Chapter 2
Sea Level Research: Methods and Techniques

2.1 Introduction

Sea level can be recorded either from the direct instrumental measurements or from indirect geological evidence (Tooley 1992). Sea level change determination from geological evidence includes sedimentary records, diatom analysis, pollen analysis, carbon dating etc. On the other hand, direct observations of relative sea level changes have been derived mainly from tide gauge data. In the conventional tide gauge system sea level is measured relative to a land based tide-gauge benchmark (Emery 1980).

2.2 Sea Level Changes from Geological Records

2.2.1 Sea-Level Index Points

Over 30 years of international research, co-ordinated under the auspices of a series of International Geoscience Programme (IGCP) projects, has produced a well-defined methodology 'sea-level index points' and refined for developing records of relative sea-level change from sedimentary coasts (Edwards 2006). Central to this is the use of sea-level index points which fix the past altitude of sea level in time and space (Tooley 1978; Preuss 1979; Shennan et al. 1983; van de Plassche 1986). In brief, for a sample to be established as a sea-level index point, it must possess information regarding its location (latitude and longitude), its altitude (relative to a levelling datum), its age (commonly inferred from radiocarbon dating), and its vertical relationship to a contemporenous tide level (termed the indicative meaning). The later is important when accounting for the differing vertical distributions of coastal sub-environments and associated sea-level indicators. A sediment sample from a known location can be used as a sea-level index point if it is dated and its altitude is measured relative to a geodetic datum (Shennan 1982, 1986; Tooley 1982). Sea-level index points (Fig. 2.1) are commonly derived from

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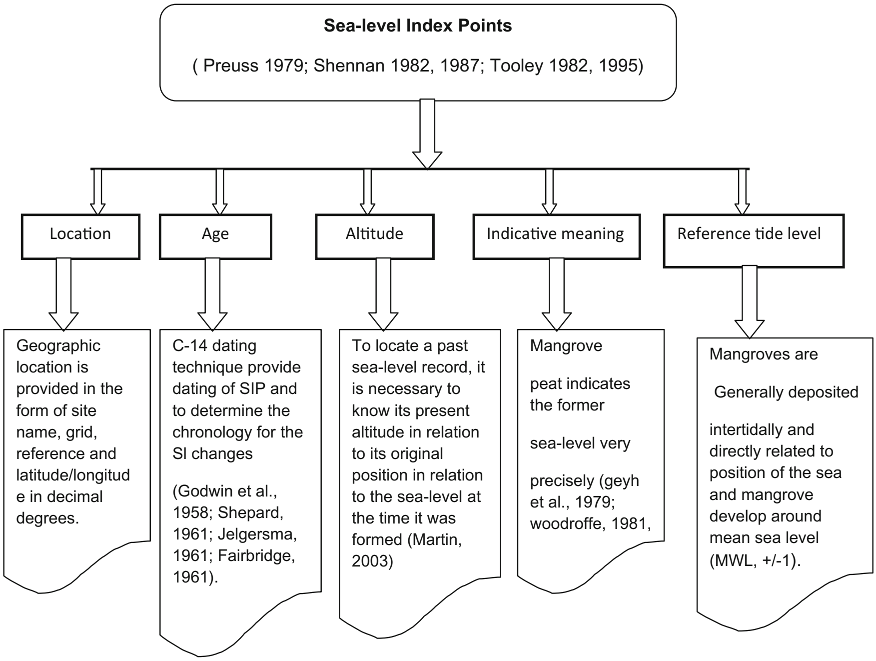


Fig. 2.1 Flow chart showing the five principal attributes of sea-level index points

lithostratigraphic contacts between terrestrial and marine sediments, with supporting microfossil data being used to delimit the onset or removal of brackish/marine conditions. The elevation at which it formed relative to a contemporaneous tide level (termed the indicative meaning) must also be determined in order to account for the range of heights at which different coastal sedimentary environments are found (Van de Plassche 1986).

2.2.1.1 Geographic Location

This information can be provided in the form of site name, and latitude/longitude in decimal degrees.

2.2.1.2 Age

The discovery of the C-14 dating technique brought a revolution to sea-level research methodology. This technique has been utilized by a number of researchers (Godwin et al. 1958; Shepard 1961; Jelgersma 1961; Fairbridge 1961). Before the discovery of the C-14 dating technique by Libby in 1955, geomorphological features had been used to make the link between land-level and sea-

