3 Geology and sedimentology

3.1 PHYSICAL SETTING

3.1.1 Background

The Bengal Basin in Bangladesh contains a 15 km thick sequence of Cretaceous to Recent sediments and occupies some 100,000 km² of lowland floodplain and delta. The combined deltas of the Ganges, Brahmaputra and Meghna (GBM) river systems lie within Bangladesh. These experience high rates of discharge and sediment transport during the annual monsoon season. The GBM produces the greatest total sediment load of any river system in the world (Table 3.1). The large volume of sediment eroded from the Himalayas has resulted in the formation of the submarine Bengal Delta that extends beyond the latitude of northern Sri Lanka. The recent studies of Goodbred and Kuehl (1999) suggest that some 1500 x 10⁹ m³ of sediment fill has accumulated in the flood plain and delta plain areas of the Bengal Basin in the last 7,000 years or so.

Sediment load is greatest in the Brahmaputra and much less in the Meghna. In Assam, the Brahmaputra is aggrading with accumulation of much coarse-grained material within an alluvial fan that extends a short way into northeastern Bangladesh. In a similar fashion, the Tista and Mahananda rivers have formed a fan-cone south of Darjeeling, extending into north-western Bangladesh. This is composed of coarse sands, gravels, pebbles and cobbles. Downstream of its confluence with the Tista, the Brahmaputra flows due south to its confluence with the Ganges at Arcicha.

In the valley between the Barind and the Madhupur Tracts (Figure 3.1), the Brahmaputra is a braided sand river with a channel some 10 km wide (Thorne et al., 1993). During 1986–87 the sediment load carried by the river, measured at Bahadurabad in Jamalpur District, totalled some 6.72 x 10¹¹ kg of which 1.62 x 10¹¹ kg was fine to medium sand and 5.04 x 10¹¹ kg was silt and mica (Thorne et al., 1993). Miah (1988) observed that the Brahmaputra was thought not to be depositing sediment along this reach. Goodbred and Kuehl (1999) estimated a long-term total annual sediment load for the Ganges-Brahmaputra system of some 10¹² kg a⁻¹. Approximately 1/3 of this has been deposited in the delta and flood plain areas, 1/3 as a sub-aqueous prograding delta in the Bay of Bengal and 1/3 in the deep sea. Modern budgets suggest a similar distribution. An average of some 7.0 km² of new land has been formed at the mouth of the delta annually since 1782 with some 4.4 km² a⁻¹ since 1840 (Allison, 1998; Allison et al., 1998).

Sediment loads vary by two orders of magnitude seasonally, with the maximum load in August. Some 10% of the discharge occurs during the four months of the SW Indian monsoon. Sediments have accumulated within the incised channels following the low sea level during the glacial maximum and within the subsiding delta where accommodation space is being produced at about 0.5 mm a⁻¹.

Much of the sediment load of the main rivers has been eroded by glacial and periglacial activity from the high Himalayas and should therefore be moderately fresh when deposited. These sediments include eroded ultramafic rocks from the northern parts of the high Himalayas and

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### Table 3.1. Average monthly discharge and sediment load of major rivers.

Discharge figures are long-term monthly averages (pre-Farakka barrage) in m³ s⁻¹ (Rashid, 1991). Sediment loads are in millions of tons per annum (Coleman, 1969).

<table>
<thead>
<tr>
<th>Month</th>
<th>Ganges (Harding Bridge)</th>
<th>Brahmaputra (Bahadurabad)</th>
<th>Meghna (Bhairab Bazaar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>3113</td>
<td>5194</td>
<td>594</td>
</tr>
<tr>
<td>February</td>
<td>2712</td>
<td>4308</td>
<td>495</td>
</tr>
<tr>
<td>March</td>
<td>2312</td>
<td>4711</td>
<td>635</td>
</tr>
<tr>
<td>April</td>
<td>2056</td>
<td>6823</td>
<td>937</td>
</tr>
<tr>
<td>May</td>
<td>1971</td>
<td>15844</td>
<td>1934</td>
</tr>
<tr>
<td>June</td>
<td>4311</td>
<td>32488</td>
<td>3821</td>
</tr>
<tr>
<td>July</td>
<td>17871</td>
<td>44080</td>
<td>7814</td>
</tr>
<tr>
<td>August</td>
<td>37546</td>
<td>45107</td>
<td>8279</td>
</tr>
<tr>
<td>September</td>
<td>36970</td>
<td>36295</td>
<td>8222</td>
</tr>
<tr>
<td>October</td>
<td>17244</td>
<td>21955</td>
<td>6239</td>
</tr>
<tr>
<td>November</td>
<td>7109</td>
<td>10477</td>
<td>3078</td>
</tr>
<tr>
<td>December</td>
<td>4195</td>
<td>6737</td>
<td>990</td>
</tr>
</tbody>
</table>

---
granitic and high-grade metamorphic rocks from the central and southern parts. These are the main sources of the dominant mineralogy: quartz, biotite and feldspar. At lower altitudes, the main rivers cross the Damodar and Darjeeling coalfields (coals and shales containing significant amounts of pyrite), the Rajmahal Traps (basalts with significant pyrite) and the Gangetic Plains (lateritic materials).

The geomorphology of the GBM system has developed in response to a series of glacio-eustatic sea-level cycles and long-term tectonic activity. The unconsolidated near-surface Pleistocene to Recent fluvial and estuarine sediments that underlie much of Bangladesh form prolific aquifers. Studies of the geomorphology, geology, and hydrogeology of the GBM system have been prompted by:

- major flood events and their effects upon infrastructure;
- exploration for gas and minerals;
- development of groundwater for irrigation and rural/urban water supply;
- academic research and general survey work.

3.1.2 Geomorphology

Quaternary sediments of the GBM system were deposited in two geomorphologically distinct environments to the north and to the south of the Ganges and lower Meghna rivers. To the north, continental fluvialite sediments were deposited within mountain front fan deltas and floodplains of the major rivers. To the south, thinly bedded alluvial sediments were deposited within an estuarine delta environment.

During the Quaternary, patterns of river incision and sediment deposition in the GBM system were controlled by climatic change and sea-level oscillations related to periods of glaciation (Umitsu, 1993). Sediments derived from erosion of the Himalayas and the Indo-Burman Hills were deposited in this area by major river systems. Morgan and McIntire (1959) and Coleman (1969) noted that the present north-south direction of flow of the Jamuna-Brahmaputra is at variance with the course of the then Old Brahmaputra main channel reported by Fergusson (1863). Rashid (1991) described how the Tista changed its main course following a catastrophic flood in 1787. Changes in the courses of the Brahmaputra, Tista, Ganges and other rivers of the GBM system have been caused by tectonic activity. Morgan and McIntire (1959) first described the geomorphology and near-surface geology of the Bengal Basin using aerial photography to distinguish the main geomorphologic units (Figure 3.1). These include:

- mountain front fan deltas of the Tista and Brahmaputra;
- fluvial floodplains of the Ganges, Brahmaputra, Tista and Meghna Rivers;
- the delta plain of the lower GBM system south of the Ganges-Meghna valleys, including the moribund Ganges delta and the Chandina Plain;
- Pleistocene terraces of the Barind and Madhupur Tracts and associated fault systems;
- subsiding basins within the eastern Ganges tidal delta and the Sylhet basin adjacent to the Dauki Fault.

Coleman (1969) described patterns of fluvial sediment deposition by the GBM rivers and their distributaries. Brammer (1996) explained the distribution of the soils and physiographic regions of Bangladesh. He contrasted the high calcium carbonate contents of the Ganges-derived sediments with the low contents of those deposited by the Brahmaputra and Meghna rivers. Bristow (1987), Bristow and Best (1993), Bristow (1993), Thorne et al. (1993) and Bristow (1999) reported further studies of the geomorphology and sedimentology of the Brahmaputra including the causes of channel avulsion, or switching, between the old and young Brahmaputra courses. Goswami (1985), in his study of the upper reaches of the Brahmaputra in Assam, commented that the 8.7 magnitude earthquake of 1950 with its epicentre in Assam resulted in several large landslides that dammed various tributaries of the Brahmaputra.

The bursting of these natural dams produced devastating floods that carried large volumes of sediment downstream. Miah (1988) and Brammer (1990a) documented...
the major GBM system floods of 1987 and 1988. In response to these catastrophic floods, a series of studies was undertaken under the Flood Action Plan of the 1990s to investigate aspects of river channel movement, bedform structure, bank erosion and sediment deposition in response to flood events (Brammer, 1990b).

