those concentrations were found to vary with depth and distance from the coast.

Most of the recent studies of groundwater chemistry in the Bengal basin have advocated that the dominant redox process in the main aquifer is FeOOH reduction coupled to microbially mediated oxidation of natural organic matter (NOM) (Bhattacharya et al., 1997; Nickson et al., 1998, 2000; McArthur et al., 2001, 2004; Harvey et al., 2002, 2005; Zheng et al., 2004). NOM may be in forms of dissolved organic carbon or peat (McArthur et al., 2001, 2004; Ravenscroft et al., 2001, 2005; Harvey et al., 2002), and oxidation of NOM may result in elevated HCO_3 concentrations. On the basis of chemical and stable isotopic data, Zheng et al. (2004) and Mukherjee and Fryar (2008) suggested local-scale reoxidation of authigenic Fe sulfides, which indicates that Fe, S and C cycles within the subsurface are interrelated and complex.

In the past two decades, elevated concentrations of arsenic (As) have been found in groundwater of the Bengal basin. Prolonged ingestion of As contaminated water causes severe health effects, including cancer, and can be fatal (Smith et al., 2000). Arsenic concentrations vary widely in the basin, generally ranging from less than 0.005 to 3.2 mg/L (CGWB, 1999; BGS/DPHE, 2001), but concentrations as high as 4.1 mg/L have been identified (Ghosh and Mukherjee, 2002). The contaminated area is mostly restricted by the River Bhagirathi–Hoogly (distributary of River Ganges) in the west, the Rivers Ganges and Padma in the north, the flood plain of the River Meghna (tributary of the River Padma), and the River Jamuna in the northeast (Acharyya et al., 2000).

There has been much speculation about the primary source of As in this basin. It may have been transported by the River Ganges and its tributaries from the Gondwana coal seams in the Rajmahal trap area (Saha, 1991), by the north Bengal tributaries of the Ganges from near the Gorubathan base-metal deposits in the eastern Himalayas (Ray, 1999), or with other fluvial sediments derived from the Himalayas (e.g., McArthur et al., 2004). Arsenic may also have been biogenically deposited in the paleo-channels of the River Bhagirathi–Hoogly and the River Padma under euxinic conditions (P. Chakrabarty, West Bengal State Remote Sensing Board, 1999, personal communication).

Four main mechanisms have been identified by various workers to explain the mechanism of As mobilization in groundwater of the Bengal basin. These are:

(1) As is released by oxidation of As-bearing pyrite in the alluvial sediments (e.g., Mallick and Rajgopal, 1995).
(2) Arsenic anions sorbed to aquifer mineral grains are displaced into solution by competitive exchange of PO_4^{3-} available from fertilizers of surface soils (Acharyya et al., 2000).
(3) As sorbed to FeOOH (HFO) is released by reduction of solid-phase Fe(III) coupled to oxidation of peat (Bhattacharya et al., 1997; Nickson et al., 1998, 2000; McArthur et al., 2001, 2004; Ravenscroft et al., 2001) or of dissolved organic carbon (DOC) (Harvey et al., 2002, 2005).
(4) As is released from HFOs or other sediment phases by redox reactions related to Fe and S cycling (Zheng et al., 2004) and is retained in solution by partial redox equilibrium (Mukherjee et al., 2008). This proposed mechanism is a combination of mechanisms 1 (involving reoxidation of authigenic pyrite) and 3. In addition to these views, many workers have agreed

that indiscriminate agricultural and industrial pumpage may have facilitated the spread of As within groundwater (e.g., Harvey et al., 2005; Klump et al., 2006; Mukherjee et al., 2007a).