Table 2.1 Radiocarbon dates of the three sites in and around Dhaka city

Name of the Site	Altitude	Material	^{14}C Age Conventional	^{14}C Age Calibrated (cal BP)
Site-1(Sony)	+1.80	Peat	1760 ± 60	1820–1530
	+0.90	Peat	3560 ± 60	4080–4030
	−1.60	Peat	5819 ± 60	6670–6410
	−3.75	Wood	6690 ± 40	7570–7430
Site-2(Vatpara)	+0.40	Peat	4670 ± 60	5580–5300
Site-3(Nayanipara)	−0.20	Peat	3320 ± 50	3690–3440
Site-4 (Dobadia)	+5.7	Peat	5120 ± 50	5980–5970
	+4.7	Wood	5330 ± 60	6280–5940
Site-5 (Chatbari)	+3.1	Peat	2800 ± 70	3080–2760
	+2.1	Peat	4230 ± 60	4870–4780
	+0.9	Peat	4520 ± 70	5440–5410

level movement. The use of dates from different materials, without knowing their indicative meaning as to sea-level movements, may produce a completely false sea-level history at any location (Tooley 1978). Nine peat samples and two wood fragments were measured by the Radiometric and Accelerator Mass Spectrometry (AMS) method, respectively. 14C ages were determined by Beta Analytic Radiocarbon Dating Laboratory, Miami, Florida to explore the sea-level changes scenario of Bangladesh during the Holocene. For determining the age of the peat/wood samples by radiocarbon dating, four samples were collected at Sony at altitudes of +1.80, +0.90, −1.60, and −3.75 m ASL, one was at Vatpara at +0.4 m and Nayanipara at −0.2 m, three were at Chatbari at +0.9, +3.1 and +2.1 m, two were at Dobadia at +5.7, 4.7 m, respectively (Table 2.1).

2.2.1.3 Altitude

A sediment sample from a known location can be used as a sea-level index point if it is dated and its altitude is measured relative to a geodetic datum (Shennan 1982, 1986; Tooley 1982). Datum level of any country is the reference level above or below which the altitude of any given point is measured (Jardine 1982). This is the most useful reference level for national surveying in any country. In Bangladesh, topographic maps are not yet been prepared on the basis of datum level as the datum levels are not uniformly pointed out in this country. To find the altitude at the top of the surface of six sections around in the central part of Bangladesh, the nearest datum levels of respective stations were used. Six leveling datum have been employed in research around the study region. With the help of the closest reference datum, Mean Sea Level (MSL) of the six outcrops was calculated by "differential leveling" method. Differential leveling (also called direct leveling) is used in determining elevations of points to establish a chain or network of BMs for future use. It requires a series of instrument setups along the survey route; and for setup, a horizontal line of sight is established, using a sensitive level.

2.2.1.4 Indicative Meaning and Reference Tide Level

The indicative meaning of a sample describes its vertical position relative to the tidal frame at the time of its formation. Where available, the database provides information on the inferred indicative meaning, the nature of the evidence from which this is derived, and the local tidal parameters used in reconstruction.

Sea-Level Indicators

Every marine feature or organism which has a quantifiable vertical relationship to a reference water level, the height of which is ultimately controlled by tidal amplitude at the coast, can be regarded as a sea-level indicator (Devoy 1987). On a global basis many different categories of indicators are used in sea-level studies, such as raised beaches, benchrock, notches, slope breaks shells, coral reefs, and archaeological features. Kidson (1981) urged that erosional features, such as shore platforms and notches can only rarely be used as precise indicators of former sea level.

Biological in depositional sequences

Any good sea-level must provide three essential elements: (1) accuracy, (2) preservability, and (3) be datable. Fossils within depositional sequence have the highest probability to provide all three of these elements.

Microfossil plant remains

The most useful indicators are microfossils because they occur in large numbers in small diameter cores which are often where the sea level records come from in Holocene submerged coastlines. Some attempts have been made to use pollen (Fig. 2.2) which is the microscopic part of the sexual reproductive organs of all angiosperm plants. Palynology is the study of pollen, spores, and similar palynomorphs, living and fossil. This is a powerful and useful tool to reconstruct the Quaternary environment (Birks and Birks 1980). The technique of qualitative pollen analysis was initiated by the Swedish geologist Lennart Von Post in 1916 (Birks and Birks 1980) which were later taken up and continued by his students (Faegri and Iversen 1989). Mangrove pollen is a very useful indicator of relative movements of sea-level in tropical environments (Belperio 1979; Ellison 1989), as well as the principal technique for reconstructing the Quaternary environment (Birks and Birks 1980).

A mangrove is a plant and *mangal* is a plant community and habitat where mangroves thrive. They are found in tropical and sub-tropical tidal areas, and as such have a high degree of salinity areas where *mangals* occur include estuaries and marine shorelines. Many, not all, mangrove swamps fringe estuaries and lagoons where the salinity changes with each tide. The tides rise along the coastline and enter the estuaries and travel inland as far as elevation allows.

Heritiera sp (m)

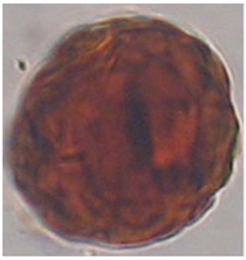
Aegicerus sp (m)

Xylicarpus sp(m)

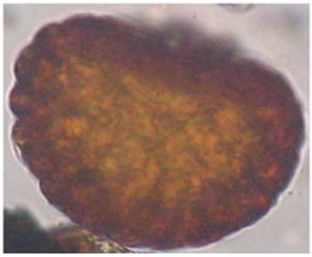
Lumnitzera racemosa (m)

Bruguiera sp(m)

Phoenix paludosa (palm)