3.1.3 Geology

Morgan and McIntire (1959) described the Pleistocene Madhupur and Barind Tracts separated by the Jamuna-Brahmaputra River, and other Quaternary surfaces such as the Chandina surface of the Bengal Basin. Sengupta (1966) reporting the results of oil and gas exploration undertaken in the Indian sector of West Bengal, described the depth distribution of thick Cretaceous to Recent sediments and the tectonic evolution of the Bengal Basin. Banerji (1984) described the stratigraphy and composition of the Cenozoic sediments and associated rocks of the basin. Seismic surveys with follow-up drilling have shown the presence of significant gas and oil reserves in north-eastern and eastern Bangladesh. Salt et al. (1986) and Lindsay et al. (1991) used seismic data to interpret the geological evolution of western Bangladesh. Alam et al. (1990) combined geological information derived from remotely-sensed data, superficial deposits and data from oil field exploration to produce a national geological map of Bangladesh, including an annotated description of the main geological units. This is summarised in Table 3.2. National gravity and aeromagnetic data have been used to determine the thickness of the Cretaceous to Recent sediment pile and the nature of the basement beneath Bangladesh (Rahman et al., 1990). Jones (1985) analysed borehole data from oil exploration to assess the possible distribution of deep aquifers (1800 m depth) beneath the GBM. Little pre-Pleistocene geology is exposed within Bangladesh; these rocks are only seen in the eastern hills and along the southern edge of the Shilong Plateau in the north-east.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Group</th>
<th>Formation</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holocene</td>
<td></td>
<td>Alluvium</td>
<td>Silt, sand, gravel and clay</td>
</tr>
<tr>
<td>Pleistocene/Pliocene (up to 6375 m)</td>
<td>Madhupur</td>
<td>Dihing Formation/Madhupur Clay</td>
<td>Yellow to yellowish grey, massive, fine to medium sandstone and claystone/sticky clay</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dupi Tila Formation</td>
<td>Yellow to ochre, pink, light brown, light grey to greyish-white sandstone, siltstone and conglomerate. Several oxidised, iron-rich, clayey palaeosols. Petrified wood</td>
</tr>
<tr>
<td>Pleistocene/Neogene</td>
<td>Tipam Group (U. Jamalganj in NW)</td>
<td>Girujan Clay</td>
<td>Grey to greenish grey, red mottled, silty shale, shale and claystone</td>
</tr>
<tr>
<td>Neogene</td>
<td></td>
<td>Tipam Sandstone</td>
<td>Light yellow to yellowish grey, grey, brownish grey and orange fine to medium grained pebbly sandstone, siltstone and shale</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Surma Group (L. Jamalganj in NW)</td>
<td>Greenish to bluish grey and yellowish grey marine pyritic shale, siltstone and very fine to medium grained sandstone, marine fossils</td>
</tr>
<tr>
<td>Miocene</td>
<td>(3100 m)</td>
<td>Bhuban Formation</td>
<td>Grey to bluish grey fine to medium sandstone, siltstone, claystone</td>
</tr>
<tr>
<td>Oligocene</td>
<td>(800–1000 m)</td>
<td>Bara Formation</td>
<td>Brown, yellow-brown, pink and grey sandstone, siltstone and carbonaceous shale</td>
</tr>
<tr>
<td>Late Eocene</td>
<td>(Eocene 600–800 m)</td>
<td>Kupili Formation</td>
<td>Grey, greenish grey to black silty claystone, fossiliferous shale, thin beds of glauconitic sandstone and limestone</td>
</tr>
<tr>
<td>Middle–Early Eocene</td>
<td></td>
<td>Tura Formation</td>
<td>Grey to greenish brown massive nummulitic limestone</td>
</tr>
<tr>
<td>Eocene and Palaeocene</td>
<td></td>
<td>Sylhet Limestone</td>
<td>Grey, brown, pink and greyish-white ferruginous sandstone, coal and shale</td>
</tr>
<tr>
<td>Late-Middle Cretaceous</td>
<td>Upper Gondwana</td>
<td>Sibgan Trapwash</td>
<td>Coarse yellow brown sandstone; white clay; volcanic ash</td>
</tr>
<tr>
<td>Early Cretaceous–Jurassic</td>
<td>Rajmahal Traps</td>
<td>Amgdaloidal basalt; serpentinitised andesite; shale; argillamictic and eurygentic limestones</td>
<td></td>
</tr>
<tr>
<td>Late Permian</td>
<td>Lower Gondwana</td>
<td>Paharpur Formation</td>
<td>Sandstone; feldspathic greywacke; coal, shale; coarse sandstone</td>
</tr>
<tr>
<td>Early Permian</td>
<td>Lower Gondwana</td>
<td>Kuchma Formation</td>
<td>Coarse grained sandstone, shale; thick coal seams</td>
</tr>
<tr>
<td>Precambrian</td>
<td></td>
<td>Basement Complex</td>
<td>Gneiss and schist</td>
</tr>
</tbody>
</table>

3.1.4 Structural Geology

Tectonic processes have played a major role in the development of the GBM delta system. The Bengal Basin, at the junction of the Tibetan, Indian and Burmese continental plates, formed after the separation of the Indian plate from the southern continent of Gondwana (Curray and Moore, 1974). Initially, marine sediments were deposited within the Basin during Cretaceous times. During the Eocene, the Indian Plate collided with the Burmese Plate, and sediments eroded from the uplifted Burmese Hills were deposited within the Basin. The Indian Plate further collided with the Tibetan and Burmese Plates during Miocene times, causing a large influx of sediment into the basin south of the Himalayas and west of the Burmese Hills.

During the Pliocene, large-scale movement along the
Dauki Fault caused uplift of the Shillong Plateau and subsidence of the Garo-Rajmahal Gap. The entry of the Brahmaputra into the Bengal Basin was thus diverted from the area east of Sylhet to the west of the Shillong Hills. This tectonic activity resulted in the formation of the north-south-trending Tripura-Chittagong fold belt (Alam, 1989). Two other main structural trends are apparent; east-west, as seen in the Dauki Fault, and north-east–south-west, the trend of the Hinge Zone. Fault systems occur parallel and normal to these two trends.

The Barind and Madhupur Tracts form two uplifted and tilted horst blocks separated by a north-south trending faulted graben, now occupied by the Brahmaputra River (Khandoker, 1987). The Bengal Basin can be divided into two crustal domains about a north-east to south-west palaeo-continental margin, namely the Calcutta-Mymensingh Hinge Zone. The Rangpur Platform and Bogra Shelf form a basement high beneath a thin cover of Cretaceous to Recent sediments in north-western Bangladesh in the Garo-Rajmahal gap to the west of the Shillong hills. South and south-east of the Hinge Zone are the Faridpur, Hatia and Sylhet Troughs, areas of thick sediment underlain by oceanic crust that continue to subside above the plate subduction zone (Figure 3.2) (Lindsay et al., 1991).

The Dauki Fault forms the southern edge of the Shillong Hills and is an intercrustal thrust zone developed at the junction of the Indian and Tibetan Plates (Khan, 1991). The Shillong Massif is presently undergoing north-south compressional shortening by being thrust over the 15 ± 2 km thick pile of sediments to the south (Johnson and Alam, 1991). The Great 1897 Assam Earthquake whose epicenter was beneath the western Shillong Massif indicates ongoing tectonic activity (Mukhopadhyay et al., 1997). Mukhopadhyay (1984) and Khandoker and Hoque (1990) reported that this earthquake also altered the courses of the Tista, Padma and Atrai rivers, all developed on apparent fault lineaments within the Bengal Basin. The 1897 earthquake was particularly destructive in the Sunamganj area of the Sylhet Basin where, adjacent to the Dauki Fault, severe damage was caused to masonry. Many crevices, through which sand and water were ejected, appeared in an area of ongoing tectonic subsidence.

### 3.1.5 Quaternary Geology

The Quaternary period, of about 1800 ka duration, is dominated by the effects of approximately 120 ka glacio-eustatic cycles. At the time of the glacial maximum during the most recent cycle, 21 ka BP, sea levels declined by up to 130 m below present-day levels. Approximately 20 such cycles occurred during the Quaternary (Williams et al., 1993). The study of Quaternary sediments has been hampered by lack of suitable correlative data for mapping pre-last-interglacial sediments. Studies undertaken in the USA of sediments of similar age have used palacosols and peat horizons to establish lithostratigraphic boundaries (Clark and Lea, 1992). Seismic data can be interpreted to produce stratigraphic sequences within prograding deltas but the application of such methods of analysis to continental fluviatile sequences is difficult (Emery and Myers, 1996). The lithostratigraphy of Quaternary sediments in Bangladesh has been studied by:

- Davies (1989) – the Dhaka/Manikganj area;
- Mott MacDonald (MMI, 1992) – central and north-eastern areas;
- Umitsu (1993) – the Brahmaputra Valley between Jamalpur and Atricha;
- Ahmed (1994) – the Barind Tract;

### Data sources

Many of the data referred to here were derived from boreholes drilled for groundwater irrigation projects. Little geological information has been obtained from the 6–11 million hand-drilled domestic tubewells and shallow irrigation tubewells installed throughout Bangladesh. Representative sediment samples have mostly been obtained from deep tubewells (DTWs), drilled by reverse circulation, for irrigation by the Bangladesh Agricultural Development Corporation (BADC) and urban water supplies by the Department of Public Health Engineering (DPHE). Such
sediment samples were normally obtained at five feet (1.52 m) intervals specifically for the definition of screenable horizons. The locations of these studies are shown in Figure 3.3 and outlined below.

The BADC implemented programmes for the installation of several thousand 2-cusec-capacity deep tubewells to supply groundwater for irrigation. These include:

- 3000 DTW Project (1972–1977) – with IDA and Sir M MacDonald and Partners;
- 4000 DTW project (1983–1993) – with IDA/ODA/Australian Aid and Mott MacDonald;
- Barind Integrated Area Development Project (mid 1980s – early 1990s);
- Milners/BADC project (late 1970s to late 1980s);
- 200 Deep Tubewells Bangladesh Project in Dinajpur with the Abu Dhabi Fund for Arab Economic Development (mid 1980s);
- Sir M MacDonald and Partners (MMP) assessment of hydrogeological conditions within the northern half of the country (MMP, 1983).

The DPHE supplies water by reticulation to urban areas and by the construction of hand-pumped tubewells in rural areas. Geological borehole logs and reports are available from the following:

- Coastal Areas Project – with BWDB and IWACO consultants;
- 18 District Towns Project – with DHV consultants;
- 9 District Towns Project – with DANIDA.

As part of the 9 District Towns Project, several deep boreholes were drilled in the Lakshmipur-Noakhali area to develop a deep sand aquifer containing fresh water below several sandy zones affected by saline intrusion. These deep boreholes were drilled by direct circulation, with bentonite mud. Lithological samples were obtained at 3 m intervals and boreholes were logged using wireline equipment on reaching the required depth. Geological logs were interpreted from resistivity and natural gamma wireline logs run in three boreholes. Deep boreholes have tapped a similar deep freshwater sand aquifer within the Khulna-Barisal area (Haskoning/IWACO, 1981).

Since 1978, the Bangladesh Water Development Board (BWDB) has, with the assistance of UNDTCD, drilled a series of deep exploration boreholes country-wide and in a series of special study areas. The deep borehole logs held by BWDB provide the only data on lithological variation within the Quaternary sediments at depths below 150 m for much of Bangladesh.
The Geological Survey of Bangladesh (GSB) has drilled deep boreholes to explore for coal, limestone, hard rock, oil and gas deposits. Regional aeromagnetic, gravity and seismic surveys have also been undertaken. Additional information is available from:

- the Khulna Power station groundwater supply project;
- mapping projects undertaken by MSc and PhD students at the Dept. of Geology, University of Dhaka;
- sediment provenance studies of parts of the GBM system by the Department of Geology, University of Dhaka.