8. Summary

The Bengal basin in eastern India and Bangladesh is the largest fluvio-deltaic system of the world. It has been shaped by the rivers Ganges, Brahmaputra, Meghna and their tributaries and distributaries, which drain into the Bay of Bengal. The basin lies between the eastern Himalayas and the Bay of Bengal at the junction of the Indian plate with the Eurasian and Burmese plates. The basin was initiated as a subsiding foredeep basin beneath the uprising Himalayan front and the Indo-Burma range formed by the collision of the Eurasian, Indian, and Burmese plates starting in the late Mesozoic. By the mid-Miocene, the basin had become a huge sink for the sediments eroded from the rising mountain ranges. The basin can be broadly tectonically divided into a stable shelf, which mostly constitutes the extension of the Indian plate in the west, and the foredeep basin. These are separated by a deep-seated zone of flexure, known as the Calcutta–Mymensingha hinge zone. At present, about 1 to 8 km of Permian to Holocene clastic sediments rest on the stable shelf in the western part of the basin and as much as 16 km of Tertiary to Quaternary alluvial sediment fills the foredeep of the basin, which at present lies at the mouth of the Ganges and Brahmaputra rivers. The ongoing Himalayan orogeny has caused vertical uplift to divide the foredeep basin into numerous poorly connected sub-basins, which in turn has led to conspicuous differences in sedimentary environments and lithology.

The formation of the Bengal basin started with the break-up of Gondwanaland in the late Mesozoic, at about 126 Ma. During the middle Eocene, basin-wide subsidence caused an extensive marine transgression in the basin, which resulted in the deposition of a nummilitic limestone, the Sylhet Limestone. At about 49.5 Ma, a major shift in the sedimentation pattern began. The carbonate-clastic platform sedimentary sequence was succeeded by a predominantly clastic deposit. The western part of the basin saw deposition of lagoonal argillaceous and arenaceous sediments, whereas the eastern and northeastern parts were occupied by an open neritic sea. At about 10.5 Ma, intense tectonic activity began, resulting in basin-wide regression with a major eustatic low. This initiated the modern Bengal delta as a shift from a marine-estuarine environment to a predominantly fluvial–tidal dominated environment.

Physiographically, the Bengal basin can be divided into two major units, the Pleistocene uplands and Holocene sediments. The Pleistocene uplands include the Barind tract and the Madhupur terrace. The Holocene sediments include the alluvial fans in the foothills of the Himalayas, the uplands such as the Tippera surface, the deep tectonic basin (Sylhet basin), and the Ganges–Brahmaputra–Meghna flood and delta plain, the most extensive unit of the basin. The flood and delta plain consists of clastic fluvial deposits with elevations no more than 15 m above MSL in most areas. Radiocarbon dating of sediments from the plain yields an age of generally less than 10,000 years to a depth of 30 m below land surface in most areas.

Deposition of the lowest unit of the GBM delta began at the onset of the local Pleistocene glacial maximum. The rivers draining the previous plains during that time must have scoured through the earlier plains and deposited the basal gravel at a depth analogous to the sea-level at that time. The next unit of the GBM plain was probably deposited at about 12,000–11,500 years BP as an extensive flood plain in the central region. Major eustatic sea-level rise around 10,500 years BP caused extensive back-flooding and sedimentation, initiating the present GBM delta. From about 10,000 to 7000 years BP, a major and rapid transgression probably resulted in the deposition of fine sediments of the upper unit of the GBM plain.

The Bengal basin sediment is dominated by detrital quartz and feldspar grains. The clay minerals include illite and kaolinite, with minor chlorite and montmorillonite. The heavy mineral assemblages include amphibole, pyrope, and epidote. Some pyrite is also found in the basin sediments. In Ganges basin sediments, concentrations of both TIC and TOC are significant, and TOC is well-correlated to TN and grain size of the sediments.

There is a lack of consensus about the nature of groundwater flow and the stratigraphic framework of the aquifers in the basin. In general, three to five classes of aquifers have been proposed for Bangladesh, but only two to three for West Bengal. The gray Holocene sediments tend to have higher hydraulic conductivity than the brownish Pleistocene sediments. Regionally, groundwater tends to flow toward the coast with a very low hydraulic gradient, particularly in the south. The water is mostly of monsoonal origin with an isotopic composition consistent with the present-day climate. Groundwater chemistry is generally a Ca–HCO_3 type with some Na–Cl waters; the water also has high As, Fe, and Mn and is low in SO_4 and NO_3. Processes controlling groundwater chemistry include carbonate dissolution, silicate weathering, redox reactions (especially including Fe, C, and S), and mixing between fresh and saline waters.

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