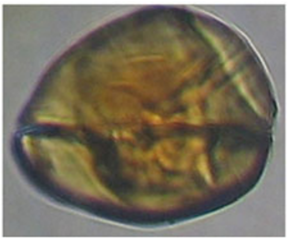
Temporina globate(a)



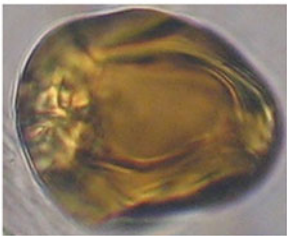
Corrugatisporites turpitus

Tricolpites tressireticulatus

Dyadoporonites sp(f)



Dyadoporonites sp(f)



Octaplata palanaensis(a)

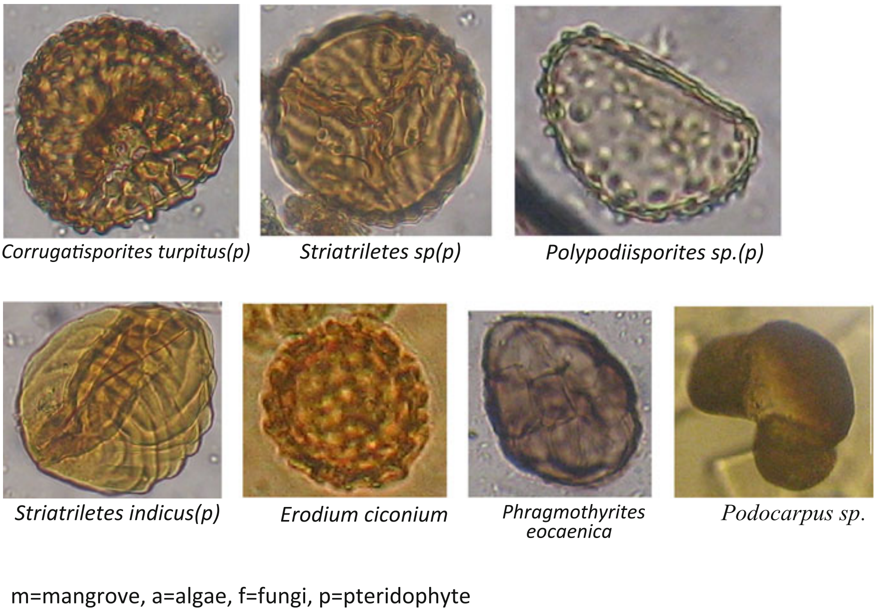


Fig. 2.2 continued

Mangrove swamp or *mangal* is one of an important habitat in brackish water environment. Brackish water is a result from mixing of seawater with fresh water with the salinity ranges between 0.5 and less than 35 ‰. Thus, rising sea level allows saltwater to penetrate farther inland and upstream (Gornitz 1991) and this effect impairs water supplies, ecosystems, and coastal farmland. In humid equatorial climates, gradual sea level rise may cause a brackish-water zone to migrate inland (Gornitz 1991).

The mangrove ecosystem is considered as highly susceptible to sea level changes (e.g. Gornitz 1991), and the sediments deposited beneath mangrove vegetation can provide useful indications of former sea levels (Scholl 1964; Woodroffe 1981; Van de Plassche 1986). The composition (lithology) of coastal sediments, coupled with any biological components they contain, represents a rich source of information on past changes in relative sea-level (Godwin 1940; Tooley 1978). Hence, the most reliable indicators are considered to be organic remains in their growth position, preferably in situ peat. Mangrove peats, which indicate the former sea-level very precisely, have been applied in some studies (e.g. Geyh et al. 1979; Woodroffe 1981; Woodroffe et al. 1985; Grindrod 1985, 1988) as sea-level indicators. Mangrove deposits aid the reconstruction of historical sea levels (Cohen et al. 2005).

Mangroves (generally) are trees and shrubs that grow in saline (brackish) coastal habitats in the tropics and subtropics. *Mangals* are found in depositional coastal environments where fine sediments, often with high organic content,