Hydrogeological studies undertaken in Bangladesh include:

- a UNDTC/BWDB national study (UNDP, 1982);
- JICA investigation of deep alluvial sediments as part of a study for the Brahmaputra (Jamuna) bridge foundations (included drilling of exploration boreholes, sediment analyses and radiocarbon dating (Umitsu, 1987; Umitsu, 1993);
- IDA 4000 Deep Tubewells project in Sylhet, Kapasia and Comilla (MMP reports 1983–1993);
- BGS study of the design of 2 cusec-capacity deep tubewells and geology and hydrogeology of Late Quaternary and Holocene sediments in the Dhamrai, Satura, Manikganj, Singair and Savar areas (part of the IDA 4000 Deep Tubewell project; Davies, 1989);
- a BGS hydrochemical survey of aquifers in central and north-eastern Bangladesh (Davies and Exley, 1992).

Borehole data from the above sources and sediment logs from the current study have been used to construct a series of geological cross-sections across the GBM system. These provide the first indication of sediment distribution with depth within the two primary environments of sediment deposition. Geological data are not yet available from the 170 deep test boreholes drilled during 1997–2000 for UNICEF.

### 3.2 Sea-level Change and Patterns of Sedimentation

The Quaternary period comprises four stages:

- Holocene 10–0 ka BP;
- Upper Pleistocene 128–10 ka BP with glacial maximum at 21 ka BP;
- Middle Pleistocene 750–128 ka BP;
- Lower Pleistocene 1800–750 ka BP (based on the Oldovian palaeomagnetic event at 1800 ka).

#### 3.2.1 Sea-level change during the Upper Pleistocene and Holocene

The Upper Pleistocene includes the last interglacial-glacial period between 128–10 ka BP. Worldwide studies of sea-level movement, in response to glacio-eustatic events during the Holocene and Late Quaternary have been undertaken by Chappel and Shackleton (1986) and Pirazzoli (1991) and others. Shifts in sea level and climatic effects are inferred from studies of oxygen isotopes from ice core sections and dating of corals within areas of tectonic uplift in Barbados and New Guinea (Aharon and Chappell, 1986; Chappell and Shackleton, 1986; Shackleton, 1987; and Williams et al., 1993). The Upper Pleistocene stage is divided into three substages after the interglacial substage:

- Late substage, 24–10 ka BP with the glacial maximum period of 17–21 ka BP;
- Middle substage, 74–24 ka BP;
- Early substage, 117–74 ka BP;
- Interglacial, 128–117 ka BP.

Sea level was at about the present level during the last interglacial period. During the 100 ka duration of the Early and Middle substages (Figure 3.4), sea levels declined and were about 50 m below present-day sea level (mbpdsl) by 74 ka BP. Levels oscillated between 50 and 100 mbpdsl during the Middle substage (Figure 3.4). By 18 ka BP in the Late substage, sea level had declined to 120 mbpdsl, and remained at that level during the period of glacial maximum. By the Holocene stage at 10 ka BP, sea level had risen to about 45 mbpdsl. Sea level fell by several metres at 10 ka BP (Hautus 1) before rising again. During the Middle Dryas, sea level declined for a short period (Hautus 2) before reaching present-day levels at about 7 ka BP. The present coastline appears to have largely developed about 3 ka BP (Goodbred and Kuehl, 2000).

The significant fact is that present-day sea levels are higher than during most of the last 128 ka. Hydraulic gradients now are therefore much less than they would have been during most of that period. Also the depth of the unsaturated zone, and the opportunity for deep weathering of the sediments, is now less than during most of the last 128 ka.

Patterns of sedimentation during the last 30 ka can be...
related to monsoon change in the offshore area of the Indus Fan (Table 3.3). Periods of greater monsoon intensity coincided with rises in sea level and greater sediment inflow, marked by an influx of lighter, more arenaceous sediments to the fan. Conversely, periods of less intense monsoon activity were typified by an influx of finer-grained darker sediment, rich in organic carbon. This sequence can be correlated with the geological log of the Lakshmipur test borehole (LPW6) to identify periods of high and low monsoon intensity during the last 20 ka.

### 3.2.2 Sedimentation patterns in alluvial/deltaic environments

The GBM delta system is believed to have begun to develop some 11,000 years ago, some 2,000–3,000 years before many other deltas began their rapid development (Goodbred and Kuehl, 2000). This rapid development of deltas was a response to the slow-down in the rate of post-glacial sea level rise.

Scholle and Spearing (1982), Walker (1984), Reading (1986) and Miall (1996) describe patterns (or facies) of sediment deposition within alluvial and deltaic environments. The application of sequence stratigraphy to these depositional environments is discussed in Emery and Myers (1996).

Several examples of the practical application of facies analysis to the study of deltaic and fluvial environments are available. Davies (1989) described patterns of deposition within the fluvial sediments of the Young Brahmaputra floodplain at its confluence with the Ganges from exploration borehole data. Mathers et al. (1996) used analysis of Landsat imagery to define the distribution of modern highstand deposits, i.e. deposits formed during periods of high relative sea level, where sediment deposition is largely in low-energy environments and hence sediments are typically fine grained. Mathers et al. (1996) used borehole and micropaleontological data to define lowstand (high-energy environments, coarse-grained sediments) and transgressive tract sediment distribution, and to predict the location of Upper Pleistocene and Holocene aquifers within the Red River delta of Vietnam.

Koss et al. (1994) studied the effects of base sea-level change on fluvial, coastal plain and shelf systems under laboratory conditions. They were able to model the development of drainage patterns under flow regimes coupled with (a) rapid and slow falls in base sea level, (b) lowstand hiatus, and (c) rapid and slow rise in base level, differentiating between highstand, lowstand and transgressive system tracts. The results enable interpretation of sediment deposition patterns during the last interglacial-glacial cycle and earlier eustatic-glacial cycles in the Bengal Basin. They suggest that the major period of sediment deposition occurred during the period of sea-level rise and transgression following the glacial maximum of each cycle. Blum and Tornqvist (2000) reviewed knowledge of the effects of Quaternary sea-level change upon patterns of fluvial sediment deposition.

Patterns of sediment deposition within deltaic environments, described by Coleman and Prior (1982), Miall (1984) and Elliot (1986), applicable to the Bengal Basin environment are summarised in Table 3.4. The large sediment discharge of the GBM system allowed initial delta growth some time earlier than the global average. Radio-carbon dating of wood, peat and other organic debris retrieved from Bangladesh sediments from depths of 20-70 m has given calendar dates of 5 ka–7 ka BP (Goodbred and Kuehl, 2000) in line with the time of rapid deposition.

Walker and Cant (1984) and Miall (1996) described patterns of sediment deposition within fluvial environments; and Nilsen (1982), Rust and Koster (1984) and Collinson (1986) have described fan-delta environments. Those aspects most applicable to the Bengal Basin are summarised in Table 3.5. Recognition of the effects of sea-level change within fluvial and fan-delta sequences is difficult (Emery and Myers, 1996).

### Table 3.3. Monsoon change during 0–30 ka BP related to sedimentation offshore of the Indus Fan (Von Rad et al., 1999)

<table>
<thead>
<tr>
<th>Period ka BP</th>
<th>Substage</th>
<th>Monsoon strength</th>
<th>Sediment description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–7</td>
<td>Late Holocene</td>
<td>Low</td>
<td>Laminated sediments with high carbon content</td>
</tr>
<tr>
<td>7–9.5</td>
<td>Early Holocene (Middle Dryas)</td>
<td>High</td>
<td>High sand input, bioturbated</td>
</tr>
<tr>
<td>10–12</td>
<td>Preboreal</td>
<td>Low</td>
<td>Low sand input, low carbon concentration, distinctly laminated sediments</td>
</tr>
<tr>
<td>12–13</td>
<td>Younger Dryas cool period</td>
<td>High</td>
<td>Light coloured bioturbated sediments, moderate sand input low carbon, high rates of sediment accumulation</td>
</tr>
<tr>
<td>13–15</td>
<td>Bolling Allerod</td>
<td>High</td>
<td>Increased carbon, moderate sand input, laminated sediments</td>
</tr>
<tr>
<td>15–17</td>
<td>H1</td>
<td>High</td>
<td>Low carbon, high sand input, light in colour, bioturbated</td>
</tr>
<tr>
<td>17–22</td>
<td>Peak Glacial</td>
<td>Low</td>
<td>Moderate carbon, laminated sediments</td>
</tr>
<tr>
<td>22–25</td>
<td>H2</td>
<td>High</td>
<td>Bioturbated lighter sediments</td>
</tr>
<tr>
<td>25–27.5</td>
<td>D/O3</td>
<td>Low</td>
<td>Laminated sediments</td>
</tr>
<tr>
<td>27.5–30.5</td>
<td>H3</td>
<td>High</td>
<td>Bioturbated lighter sediments</td>
</tr>
<tr>
<td>D/O – Warm interstadials – Dansgaard Oeschger events, H – Cool interstadials – Heinrich events</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Away from the main channels and areas of active erosion, only silts and very fine sands with peats were deposited within waterlogged areas. Occasionally a river channel course may have been altered by avulsion to temporarily deliver an influx of sediment into such areas, e.g. the moribund Ganges delta and Sylhet Basin.
3.2.3 Pre-Upper Pleistocene Sedimentation

Events before the last interglacial are difficult to discern and date below the base level of incision of the last glacial maximum. Sediments deposited during earlier glacial-interglacial cycles are preserved within the subsiding and aggrading delta complex. The formation of interstitial clays and weak iron-oxide cements associated with the throughflow of oxygen-rich waters during lowstand events may have affected these nonlithified sediments.

The effects of weathering, with the formation of near-surface clay residuum, are most apparent within areas of uplifted sediments in the Pleistocene Tracts. In the absence of fossil material, litho-stratigraphic correlation of these sequences depends upon recognition of fining-upward, very coarse to very fine sequences and peat and palaeosol horizons. The boundary between continental fluvial sediments and delta/marine sediments is transitional, dependent on the amount of space created by river channel incision. The rate of base-level fall, the cohesiveness of the material being incised, the load carrying capacity of the river and the climatic regime present affect the latter.

The nature of the pre-last-interglacial sediments at depths greater than 150 m can only be investigated
through the drilling of deep exploration boreholes and the use of shallow to deep seismic survey methods. Jones (1985) used oil and gas exploration borehole data to assess the nature of the deeper aquifers between 150 m and 1800 m. Lindsay et al. (1991) interpreted deep seismic survey data obtained during oil and gas exploration in western Bangladesh. They described the marine sedimentary sequence of deposition and tectonic episodes in the area since Cretaceous times.

Inspection of one of the seismic records showed the presence of numerous stacked channels within Pleistocene to Pliocene fluvial sediments at 400–1700 m depth. These mark the extent of the modern delta sediments deposited during the last 5 Ma. Lindsay et al. (1991) noted that these channels are about 8–10 km wide and 100 m deep, similar to the present day Brahmaputra channel. The rate of tectonic subsidence appears to increase from 0.17 mm a$^{-1}$ in the north-west at the Indian border, to 0.26 mm a$^{-1}$ at Jessore and 0.5 mm a$^{-1}$ in the south-east between Lakshmipur and Faridpur. In south-east Bangladesh and the coastal region, medium to coarse sands within such channels form sources of good-quality water. Enhanced digital data could be used to define the distribution of channels below 300 m in western Bangladesh, an area where shallow groundwater sources are frequently contaminated with arsenic.

### 3.3 REGIONAL CHARACTERISATION OF SEDIMENTS

#### 3.3.1 Overview

Limited geological borehole data, with varying levels of detail, are available from the Quaternary sediments of Bangladesh as discussed above. Using these data, a geological cross section has been constructed, showing the structure within the Mid to Upper Quaternary sediments north to south through central Bangladesh (Figure 3.5).

Figure 3.5 also indicates the locations of the three geological sections (A, B and C) derived from the DPHE/BGS test boreholes drilled in the three Special Study Areas (Chapter 7) as part of this project. At the northern end of the section, subsidence occurs along the Himalayan Main Boundary Fault, accommodating a wedge of coarse sediments deposited as fanglomerates. These thin to the south of the Rangpur Saddle uplift zone. Within this zone, there has been incision of the main Brahmaputra valley along which basal fan-delta sediments were deposited between uplifted Pleistocene Tracts. These coarse-grained sediments thin and pinch out south of the Hinge Zone and pass laterally into sandy deltaic deposits within the subsidizing Faridpur Trough. Here, several fining-upward sequences have been deposited, each equating with deposition during a glacial/interglacial cycle. In the coastal zone, this alternation of sandstones and silts contains saline water above fresh water in a series of discrete aquifers. Away from the coastal zone of saline intrusion, these aquifers unite to form a single body of fresh water (Figure 3.5).
3.3.2 The BGS/DPHE test boreholes

Motivation

Few detailed geological data describing the Upper Pleistocene and Holocene sediments of Bangladesh are available. The most detailed investigations which had been undertaken before this project were probably those concerned with the building of the Bangabandhu (Jamuna) bridge. During the inception stage of this project, some detailed sediment investigations were also being undertaken by DPHE, BWDB and DU as part of their arsenic investigations. These were supported in part by UNICEF. Three deep boreholes (down to 152 m) were drilled in Chapai Nawabganj, a known arsenic hot spot, with continuous coring undertaken to provide sediment for mineralogical investigations and arsenic analysis. These showed the presence of a thick layer of clay below about 45 m. The absence of a deeper aquifer within the top 152 m limited the options for a possible safe drinking water supply below the highly contaminated shallow aquifer.

Little was known of the detailed geology in the main part of the delta region further south and east. We also wanted to install a series of nested piezometers at different depths in order to see how arsenic concentrations, and other geochemical parameters, varied with depth and with time. The results from these piezometers would provide information that would help to determine the cause of the unusually high arsenic concentrations being found in Bangladesh groundwaters. Specifically we wanted to identify the approximate position of the redox boundary and how arsenic and sulphate concentrations varied with depth. The pyrite oxidation hypothesis would predict high sulphate and arsenic concentrations near the surface while the iron oxide reduction hypothesis would predict a build-up of arsenic at greater depths with generally low sulphate concentrations. We also wanted to obtain a general indication of the variation of the arsenic content of the sediments with depth and location.

Therefore as part of this project it was decided to drill a deep (150 m) test borehole and a series of shallow piezometers in each of our three Special Study Areas. Detailed logs were made from the recovered core. The spatial and temporal changes were expected to be greatest close to the surface and so it was decided to install the piezometers at approximately 10 m intervals down to 50 m. It was also decided to sample the water from the piezometers at two weekly intervals. This setup was felt to be the minimum required to give some idea of the variation with depth while not providing an overwhelming number of samples for chemical analysis during the routine monitoring. An important aspect of the water quality monitoring programme was to monitor a wide range of solutes, not just arsenic, in order to be able to identify the likely geochemical changes taking place with depth and time.

Drilling and construction of the DPHE/BGS test boreholes

The three cored test boreholes were drilled by BWDB using a Boyles diamond coring rig. This skid-mounted rig, illustrated in Figures 3.6 and 3.7, uses 3.05 m long 70 mm diameter drill-rods with 100 mm diameter drag bits to ream and deepen the borehole between core runs. Continuous split spoon core samples were obtained for detailed analysis at 0.3 m intervals to a depth of 46 m at Lakshmipur and Faridpur and 50 m at Chapai Nawabganj. Thereafter undisturbed core samples 0.3 m long were obtained at 3.05 m intervals to 153 m at Lakshmipur, and 131 m at Faridpur. The latter borehole was completed to 155 m but cored sampled could not be obtained below 131 m due to the presence of gravel in the hole. On some earlier projects, the BWDB had removed the samples by forcing them out of the plastic tubes so that only disturbed samples could be obtained.

For this project, most of the sample tubes were cut length-wise so that variations in sediment bedding and texture could be observed, photographed and described. Representative samples from each of the test boreholes are illustrated in the plates described below.

At each site, a series of 5 piezometer boreholes completed to depths of 10, 20, 30, 40 and 50 m where possible.

Sampling sites and piezometer construction

Piezometers were installed at Chapai Nawabganj, Faridpur and Lakshmipur. The Chapai Nawabganj piezometers
Geology and sedimentology 27

were installed in the grounds of Chanlai Primary School, within the ‘hot spot’ area described in detail later (Chapter 7). Piezometers in Faridpur were installed close to the Union Parisad Building of Faridpur Municipality and those in Lakshmipur were installed within the DPHE compound. The individual piezometers were installed at 10 m, 20 m, 30 m and 40 m at Chapai Nawabganj and at 10 m, 20 m, 30 m, 40 m, 50 m and 150 m at both Faridpur and Lakshmipur. In each case, the piezometers were drilled as discrete holes, drilled within about 3 m of each other and centered on the deep, cored borehole. Drilling of these shallow piezometers was carried out using the ‘sludger method’ (hand-flapped percussion drilling). After all of the holes had been drilled to the desired depth, the screening and casing were installed and the piezometers completed at the surface. They were sealed at all but the prescribed depths. The absence of a deep piezometer at Chapai Nawabganj reflects the lack of viable aquifer at depth in that region. In addition, due to the presence of clay at 50 m, the 50 m well at Chapai Nawabganj (CPW5) was not completed as a piezometer.

Each piezometer was constructed with a 1 m GI pipe at the top (with 1/3 above the ground), followed by a section of PVC casing. A section of 2 m PVC screen was used at the desired depth, followed by a 0.5 m bail plug. Sections were joined together using liquid cement and sealing tapes. At Faridpur, 38 mm diameter casing and screens were used. At Chapai Nawabganj and Lakshmipur, casing diameter was increased to 51 mm for easier access of the sampling pump. The screened section was packed with coarse sand. Bentonite was used to seal the portion immediately above the screened section. Cement grout was used up to the surface to seal the annulus. The high-quality seals used in each piezometer preclude the possibility of hydraulic connection between the various piezometers. The wells were developed for up to several hours until turbidity disappeared. A cement platform was constructed around each piezometer and rubber bungs were used to minimise air contact.

Of the other wells in the monitoring network, the three dug wells are located in Chapai Nawabganj and the hand-pump tubewells are from all three areas. These were mostly into the shallow aquifer, but one deep tubewell (LHTW7, depth 275 m) was also monitored at Lakshmipur. This was situated around 40 m from the Lakshmipur piezometers. The other dug wells and tubewells were all located within 1 km of the piezometer clusters.

3.3.3 Chapai Nawabganj

Alluvial sediments deposited by the meandering channels of the Ganges and Mahananda Rivers underlie much of the Chapai Nawabganj area. The floodplain lies at about 20 m above mean sea level (asl). A north-south-trending fault, downthrown to the west, forms a boundary between the present course of the Mahananda River and the elevated (40 m asl) Barind Tract to the east. The sediments underlining the Chapai Nawabganj area can be divided into four units (Figure 3.8).