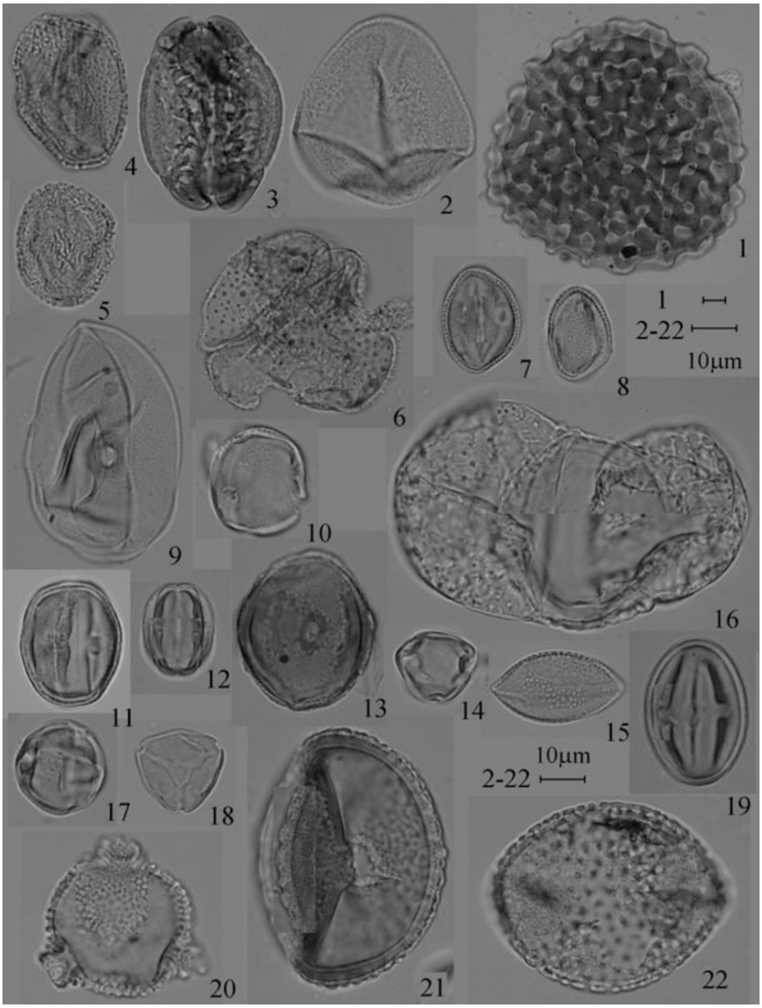


Fig. 2.2 Pollens and spores obtained in the study area. Pollen and spore types obtained from Sony with specimen number and sample horizon. *1*. Lygodium, NOS-9374, 1.8 m. *2*. Cyperaceae, NOS-9372, 1.8 m. *3*. Barringtonia, NOS-9369, 1.8 m. *4*. Semecarpus, NOS-9375. 1.8 m. *5*. Mangifera, NOS-9387, 1.2 m. *6*. Drosera, NOS-9386, 1.2 m. *7*. Phyllantus, NOS-9389, 1.2 m. *8*. unknown (tricolporate, prolate, small, fine-reticulate type), NOS-9492, 1.2 m. *9*. Gramineae, NOS-9394, 1.2 m. *10*. Vitis, NOS-9401, −1.6 m. *11*. Rhizophoraceae, NOS-9408, −1.6 m. *12*. Combretaceae. NOS-9424, −1.6 m. *13*. Lagerstroemia, NOS-9433, −1.6 m. *14*. Rhamnaceae, NOS-9412, −1.6 m. *15*. Arecaceae S type, NOS-9418, −1.6 m. *16*. Podocarpus, NOS-9406, −1.6 m. *17*. Rhizophoraceae, NOS-9448, −3.75 m. *18*. Myrtaceae, NOS-9441, −3.75 m. *19*. Leguminosae, NOS-9472, −3.75 m. *20*. Byttneria, NOS-9444, −3.75 m. *21*. Sonneratia, NOS-9452. −3.75 m. *22*. Arecaceae L type, NOS-9445. −3.75 m

collect in areas protected from high energy wave action. The geomorphic setting of mangrove systems comprises range of inter-related factors such as substrate types, coastal processes, sediment delivery, and freshwater delivery, all of which influence the occurrence of and survivorship of mangroves, while the tidal range will determine whether or not a sea-level rise will involve a significant proportion of the present mangrove habitat (Semeniuk 1994). Mangroves are generally deposited intertidally and may be directly related to the position of the sea at their time of deposition, and their sediments may contain large amounts of organic carbon suitable for radiocarbon dating (Woodroffe 1981). In reconstructing historical sea levels several studies (e.g. Scholl 1964; Geyh et al. 1979; Grindrod, 1985 and 1988; Mildenhall 1994; Clark and Guppy 1988; Bryant et al. 1992; Chappell 1993; Fujimoto and Miyagi 1993; Woodroffe et al. 1993; Beaman et al. 1994; Fujimoto and Miyagi 1993; Rashid et al. 2009, 2013) have departed from the assumption that mangroves develop around mean sea level. It is known that erosion, accretion or other disturbances may cause variation on the order of ±1 m (Bunt et al. 1985). Therefore, the topographical distribution of the mangroves in relation to mean sea-level is variable and may result in the sea level curve being displaced (Larcombe et al. 1995). In Grand Cayman (West Indies) the substrate of the marine mangrove is generally 15–30 cm above the mean sea level (Woodroffe 1981), and in Florida at 0–12 cm above the mean sea level (Scholl and Stuiver 1967). In the Townsville coastal plain (Australia), mangroves are found from 1.5 to 3.0 m amsl (Belperio 1979), while in Coral and Cocoa creek, northern Australia, the lower part of the mangrove forest is between 0 and 1 m above the mean sea level (Aucan and Ridd 2000).