1. 0–45 m of grey silts and very fine-grained sandy overbank flood deposits with interbedded fine to medium channel sands.
2. 45–80 m of grey fine, medium and coarse sands in a meandering channel system deposited upon orange grey hard clays and siltstones of the Barind Tract formation.
3. Ganges sediments laterally interdigitating with sediments of the Mahananda River meander belt. This sequence of 35–45 m of sediments is composed of grey-brown micaceous, fine to medium channel sands with associated silty overbank sediments. Clay deposits occur along the faulted junction with the Barind Tract to the east. Orange-grey, weathered and lithified clays, silts and very fine sands of the Barind Tract Formation underlie the alluvial sediments. A thin, very hard dark red tabular ferricrete occurs at the contact surface.
4. The Barind Tract Formation, which forms the hills to the east, is made up of orange-grey clays and silty, very fine sandstones with interbedded fine to coarse sandstone (Ahmed and Burgess, 1995). The sandstones form an aquifer that is terminated by the fault zone to the west. The fault line is marked by a number of elongated swampy depressions that appear to be fed by water rising along the fault from the sandstone aquifer within the Barind Tract Formation (Figure 3.8).
The Chapai Nawabganj test borehole (CPW5) was drilled to a depth of 50 m through 37 m of unconsolidated fluviatile sediments which unconformably overlie lithified, weathered clayey siltstones of the Barind Tract formation (Figure 3.9). The Barind Tract clayey silts are oxidised yellow-brown fluviatile overbank sediments (Figure 3.10, CN18) capped with a hard dark red tabular lateritic ferricrete band, indicative of hot humid climatic conditions. Overlying these are two sequences of grey-brown unconsolidated fluviatile micaceous sands. These were deposited in the active meander channel of the Mahananda River, the lower some 5 ka BP (Figure 3.10, CN13) and the latter from 1.9 ka BP (Figure 3.10, CN6; Table 3.6). The upper 11 m of fluvial sands were deposited within a waning meander channel, capped by over-bank flood micaceous silts (Figure 3.10, CN3). These fluvial sediments form a highstand sequence deposited adjacent to the floodplain of the Ganges River.

Lithological logs of other boreholes from Chapai Nawabganj and neighbouring upazilas are shown in Figure 3.11. Boreholes DW1 and DW2 were drilled in 1998 by BWDB-DU in the centre of the Chapai Nawabganj arsenic hot spot area in order to obtain more sedimentological information about the hot spot. The boreholes each show a surface layer of brown to grey-brown overbank silts with underlying fine to medium and coarse sands down to around 40 m. Below this, fine grey silts and clays predominate.

**Table 3.6. Radiocarbon dates of samples obtained from the Chapai Nawabganj test borehole (CPW5)**

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Depth (m)</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA36199</td>
<td>18.90</td>
<td>1310±180</td>
</tr>
<tr>
<td>AA36213</td>
<td>24.99</td>
<td>1895±45</td>
</tr>
<tr>
<td>AA36214</td>
<td>25.60</td>
<td>5140±120</td>
</tr>
</tbody>
</table>

Figure 3.8. Geological cross section through the Chapai Nawabganj Special Study Area.

Figure 3.9. Lithological log of the DPHE/BGS test borehole at Chapai Nawabganj (CPW5). The colouring reflects the colour of the sediments.
CN3 31–32 ft, 9.5–9.8 m Light brown/grey fine sand with little mica; above dark brown grey silty very fine sand with thin light grey-brown layers, a little mica and some pelecipod fragments. The top sand has been forced up into overlying dark brown grey silty very fine sand.

CN6 52–54 ft, 15.8–16.5 m Brown micaceous medium sand with darker very micaceous layers containing dark brown mica; above light grey medium sand with some black mica; above brown medium to coarse sand.

CN13 94–96 ft, 28.7–29.3 m Light grey cross bedded medium sand with little mica, above grey very micaceous medium to fine sand with black to clear coarse-grained micas; above light grey fine to medium sand with little mica and some orange stained grains.

CN18 126–128 ft, 38.4–39.0 m 2.5Y6/4 light yellow brown finely laminated clayey silt becoming more clayey and greyer with depth.

Figure 3.10. Photographs of core from the Chapai Nawabganj test borehole (CPW5). The scale is indicated by the length of the core.
The borehole at West Bilat Haripur (samples courtesy of the Barind Integrated Agricultural Development Project) is located in the Ganges River floodplain area and shows a similar sequence of fine surface silts and underlying aquifer sands at around 12–40 m depth (Figure 3.11).

Boreholes at Khitta, 12 km east of Chapai Nawabganj town and Purba Fargilpur, 25 km north of the town are sequences in the Barind Tract showing well-developed grey fine silt and clay from approximately 0–30 m with underlying fine to medium yellow-brown sands of the Barind Aquifer (Dupi Tila Formation). Samples from these five boreholes displayed in Figure 3.11 have been subjected to geochemical investigation and are described more fully in Chapter 11.

### 3.3.4 Faridpur

The geological section investigated at Faridpur is about 17 km wide and 220 m deep (Figure 3.12). The section is composed of alluvial sediments deposited by the Brahmaputra/Atrai/Ganges system during the last 240 ka and consists of two main sections, a shallow aquifer, 60–120 m thick (Cycles 1a, 1b; Figure 3.12) and a deep aquifer 100–160 m thick (Cycles 2, 3).

The section is based upon geological data from five borehole logs provided by BWDB and a description of core and chip samples obtained from the Faridpur test borehole drilled for this project.

The shallow aquifer can be divided into two main parts:

1. The **upper shallow aquifer highstand sediments** (Cycle 1a, 0–45 m) are composed of:
   - near-surface grey micaceous silts and clays deposited as overbank deposits that thicken from east to west (0–20 m);
   - grey micaceous fine to medium sands deposited within waning meander channels and dipping from east to west (0–45 m);
   - basal grey medium sands with disseminated wood and mica deposited within active channels.

2. The **lower shallow aquifer Transgressive Tract and lowstand sediments** (Cycle 1b) are composed of fining-upward gravels and coarse to medium sand within a channel, some 75 m deep and 5 km wide, located to the west of the present Padma Channel. Between 80–120 m depth, the main channel of the shallow aquifer has been incised into the pre-existing sediment.

   To the west, thin medium sands were deposited within an adjacent distributary channel from 45–70 m depth, on top of pre-existing highstand deposits. To the east, the main channel is abutted against a thick sequence of overbank silts and fine sands. These are pre-existing highstand deposits, forming a barrier between the incised channel and that of the main Brahmaputra Channel to the east, capping the deep aquifer system below. Evidence from the Faridpur test borehole indicates that these sediments have been extensively weathered, with deposition of red-brown iron oxide cement and kaolin clay.
The deep aquifer, found below an undulating erosion surface and the highstand deposits, are composed of sediments deposited presumably during the 120–240 ka BP interglacial period, which have been preserved by subsidence. These sediments overlie two stacked sequences of fining-upward gravels and coarse to medium sands which are deposited within the basal sections of pre-existing incised main channels, themselves deposited during Cycles 2 and 3. The coarse sands and gravels, 60–80 m thick, form the deep aquifer above an erosion surface of sandy clays.

The Faridpur test borehole (FPW6) was drilled to a depth of 155 m (Figure 3.13) through 133 m of unconsolidated fluvial sediments deposited by the Brahmaputra River, underlain by brown-grey, medium and fine fluvial sands of possible Middle Pleistocene age (Dupi Tila Formation) (Table 3.7). A continuous core was obtained from 0–62 m, below which samples were cored 1 m in every 3 m. Representative sectioned core samples, summarised in Table 3.7, are described and illustrated in Figure.

These highlight the very micaceous nature of the sediments between 0–45 m depth and the low mica content of coarse sands below. Radiocarbon dating of organic matter from the cored sequence shows that the grey sediments at less than 91 m depth have been deposited since the last glacial maximum at 21 ka BP (Table 3.8).

The fine-grained silts and peats at 45 m depth form the Hiatus 2 (Middle Dryas) horizon that can be correlated with a similar horizon on the other side of the Brahmaputra in BGS test borehole logs at Saturia, Manikganj and Dhamrai. A geological section between Faridpur and Dhamrai through the main channel of the Brahmaputra

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**Table 3.7. Lithology and facies of deposition recognised in the Faridpur test borehole (FPW6)**

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Lithology and facies of deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–13</td>
<td>Brown grey micaceous silts to fine sands deposited within a waning channel capped by overbank flood silts (FD3 and FD4)</td>
</tr>
<tr>
<td>13–25</td>
<td>Brown grey fine to medium fining-upwards sands deposited by an actively meandering channel (FD6)</td>
</tr>
<tr>
<td>25–44</td>
<td>Grey fining upward fine to medium sands with disseminated wood and ferricrete fragments (FD11)</td>
</tr>
<tr>
<td>44–45</td>
<td>Hiatus 2 layer composed of a grey micaceous peaty clay with thin hard platey brown iron carbonate fragments (FD15).</td>
</tr>
<tr>
<td>44–71</td>
<td>Grey fining-upward medium to fine medium micaceous sands deposited within active to waning meander channels (FD19).</td>
</tr>
<tr>
<td>71–98</td>
<td>Grey micaceous fining-upward medium and fine sands with basal coarse sand and gravel, deposited in an active meander channel. Grey micaceous silty fine sand between 73–80 m (FD21).</td>
</tr>
<tr>
<td>98–110</td>
<td>Grey coarse to medium fining-upward sands deposited with an active braided channel sequence (FD26).</td>
</tr>
<tr>
<td>110–134</td>
<td>Structureless grey coarse sands and gravels with a conglomeratic base, deposited under braided channel to gravely-flow conditions – forming the base of the Transgressive Tract sediments deposited within the incised Brahmaputra Channel (FD34).</td>
</tr>
</tbody>
</table>

*Pre-Lowstand deposits*

| 134–155 | Brown grey medium to fine sand |

---

Figure 3.12. Geological cross-section through the Faridpur Special Study Area.
shows the distribution of the four main layers that comprise the shallow aquifer. Also shown is a remnant pre-100 ka lowstand segment composed of reddened fluvial sediments beneath the Dhamrai area (see Figure 4.8).

3.3.5 Lakshmipur

The Lakshmipur test borehole (LPW6) was drilled to a depth of 153 m (Table 3.9) through unconsolidated deltaic sediments, deposited within the incised Padma channel. A continuous core was obtained to 62 m, discontinuous core being taken thereafter at 3 m intervals from every 10 m drilled (Figure 3.15).