Among all other microfossils, diatoms are also very useful to trace sea-level changes and have successfully been applied by Tooley (1978), Devoy (1979), Shennan (1986), Ireland (1987), Rashid (2009) among others. Diatoms are one-celled algae which leave a siliceous shell in the sediments (Shennan et al. 1998). These fossils appear to leave a record that can partially be subdivided the marsh into zones with varying accuracies (±20–50 cm at best). The most useful technique involving microfossil plants is determining sea levels in an indirect way where coastal ponds either become submerged or emerged (Palmer and Abbott 1986; Shennan et al. 1996). If they are emerged they go from marine to freshwater and vice versa for submergence; the key is to be able to determine the sill depth of the basin and then relate that to the radiocarbon dated transition. This method is usually accurate to within ±1 m depending on the depth and size of the basin (Laidler and Scott 1996). Either diatoms or dinoflagellates can be used in this manner. Dinoflagellates are also microscopic algae but they are organic-walled as opposed to the siliceous shells of diatoms. Both of these groups occur in large numbers such that 1 cm3 of wet sediment is often sufficient to obtain a valid result (Haq and Boersma 1978).

In case of diatom, they are useful for sea-level study because they are widespread in natural aquatic environments, many species prefer specific salinity conditions, the silica constituting the valves is relatively resistant to chemical alteration after burial and diatoms are often preserved within radiometrically dateable carbonaceous materials (Palmer and Abbott 1986).

Macro-animal fossils

Though the invertibrate macrofossils are limited in their value as sea level indicators by their vertical range in the water column, some groups such corals or attached biological indicators have extremely narrow ranges and have been used to produce some of the best and longest sea level curves (Fairbanks 1989). However, these are limited in occurrence and rocky intertidal forms are often not well preserved, especially in a submergent regime.

Corals may often be used as sea level indicator very effectively in tropical waters at depths ranging between MLWS and over 100 m. The depth varies in different coasts which are described below:

(a) On coasts with a strong vertical thermal gradient such as West Africa and Brazil, south of Cabo Frio; low water temperatures can be found at very shallow depths, and reef corals are thus confined to a very narrow vertical range (a few metres only). (b) On characteristic tropical coasts, where vertical thermal gradient is low, the composition of coral assemblage varies with depth just as the morphological and structural characteristics of the coral colonies do also. (c) Some reef coral species of the Indo-Pacific region are adapted to periodic emergence at low tide and are thus closely related to the low tide level. Some corals living in sheltered lagoons or in moats develop characteristic microatoll shapes: these may sometimes register water level variations.

The combination of these various criteria produced the best results, in the study of a fossil reef, when associated with morphological, sedimentological and geological studies. Special attention must be given to the possibility of coral colonies being broken by waves, displaced and later cemented once again on to the reef: large colonies of branching corals situated on the inner reef flat are generally good indicators.

Micro-animal fossils

There are two principal groups of animal microfossils that have been used extensively in sea-level studies, ostracods (Van Harten 1986) and foraminifera (Scott and Medioli 1986). Ostracodes leave a calcareous shell as a fossil and that in itself presents a problem because many of the best deposits for sea-level studies are not conducive to the preservation of CaCO3 hence the fossils are not present. Van Harten (1986) suggests the resolution with ostracodes to be within 100 m which not useful at all for modern se level studies but they can be used as accurate salinity traces and hence suggest transgression and regression (Haq and Boersma 1978).

On the other hand, foraminifera have both calcareous and agglutinated shells, agglutinated shells are resistant to dissolution in low pH, highly organic sediments, and often are very abundant in some highly organic deposits such as marshes (Scott and Medioli 1980).

Beachrock: modern indicator

In the catalogue of sea-level indicators, beachrock plays a significant role because of its wide distribution and extension on long stretches of coastlines.

Beachrock is defined by Scoffin and Stoddart (1987) as "the consolidated deposit that results from lithification by calcium carbonate of sediment in the intertidal and spray zones of mainly tropical coasts." Beachrock units form under a thin cover of sediment and generally overlie unconsolidated sand, although they may rest on any type of foundation. Maximum rates of subsurface beachrock cementation are thought to occur in the area of the beach that experiences the most wetting and drying-below the foreshore in the area of water table excursion between the neap low and high tide levels (Amieux et al. 1989; Higgins 1994). The majority of recent beachrock is formed on beaches in the same regions that favour coral reef formation (Turner 2005). Most publications, however, deal with beachrock cements rather than their incorporation into the coastal environment and its evolution. The relic character and age of most beachrocks has been overlooked, and beachrocks are called "modern" because of their position at or close to sea level.

Indicators of abandoned shorelines may be categorized as geological, biological, or archeological. Relict abrasion and accumulative relief types such as abrasion terraces, wave-cut notches, beach ridges, and aggradational terraces are related to former sea levels and can provide useful data for these reconstructions. Erosional scarps and coastal solution holes can also be useful indicators of former sea stands. In tropical and sub-tropical areas, beach-rock formation and deposits of oolite are often useful indicators of abandoned shorelines, as are peats and marsh and mudflat deposits. Organic materials such as peat and mollusk shells can be dated by radiometric methods.

2.2.1.5 Sedimentary Facies

Sedimentary rocks can be formed only where sediments are deposited long enough to become compacted and cemented into hard beds or strata. Sedimentation commonly occurs in areas where the sediment lies undisturbed for many years in sedimentary basins. Whereas some such basins are small, others occupy thousands of square kilometres and usually have within them several different local depositional environments. Physical, chemical, and biological factors influence these environments, and the conditions that they produce largely determine the nature of the sediments that accumulate. Several different local (sedimentary) environments may thus exist side by side within a basin as conditions change laterally; the sedimentary rocks that ultimately are produced there can be related to these depositional environments. These different but contemporaneous and juxtaposed sedimentary rocks are known as sedimentary facies.

In geology, a **facies** is a body of rock with specified characteristics. Ideally, a facies is a distinctive rock unit that forms under certain conditions of sedimentation, reflecting a particular process or environment (Encyclopedia Britanica online 2012). The term facies was introduced by the Swiss geologist Amanz Gressly in 1838. Facies is the study and interpretation of the textures, sedimentary structures, fossils, and lithologic associations of the sedimentary successions (Miall 1990) to interpret a paleoenvironment. It is a body of rock with specified

Table 2.2 Description of bedding thickness

	Thickness (cm)	Descriptive term
1	100+	Very thick bed
2	30–100	Thick bed
3	10–30	Medium bed
4	3–10	Thin bed
5	1–3	Very thin bed
6	0–1	Laminae: Thick laminae, 3–10 Thin laminae, 0–3

characteristics where sedimentary rocks can be handled on the basis of color, bedding, composition, texture, fossils and sedimentary structures. A biofacies is one for which prime consideration is given to the biological content. If fossils are absent or of little consequence and emphasis is on the physical and chemical characteristics of the rock, then the term lithofacies is appropriate.

Sedimentary structure

Sedimentary structure is the features formed in sediment at time (or very shortly thereafter) of deposition. Bedding/Stratification is most characteristic feature of sedimentary deposits. Fluctuation in current causes preferential deposition of grains. In some instance currents impart a distinctive orientation to deposited grains. In other cases grains on sediment may become packed differently during or shortly after deposition. Any of these factors can cause sediment to have a different appearance from that above and below, and therefore be observed as a separate bed. Bedding is generally defined as a sedimentary layering thicker than 1 cm (Table 2.2). The finer scale layering, only millimeters thick, is termed lamination (Table 2.2). Lamination is frequently an intertidal structure of a bed. The majority of beds have been deposited over a period of time ranging from hours or days, as in the case of turbidities and storm beds, 2 years, ten of years or even larger, as in the case of many marine shelf sandstones and limestones. The surface separating one bed from another is known as the bedding plane.

(A) Massive beds–beds with very little or no internal structures (Table 2.2; Fig. 2.3) which deposited under single uniform flow conditions or internal structures subsequently destroyed by bioturbation (disturbance by organisms).
(B) Graded bed—bed shows a progressive vertical change in grain-size—normal grading (fines upward) is common, but reverse grading (coarsen upward is rare).
(C) Cross-bedding—inclined layering commonly formed by deposition on a sloping face such as the inclined surfaces of bars, dunes, and sand waves.
(1) Planar cross-bedding—cross-beds parallel one another and intersect bedding at a consistent angle– formed by sand waves (straight crested dunes)

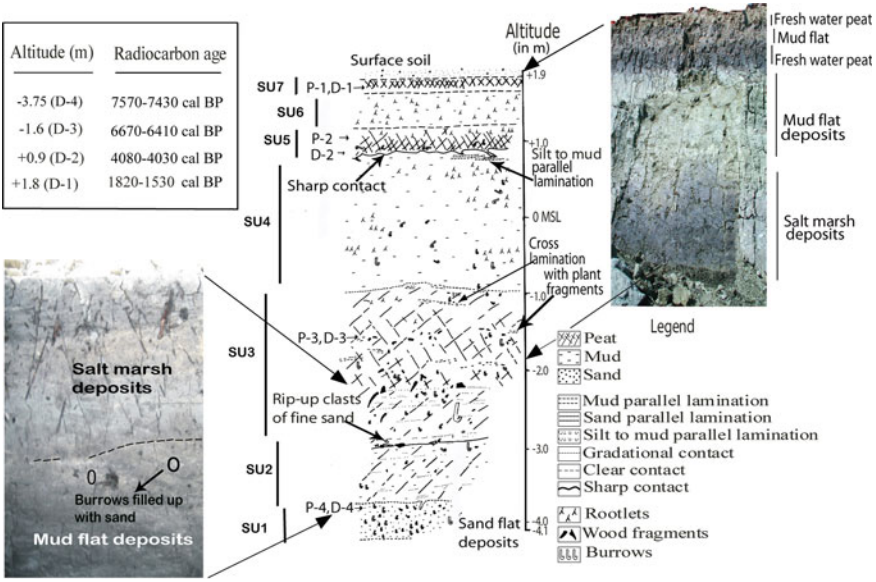


Fig. 2.3 Lithostratigraphic description at Sony

(2) Trough cross-bedding—cross-beds non-parallel and approach one another near base of bed becoming tangential or asymptotic to base– formed by sinuously crested dunes.

(D) (Ripple) Cross-lamination—current similar to cross-bedding (Fig. 2.3), but sets less than 3 cm thick, ripple have asymmetric form (one side steeper), and can have straight or sinuous crest or be isolated, formed unidirectional flow.

Wave ripples formed by bidirectional flow. Ripple have symmetrical form, sharp crest form in lower energy settings and rounded crest in higher energy.