The compositions of the deltaic deposits examined are summarised in Table 3.9. Representative sectioned core

<table>
<thead>
<tr>
<th>Sample No</th>
<th>Depth (m)</th>
<th>Age (Years BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA36203</td>
<td>6.2</td>
<td>106.6±0.58</td>
</tr>
<tr>
<td>AA36204</td>
<td>9.2</td>
<td>3085±50</td>
</tr>
<tr>
<td>AA36198</td>
<td>9.8</td>
<td>960±45</td>
</tr>
<tr>
<td>AA36197</td>
<td>10.2</td>
<td>855±45</td>
</tr>
<tr>
<td>AA36212</td>
<td>44.5</td>
<td>8260±75</td>
</tr>
<tr>
<td>AA36209</td>
<td>55.2</td>
<td>11890±80</td>
</tr>
<tr>
<td>AA36211</td>
<td>73.2</td>
<td>18560±130</td>
</tr>
<tr>
<td>AA36208</td>
<td>91.4</td>
<td>22090±190</td>
</tr>
<tr>
<td>AA36210</td>
<td>125</td>
<td>9925±70</td>
</tr>
</tbody>
</table>
FD3 30–31 ft, 9.1–9.4 m Dark grey sticky clayey silt above light brownish grey fine sand with several interbedded thin dark brown micaceous hands with odd wood fragments.

FD4 37–38 ft, 11.3–11.6 m Dark grey brown silt; above interbedded layers of light grey and dark grey fine sand, the dark grey layers are very micaceous with much biotite.

FD6 60–61 ft, 18.3–18.6 m Brownish grey to grey micaceous medium to fine sand.

FD11 111–112 ft, 33.8–34.1 m Light grey fine to medium sand with some clear mica.

FD15 146–147 ft, 44.5–44.8 m Hard dark grey very micaceous slightly clayey silts with included sub-angular to sub-rounded platey orange brown fragments of ferricrete (or pottery?) with large fragment of black peat.

Figure 3.14. Photographs of core form the Faridpur test borehole (FPW6). The scale is indicated by the length of the core.
**FD19** 220–221 ft, 67.1–67.4 m Grey fine to medium fairly micaceous sands.

**FD21** 251–252 ft, 76.5–76.8 m Light grey fine sand with some mica above black micaceous silt, above black very micaceous silty fine sand, above black to dark grey micaceous fine sand, above grey fine sand.

**FD26** 340–341 ft, 103.6–103.9 m Grey coarse to medium quartz sand.

**FD34** 430–431 ft, 131.1–131.4 m Grey quartzose coarse sand and fine-sized gravel with some medium sand, mainly fairly well rounded clear quartz grains, some large prominent sub-angular pink and yellow white quartzite and black angular amphibolite fragments.

*Figure 3.14 continued.*
samples are described and illustrated in Figure 3.16. These highlight the thinly-bedded alternations of micaceous silt and sands with interbedded peats that characterise the upper 45 m of sediment, periodically deposited by flood waters. Radiocarbon dating of organic carbon collected from the cored sequence above 140 m depth has produced a mixed series of dates (Table 3.10). Such mixed sequences with date inversions have been reported from other estuarine sediment profiles in the Nile, Brahmaputra and Yangtze deltas (Stanley and Hait, 2000). These patterns may be due to the reworking of detrital organic material such as wood fragments. However, the ages derived from a thick peat zone at 76–80 m are in excess of 40 ka BP. These are anomalous and difficult to explain. If these dates are correct, then this peat layer would mark the limit of incision during the last interglacial period. Sediments above the peat layer would therefore have been deposited during the last 10 ka.

Data from the Lakshmipur boreholes were correlated with geological information from boreholes drilled by DANIDA/DPHE in the Raipur-Lakshmipur-Eklashpur area of the delta. The lithological logs of these boreholes are interpreted from geophysical borehole logs, with little colour definition. Below the 150 m depth of the Lakshmipur cored borehole, the ages of the highstand/lowstand and estuarine/deltaic deposits have not been determined. The depth distribution of lithologies and aquifers in the Raipur-Lakshmipur-Eklashpur area is summarised in Table 3.11 and in Figure 3.17. Note that the main freshwater aquifer lies at 230–280 m, below the level of incision at the last glacial maximum. Saline and brackish to saline waters occur in sandy layers above this horizon.

Table 3.10. Radiocarbon dates with depth of samples taken from the Lakshmipur test borehole (LPW6)

<table>
<thead>
<tr>
<th>Sample No</th>
<th>Depth (m)</th>
<th>Age (Years BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA36202</td>
<td>10.7</td>
<td>110±0.58</td>
</tr>
<tr>
<td>AA36215</td>
<td>35.4</td>
<td>6920±60</td>
</tr>
<tr>
<td>AA36216</td>
<td>38.7</td>
<td>10020±85</td>
</tr>
<tr>
<td>AA36217</td>
<td>45.4</td>
<td>8870±75</td>
</tr>
<tr>
<td>AA36218</td>
<td>46.0</td>
<td>7860±65</td>
</tr>
<tr>
<td>AA36219</td>
<td>46.3</td>
<td>9155±70</td>
</tr>
<tr>
<td>AA36200</td>
<td>51.8</td>
<td>8000±85</td>
</tr>
<tr>
<td>AA36201</td>
<td>54.9</td>
<td>8355±65</td>
</tr>
<tr>
<td>AA36220</td>
<td>55.2</td>
<td>9210±70</td>
</tr>
<tr>
<td>AA36221</td>
<td>73.2</td>
<td>8855±70</td>
</tr>
<tr>
<td>AA36205</td>
<td>91.7</td>
<td>11320±75</td>
</tr>
<tr>
<td>AA36207</td>
<td>116.1</td>
<td>6525±60</td>
</tr>
<tr>
<td>AA36206</td>
<td>137.5</td>
<td>12585±95</td>
</tr>
</tbody>
</table>

Table 3.11. A summary of the hydrogeological units of the Raipur-Lakshmipur-Eklashpur area

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Lithology and water content</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–25</td>
<td>Inter-tidal zone alternating thin micaceous silts and very fine sands with peat and disseminated wood fragments deposited by annual cyclonic events</td>
</tr>
<tr>
<td>25–100</td>
<td>Upper fast zone fluvial medium to fine and medium sands containing saline water</td>
</tr>
<tr>
<td>100–130</td>
<td>Micaceous clay and silt aquiclude</td>
</tr>
<tr>
<td>130–190</td>
<td>Middle fast zone of fluvial silty fine to medium sands and interbedded medium to coarse sands, containing brackish to saline groundwaters</td>
</tr>
<tr>
<td>190–230</td>
<td>Silty clay aquitard</td>
</tr>
<tr>
<td>230–280</td>
<td>Lower fast zone of fluvial medium to fine sands with thin basal coarse sands containing fresh water</td>
</tr>
<tr>
<td>280–320</td>
<td>Silts, clays and fine to medium sands, capped by a hard layer, containing brackish to saline water</td>
</tr>
</tbody>
</table>
LK3 14–15 ft, 4.3–4.6 m Light grey fine sand (>2" thick); above grey to brown silty fine sand with some mica (2" thick); brown grey to dark orange brown iron oxide rich silty fine sand with some mica (1.5" thick); Grey silty very fine sand (>2" thick).

LK6 48–49 ft, 14.6–14.6 m Alternations of dark grey silt and light grey fine sand: silt (>0.5" thick); above sand (0.25" thick); above silt (0.5" thick); above sand (0.25" thick); above silt (0.5" thick); above sand (0.25" thick); above silt (0.5" thick); above sand (0.25" thick); above silt (0.75" thick); above sand (0.25" thick); above silt (0.25" thick); above sand (0.5" thick); above silt (0.5" thick); above sand (1" thick); above very micaceous dark grey silt (1" thick); above light grey micaceous fine sand (>0.5" thick).

LK7 55–56 ft, 16.8–17.1 m Light grey to grey fairly micaceous fine-grained sand (>2.5" thick); above alternating layers of grey silt and light grey fairly micaceous fine-grained sand with thin black detrital mica bands (2" thick); above light grey fairly micaceous fine-grained sand (0.75" thick); above dark grey very micaceous silty fine-grained sand with much black detrital mica (0.75" thick); above dark grey very micaceous fine-grained sand with black mica below a thin light grey fairly micaceous fine-grained sand (>1.5" thick).

LK10 92–93 ft, 28.0–28.3 m Dark grey silt with some finely disseminated mica (>1" thick); above light grey fine to medium-grained sand (1.5" thick); above dark grey silt with a black micaceous base (0.5" thick); above light grey fine-grained sand (1" thick); above grey fairly micaceous silty fine-grained sand (0.75" thick); above light brownish grey fine-grained sand (0.5" thick); above grey silty fine-grained sand (0.5" thick); above light brownish grey fine-grained sand (1" thick); above brown grey fairly micaceous fine-grained sand (1.5" thick); above light brownish grey fine-grained sand (>1.25" thick).

Figure 3.16. Photographs of core form the Lakshmipur test borehole (LPW6). The scale is indicated by the length of the core.
3.4 Conceptual Models

3.4.1 Delta floodplain environment

A conceptual model of Upper Pleistocene and Holocene sediment distribution in the delta has been developed (Figure 3.18). This uses lithological data from the Faridpur, Lakshmipur and Chandina areas related to sea-level change and regional tectonism. This model suggests that by the 20 ka glacial maximum, the Padma channel was incised to a lowstand depth of 130 m and former highstand deposits have been eroded from the adjacent areas. Marine transgression followed, during which time saline water entered the former transgressive sediment sequence forming the channel sides. During the transgression, backfill of the channel started from 20 ka at Faridpur where prograding coarse-grained sediments were deposited from braided streams.

From about 13 ka BP onward at Lakshmipur, where finer-grained upward-fining sediments were deposited, probably under marine conditions, backfilling also occurred. By 10 ka at the start of the Holocene, the prograding sediment pile had backfilled to about 50 mbpsl at Faridpur but was at 80 mbpsl at Lakshmipur. At this time, there was a marine hiatus when sea level appeared to decline. This hiatus is marked by a thick peat horizon within the Lakshmipur site. Following this hiatus, the rejuvenated marine transgression was followed by a similar hiatus at 7.5 ka BP during the Middle Dryas period, by which time the incised valley had been backfilled 45 m bpsl at both sites.

The level of this second hiatus coincides with the base of the following highstand sequence, deposited during a third stage of marine transgression. During this highstand period, river gradients were shallow, with the main rivers and their distributaries depositing fine sediment within a wide delta plain environment. Whereas typical fluviatile fining-upward channel sediments were deposited at Farid-
pur, predominantly thinly bedded estuarine flood sediments composed of thin alternations of fine sands, silts and organic-rich clays were deposited within the Lakshmipur area further south.

3.4.2 Fluvial floodplain environment

Data from BADC deep tubewells and BGS test boreholes (Davies, 1989) from the Dhamrai, Singair, Manikganj, Saturia and Savar areas, were used to construct a conceptual model of the Upper Pleistocene and Holocene sediments beneath the Brahmaputra fluvial floodplain west of Dhamrai (Figure 3.19). To the east of Dhamrai, these sediments are faulted against coarse fluvial sediments that underlie the red-brown Madhupur Clay Residuum of the Savar area.

These borehole data are mainly limited to the depth of channel incision, about 90 m. Good colour definition and the dense pattern of boreholes allows good litho-correlation, enabling an understanding of weathering patterns and the relative ages of sediment deposition. The 45 m deep highstand base is defined by a clayey palaeosol layer in the Dhamrai area that is absent in Manikganj to the west. Lowstand/transgressive sediments are composed of braided river coarse sands and gravels with a conglomerate base that unconformably overlie loosely cemented red/orange weathered sands of the Dupi Tila Formation.

Colour and weathering patterns indicate several cycles of incision and deposition in successive glacial events. In each case, the highstand deposits appear to be stripped off by erosion and adjacent sediments weathered. The faulted boundary between the incised channel and the Madhupur Tract may be a series of rotational slippage faults developed along the unstable side of the deeply-incised valley or a series of en-echelon faults developed along the Brahmaputra (Jamuna) valley fault/zone of weakness. Conglomeratic material at the base of the Upper Pleistocene sequence, derived from fan-deltas of the Tista/Brahmaputra river systems, was deposited as a series of prograding fan deltas.

The Dupi Tila formation is found beneath the incised Brahmaputra channel and the Madhupur Tract to the east. A geological log of the Bhaluka borehole, located within the central part of the Madhupur Tract, shows a sequence of red-brown and grey fluvial coarse sands occurring beneath thick red-brown Madhupur Clay Residuum. These sediments, similar to the poorly-cemented fluvial sediments found in the Dhamrai/Manikganj area, were probably deposited by the palaeo-Brahmaputra that has since migrated to the west with each successive glacio-eustatic cycle. Early diagenetic processes are apparent including formation of clays and iron oxide cements.

3.4.3 Regional geological cross-sections

A series of geological cross sections has been constructed
using data from exploration, irrigation and municipal borehole records held by BWDB, with the aim of indicating the probable sediment distribution in the upper 300 m of the GBM. These sections have been divided according to approximate base of highstand at 40 m bpdsl, the limit of glacial maximum base level at about 120 m bpdsl, and deep pre-last lowstand sediments occurring between 120 m and 300 m bpdsl. The aim is to assess the potential of a deep aquifer being found below 150 m bpdsl.
Section A: Panchagarh–Sherpur–Madaripur

This section runs (Figure 3.20) from Tetulia in the northwestern corner of Bangladesh through the Tista Fan to Sherpur on the Jamuna from where it runs due south along the left bank of the Jamuna to Manikganj and thence to Faridpur. At Tetulia, Panchagar and Thakurgaon, boreholes penetrate fining-upward coarse to medium sands and gravels of the Tista Fan delta cone above the highstand limit. Stacked coarse-sand channel sediments occur down to 240 m at Panchagar, possibly associated with the former course of the Tista, otherwise very fine sands and silts predominate below the lowstand level. Between Dinajpur and Gaibandha, boreholes tend to penetrate thick sequences of very fine sands, clays and silts of the sub-Barind Dupi Tila deposits, found to depths of 260-280 m bpdsl. Near-surface gravels in highstand river channel deposits occasionally occur down to about 20 m bpdsl.

At Gaibandha, fine to medium sands occur within the highstand zone, overlying lowstand sandy silts and sub-lowstand clays to 280 m bpdsl. At Sherpur and Jamalpur, fining-upward sequences of medium to fine sands occur to sub-lowstand levels above deep very fine sands and clays. At Jamalpur, the lowstand channel of the Old Brahmaputra contains a fining-upward sequence of gravel and coarse to fine sand and near-surface silts. Consolidated black shales have been found at depth within municipal water supply boreholes at Sherpur, where sub-lowstand medium sands have been proved to about 180 m bsl. Within the central Young Brahmaputra floodplain, at Bh153, lowstand to highstand fine sands overlie thick shales and very fine sands to 300 m bpdsl.

Between Basail and Manikganj, lowstand coarse fining-upward gravels and coarse to medium sands occur as transgressive tract deposits between 40–100 m bpdsl. These are underlain by brown consolidated very fine to medium sands with infrequent coarse channel deposits beneath the lowstand limit. Across the Padma in Faridpur, highstand and lowstand alluvial silts, very fine and fine sands occur. Clays and medium to fine sands to 300 m bpdsl underlie these. Deep aquifer coarse to medium stacked deposits underlie much of the Tista Fan within the Panchagarh area.

Within the Dinajpur and Gaibandha area of the Rangpur Saddle, thick fine sands and clays occur at depth that are unlikely to form deep aquifers. In the Jamuna-Brahmaputra valley between Basail and Manikganj, the incised channel is underlain by brown consolidated fine to medium sands with some coarse sands that should form useful deep aquifers. Only at Jamalpur are stacked thick coarse sands found below 120 m depth, within the former course of the palaeo-Brahmaputra that continues southward into the Madhupur Tract.

Section B: Chapai Nawabganj–Aricha–Sylhet

This section (Figure 3.21) runs from Chapai Nawabganj via Rajshahi along the north side of the Ganges to Aricha, thence eastward across the Madhupur Tract into the valley of the Meghna and then the Sylhet Basin. The section
between Shibganj (Bh120) and Charghat (Bh117) is underlain by thick sequences of clays, silts and very fine sands below the highstand limit. Only along the course of the Mahananda River are medium to coarse channel sands deposited at Bh79.

At Ishurdi (Bh124), a thick sequence of stacked main channel coarse sands deposited by the Ganges are found to a depth of 190 m bpdsl, below the lowstand limit of incision. Towards Aricha (Bh122), thick main channel medium to coarse sands are present between the lowstand and highstand limits, deposited by the Atrai-Gur-Tista system. Fining-upward sequences of gravels and coarse to medium sands with basal conglomerate occur within the lowstand to highstand Transgressive Tract of the Brahmaputra main channel beneath the Dhamrai-Manikganj area.

On both sides of the Brahmaputra, the lowstand limit is underlain by thick sequences of fine sand with some indication of main channel stacking at Bh46. The coarse-grained lowstand to highstand gravels and coarse sands continue under the western part of the Madhupur Tract beneath an eastward thickening highstand Madhupur Clay Residuum. The eastern half of the Madhupur Clay Residuum thins toward the Old Brahmaputra, overlying lowstand to highstand medium to fine sands.

The lowstand to highstand sediments of the Old Brahmaputra in Monohadi and Katihadi are characterised by medium to coarse sands with highstand fine to very fine sands and clays which are typical overbank deposits. Medium to coarse sands are characteristic of the Meghna River deposits but these also include some thick clayey highstand deposits. Within the western Sylhet Basin, thin medium sands occur in thick clay and silt sequences, with minor medium to coarse sand horizons. Early Pleistocene or older consolidated sands and clays underlie the eastern part of the Sylhet basin. This section indicates that away from the present channels of the Ganges and Brahmaputra, little coarse-grained material occurs at depths greater than 130 m bgl.

Some coarse sediments occur beneath the Madhupur Tract, reinforcing the view that the Brahmaputra channel has migrated to the west with successive glacio-eustatic cycles of incision and back-filling, leaving remnant coarse deposits east of the channel. There is some evidence of main channel stacking of coarse sediments in the Madhupur Tract which implies that this was formerly an area of subsidence. These stacked channel deposits should form good aquifers especially if they are found to be present at depth below Dhaka. Further east, some deep coarse sediments may occur beneath the channel of the Old Brahmaputra but only fine deposits are to be found within the subsiding Sylhet Basin and the consolidated fold belts further east. These fine-grained deep deposits will make poor aquifers.

Section C: Meherpur–Dhaka–Feni

This section (Figure 3.22) runs from west to east along the southern side of the Ganges to Manikganj and thence south westward through the Chandina area towards Feni.
The western half of this section, south of the Ganges, is primarily underlain by deep sequences of fine-grained sand. However, Jhenaidah is underlain by stacked sequences of coarse sands and gravels between 50–240 m bpdsl. These coarse sediments appear to have been deposited in the former main channel of the Ganges River previously flowing south from the Ishurdi/Kushtia area towards the south-west.

In the region of the Padma the section is underlain by stacked, fining-upward coarse to medium sand, interbedded with very fine sand within the lowstand to highstand and sub-lowstand sequences at Madaripur. East of the Padma between Chandpur, Lakshmipur, Noakhali and Feni, the section includes thick alternations of silts and fine to medium sands deposited within an estuarine delta plain. The stacked main channel deposits at Jhenaidah and in the vicinity of the Padma will form good deep aquifers. However, the rest of the western half of the section is underlain by very fine sediments with poor water-yielding characteristics. Within the eastern half of the section, saline water has been recognised at shallow depth. An alternative freshwater-yielding deep aquifer has already been recognised.