Litho-bio facies

There are several ways of describing or designating sedimentary facies. By noting the prime physical (or lithological) characteristics, one is able to recognize lithofacies. The biological (or more correctly, paleontological) attributes—the fossils—define biofacies. Both are the direct result of the depositional history of a basin. By ascribing modes of origin to different facies (i.e., interpreting the lithofacies or biofacies) one can visualize a genetic system of facies. It is also common to speak of alluvial facies, bar facies, or reef facies, using the environment as a criterion.

Walther's Law of Facies, named after the geologist Johannes Walther, states that the vertical succession of facies reflects lateral changes in environment. Conversely, it states that when a depositional environment "migrates" laterally, sediments of one depositional environment come to lie on top of another. A classic example of this law is the vertical stratigraphic succession that typifies marine trangressions and regressions.

From studies of facies relationships to one another it has become recognized that the gradational, sharp, or eroded contacts between these rock bodies are also of significance in finding the mode of origin. Non-erosional contacts include that the facies immediately followed each other in time, probably by the migration of depositional environments. If contacts are sharp, even when erosion cannot be demonstrated, the facies may have been formed in depositional environments. Some contacts show extensive boring, burrowing, penecontemporaneous deformation or diagnosis of the underlying sediments so that the adjacent facies have become mixed or even inverted.

Today it is recognized that facies associations and distribution depend upon interrelated controls. The most important include sedimentary processes, sediment supply, climate, tectonics (earth movements), sea level changes, biological activity, water chemistry, and volcanic activity. Of these the environment of deposition (climate) and tectonic activity are paramount as they may ultimately regulate the other factors.

Facies association

Facies associations are groups of facies that occur together and are considered to be genetically or environmentally related. Each grouping would be identified as a distinct association. The association provides additional evidence which make environmental interpretation easier than treating each facies in isolation.

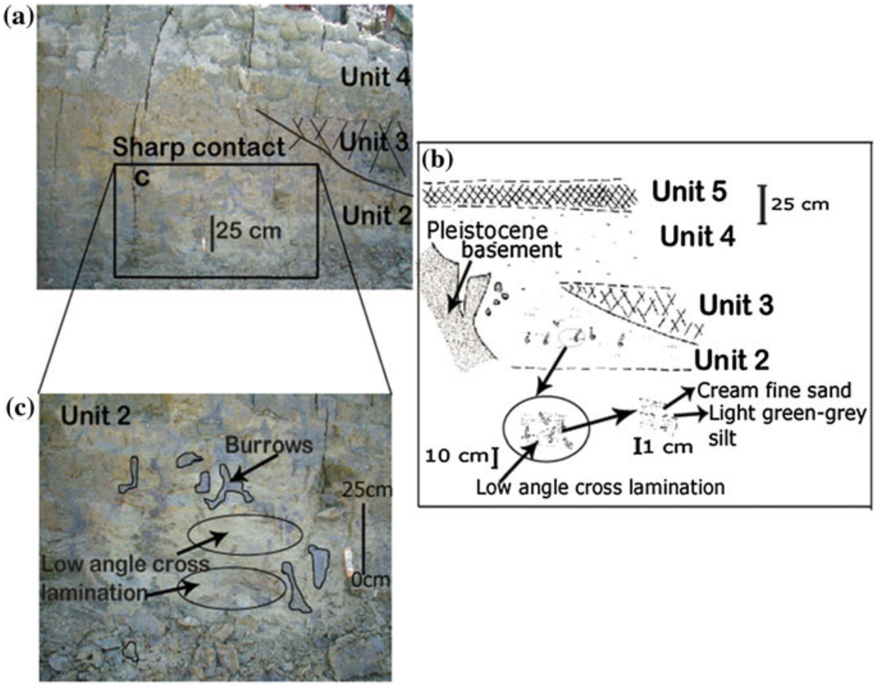
The litho- and biofacies were carefully observed to explore the paleoenvironments of the Holocene deposits at each site. On the basis of facies, together with the faunal analysis of pollen and diatom, the Holocene deposits around the study area (the central part of Bangladesh) have been assigned broadly into two sedimentary facies association; tidal environment facies association and fluvial facies association.

Tidal environment facies association

This facies association has been subdivided into 4 facies. Facies A: fine-grained sand; Facies B: marine mud; Facies C: marine organic mud; and Facies D: mud with interlaminated fine-grained sand or organic mud. These facies are described and interpreted bellow.

Fine-grained sand facies

The Facies is a massive muddy fine-grained sand to silt. Abundant burrows with sand pipes are developed at Sony (Fig. 2.3). The diameter of the pipes is approximately 1 cm. The pollen assemblages (Rashid et al. 2009) showed abundant occurrences of mangroves, such as Rhizophoraceae (28.9 %), *Sonneratia* (3.5 %), and *Avicennia* (0.9 %), with abundant occurrences of tropical forest elements. Dense burrows indicate high biogenic activity, which supports a tidal environment at Sony. Abundant mangrove pollens indicate that the mangrove ecosystem was developed very close to the deposited site. Pollens from tropical



A. Photograph showing Unit 2 and Unit 3 at the southern wall of the outcrop.
B. Sketch of photograph A . Low angle cross lamination, burrows, cream·fine sand are shown in the sketch. Sharp contact underlying with mud flat are shown.
C. Sedimentary structures of Unit 2 (extracted from photograph A).
The photograph shows low angle cross laminations and big burrows filled with fine sand.