**Section D: Meherpur–Manikganj–Chittagong**

This section (Figure 3.23) is somewhat similar to section C but runs from west to east to the south of the Ganges. It follows the delta through Faridpur, across the Padma into the Lakshmipur area to the southwest and thence towards Feni. This section passes through similar sediments to those encountered by section C. Fine sands and clays predominate along the southern side of the Ganges as far as Faridpur where main channel medium to coarse sands and gravels occur between the lowstand and highstand levels. Stacked sequences of medium sands occur beneath the Meghna between 60–320 m bpdsl.

To the south east in Ramganj, Begumganj and Feni, thick sequences of fine sands, silts and clays deposited within the delta plain predominate. At Begumganj, stacked cycles of medium to coarse sands separated by clays may indicate a former main channel of the Meghna. The stacked main channel deposits at Faridpur (Bh142) and in the vicinity of the Meghna (Bh83) will form good deep aquifers. However, fine sediments with poor water-yielding characteristics underlie the rest of the western half of the section. In the eastern half of the section, saline water has been found at shallow depths. However, an alternative freshwater-yielding deep aquifer is also usually present. The lateral extents of the stacked main channel sediments at Begumganj (Bh174) need further investigation.

**Section E: Satkhira–Lakshmipur–Feni**

This section (Figure 3.24) runs west to east across the southern part of the Ganges Delta. Within the lowstand to highstand sequence, a distributary system depositing medium to fine sands transgresses from east (Bh133) to west (Bh138). Beneath this transgression thick silts, clays and fine sands occur to a depth of 300 m bpdsl or more. Within the east of the area, Bh139 intersects coarse to
medium sands at depths of 80–160 m and 220–300 m. These stacked sediments infill the former main channel of the palaeo Brahmaputra, that formerly flowed south from the Faridpur area during pre lowstand and early lowstand times. Only the stacked main channel sediments occurring at depth beneath Khulna offer the prospect of potential aquifers. To the west, the area is underlain by thick sequences of clay with little groundwater potential.

These geological sections can only provide a first indication of the distribution of sediments below 150 m depth. More exploration boreholes need to be drilled and logged to characterise the distribution and potential of the deep aquifer. Information from these boreholes also needs to be correlated with the available seismic and other relevant data from oil and gas exploration activities.

3.5 SUMMARY

There are few available sets of detailed geological data from Bangladesh and these are mainly of a localised nature. Analysis of the available borehole data suggests that at the last interglacial highstand, the Ganges flowed south along the present India-Bangladesh border to enter the Bay of Bengal at Calcutta. At that time, the Tista probably flowed along an incised channel through the Barind Tract, presently occupied by the Atrai, then southward through the present Faridpur area. The Brahmaputra and Meghna rivers occupied their present courses (Figure 3.25).

During the early and middle glacial period, erosion occurred along the main river channels with planation of the interfluvies. During this period, the Ganges probably moved from its former course towards its present one by the process of channel switching, migration and/or river capture. This reduced the effects of planation of the land surface in western Bangladesh to the anastomosing distributaries. Areas such as the Sylhet Basin subsided and the Barind and Madhupur Tracts continued to rise slowly and tilt to the east.

During the glacial maximum, sea level dropped rapidly, promoting the rapid incision of the main rivers. This action, together with possible tectonic activity, may have resulted in the Mahananda, Ganges and Atrai Rivers attaining their present channels through river capture (Figure 3.26). Aggradation began when incised head-channels of the main rivers cut back into fan delta systems along the Himalayan Front. Gravity flow of coarse-grained material along these channels resulted, with the formation of prograding fans in the lower reaches of the incised channels (Figure 3.27).

During the sea-level rise and transgression that followed, the main channels were backfilled with fining-upward fluvial sequences within an initially braided river and then latterly in meandering channels. This process was not smooth, as indicated by a hiatus at the start of the Holocene marked by a peat deposit and another at the Middle Dryas. A renewal of marine transgression followed each event.

Following the Middle Dryas event at 7.5 ka, rivers spread out across the main floodplain, to flow through Figure 3.23. Section D: Geological section from Meherpur–Manikganj–Chittagong.
Figure 3.24. Section E: Geological section from Satkhira–Lakshmipur-Feni.

Figure 3.25. Possible main river channels at the time of the last interglacial highstand (120 ka BP).

Figure 3.26. Incisional main river channels at the time of the glacial maximum (21 ka BP).
the marine transgression since the last post-glacial maximum.

Figure 3.27. Location of gravity sediment flows and the limits of the marine transgression since the last post-glacial maximum.

- Mountain front fan-deltas – a series of large delta fans formed where major rivers emerge from the Himalayas into the mountain front plain. Such rapidly-aggrading fan cones are composed of very coarse alluvial material and reflect a large-scale switch of river channel courses. These fans formed primary sources of gravity-flow material during the latter stages of valley incision during the glacial maximum when the rivers incised into older, underlying deposits.

- Fluvial floodplains – these mainly occur within fault-controlled valleys that run between Pleistocene terraces or form antecedent valleys that cut through the Pleistocene terraces. Antecedent valleys, such as the Atrai, which cut through the Barind Tract are dependent upon the course of the Tista River. This periodically switches flow direction across the Tista Fan for stream water and sediment supply. The Brahmaputra occupies a straight, fault-controlled course between the Barind and Madhupur Tracts. The Transgressive Tract sediments deposited by the river during successive cycles of glacio-eustatic change appear to have accreted laterally. Therefore there would seem to be little long-term sediment accretion within the fluvial floodplains. Most deposits have been eroded to the same maximum glacial depth during valley incision.

- Pleistocene terraces – the Madhupur and Barind Tracts seem to be elongated uplifted blocks composed of fluvial sediments deposited under glacio-eustatic cyclic conditions. These have been subject to various degrees of weathering and diagenesis. The sediments underlying the western half of the Madhupur Tract are similar in form to those currently being deposited along the Jamuna, whilst those underlying the eastern half are similar to those deposited by the Old Brahmaputra.

- Subsiding basin – in the Sylhet Basin, aggradation has occurred during the highstand period during periodic avulsion of the Old Brahmaputra channel into the low-lying area that has also been affected by marine inundation.

The estuarine delta plain includes:

- Delta plain – this is an area of general subsidence where accumulation of coarse-grained sediments occurred along the main valleys only. Accumulation of fine-grained sediments occurred away from the main channels within areas fed by distributary channels. The stacking of channel sequences, noted from geological logs within this area, are indicative of a subsiding region.

- Subsiding basins – marked subsidence appears to have occurred within swampy areas of the Ganges tidal delta with the deposition of peaty deposits. These depres- sions occur along the Faridpur Trough and include the Sylhet Basin which may be located above the still active plate subduction zone.

- Sub-lowstand level – deep boreholes provided limited geological data but were sufficient to form a broad picture of earlier cycles of sedimentation, where these were preserved. In the delta area, these boreholes have
been drilled to about 300 m providing information about stacked-channel deposits that may be used to define areas of subsidence.

An understanding of sediment provenance, micropalaeontology and additional $^{14}$C dating of organic carbon deposits, as well as recognition of additional tephra deposits such as the Toba Ash at 74,000 years BP (Acharyya and Basu, 1993) would provide additional much-needed correlation tools.

### 3.6 CONCLUSIONS

Sediment deposition within the Bengal Basin is controlled by the interaction of tectonic activity and cycles of glacio-eustatic sea-level change.

The Ganges/Brahmaputra/Meghna delta system can be divided into two main areas:

- a stable northern block in which fluvial sediments predominate along the floodplains of the major rivers and in locally subsiding basins;
- a subsiding delta area in which sediments accumulate at a high rate. Subsidence may be of the order of 0.5 mm a$^{-1}$.

Little sediment is presently accumulating along the channels of the main river floodplains within the fluvial zone. Valleys tend to have been incised, backfilled and then incised again to a similar depth during repeated cycles of glacio-eustatic erosion. Some lateral accumulation takes place. The debris that accumulates within the mountain-front fan delta cones is presumably eroded and removed during the glacial lowstand and early Transgression Tract period. Finer-grained sediments accumulate within the subsiding areas that are normally bypassed by the main channels, receiving sediment intermittently through temporary avulsion of the main channels into these areas, e.g. the Sylhet and Atrai-Gur Basins.

Within the delta area, subsidence above the subduction zone causes the accumulation of sediments in a stacked channel form. The limited evidence available suggests that coarse-grained channel sediments appear to be stable within zones of limited width and that the main rivers tend to be present in an area for several successive cycles of sedimentation, only changing course due to tectonic activity. Hence areas between the main channels are underlain by predominantly very thick sequences of fine-grained sediments, while other areas located adjacent to the main channels are underlain by coarse-grained sediments. It is the main river channels that have been subject to the greatest erosion and deposition.

From hydrochemical and mineralogical evidence to be presented later, the sediments containing groundwaters with the highest concentration of arsenic are the shallow fine-grained highstand deposits with radiocarbon dates generally less than 10 ka old. These are concentrated within the tide-affected areas of the active Ganges, moribund Ganges, lower Meghna and lower Brahmaputra delta areas.

The areas least affected by groundwater arsenic contamination are the Madhupur, Barind and Tripura Tracts that contain older uplifted Pleistocene sediments from which the arsenic has either been flushed by repeated cycles of groundwater throughflow or the geochemical conditions have been such that it was never released. The Tista Fan sediments also tend to be low in arsenic perhaps in part because of the high rate at which water is presently moving through them. They tend to be quite coarse-grained sediments and also appear to have a low concentration of iron oxides with a correspondingly low arsenic load (see Chapter 11).

Brown sediments have never been shown to give rise to a significant groundwater arsenic problem in Bangladesh. The remaining areas consisting of grey, usually micaeous, sediments yield groundwaters with variable arsenic concentrations. Some areas such as the Jamuna-Brahmaputra floodplain and the area underlain by the former main courses of the Ganges in western Bangladesh have exploitable coarse-grained aquifers at depth which may be low in arsenic. Fine-grained sediments at depth underlie other areas such as much of western Bangladesh and the Sylhet Basin. These have little potential for groundwater development and in addition may contain arsenic that could eventually affect adjacent aquifers.