Fig. 2.4 Detailed descriptions of litho-facies at Sony

forests imply that the mangrove ecosystem had some fresh water influence. Considered with the sandy lithofacies, the environment represents a sand flat of an intertidal zone near the low water/tide line in a coastal-plain (Rashid et al. 2009).

Marine mud facies

The lithology of this facies is characterised by mud (Figs. 2.3 and 2.4). It contains a significant number of large burrows filled with fine cream-coloured sands. Rootlets and small burrows are observed here. Parallel laminations and small scale low angled cross laminations of mud and silty mud or very fine-grained sand are preserved in some parts of this facies. The Vatpara site contains some organic matter. Wood stem fragments and a large quantity of leaf fragments are found at Dobadia (Fig. 2.5). There are many pipes, occupied by organisms, in the wood stems, which are filled with mud sediments. Abundant mangrove pollens such as *Lumnitzera racemosa*, and *Xylicarpus* sp. are detected in the mud sediments. Also, a significant number of marine diatom fossils such as *Cyclotella stylorum*, *Cyclotella striata*, *Paralia sulcata*, *Tryblioptychus coccconeiformis*,

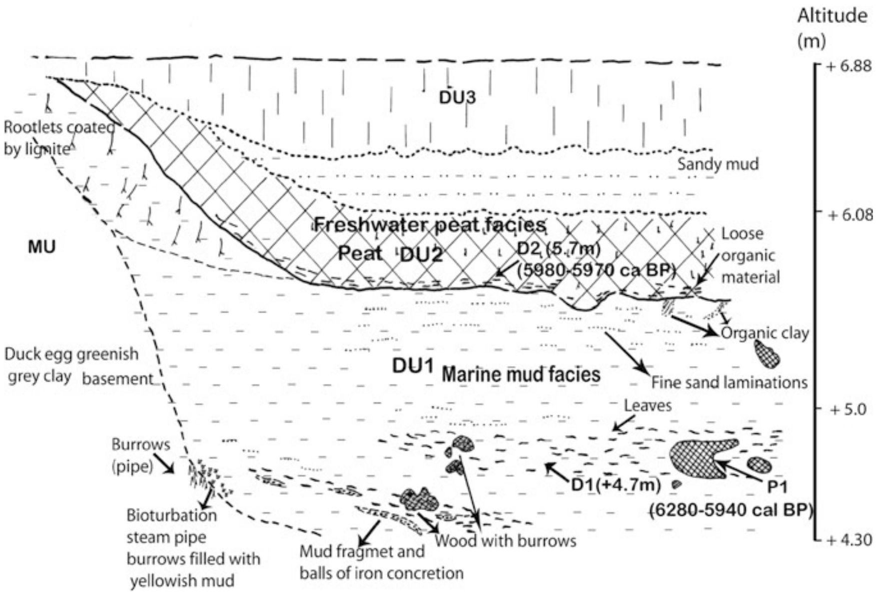


Fig. 2.5 lithostratigraphic description at Dobadia

Coscinodiscus radiatus, *Giffenia cocconeiformis, Coloneis westii,* and *Thalassiothrix* sp. are extracted from the sample from Dobadia. *Aulaeoseira granulata* is the only freshwater planktonic diatom found in Dobadia (Rashid et al 2013). The muddy lithofacies with parallel lamination and small-scale low angle cross lamination can be interpreted as a low-energy depositional environment at Dobadia. Marine evidence from the diatom fossils and mangrove pollens suggests that the mud was deposited in an intertidal mud flat (Rashid et al. 2009). The bioturbation also supports the mud flat environment. The lamination with fine-grained sand is thought to be formed by a tidal current. The sediment of this facies is interpreted as mud flat deposits.

Marine organic mud facies

Peaty mud with a high content of wood and plant fragments is the significant characteristics of this facies. Abundant small and large burrows are observed in Sony. Rootlets are common in the Vatpara and Sony. The pollen assemblage contains remarkable occurrences of Rhizophora (%)*, Sonneratia* (%) with *Nypa* (%) and abundant algae and fungal and pteridophytic spores. Marin to brackish water diatoms are also obtained from the Sony (Rashid et al. 2009). The Vatpara is also characterised by mangrove pollens such as *Rhizophora* sp., *Bruguiera* sp, *Aegicerus* sp.*, Heritiera* sp.*, Xylicarpus* sp., and *Phoenix paludosa* (Rashid et al 2013). Some cross laminations of plant fragments were observed in Sony (Rashid et al. 2009). Thin layers of fine-grained sand are interlaminated in Sony and Vatpara (Figs. 2.3 and 2.6). The bottom of SU3 cuts the lower unit. Part of the boundary is covered by rip-up clasts of fine-grained sand fragments (Rashid et al.

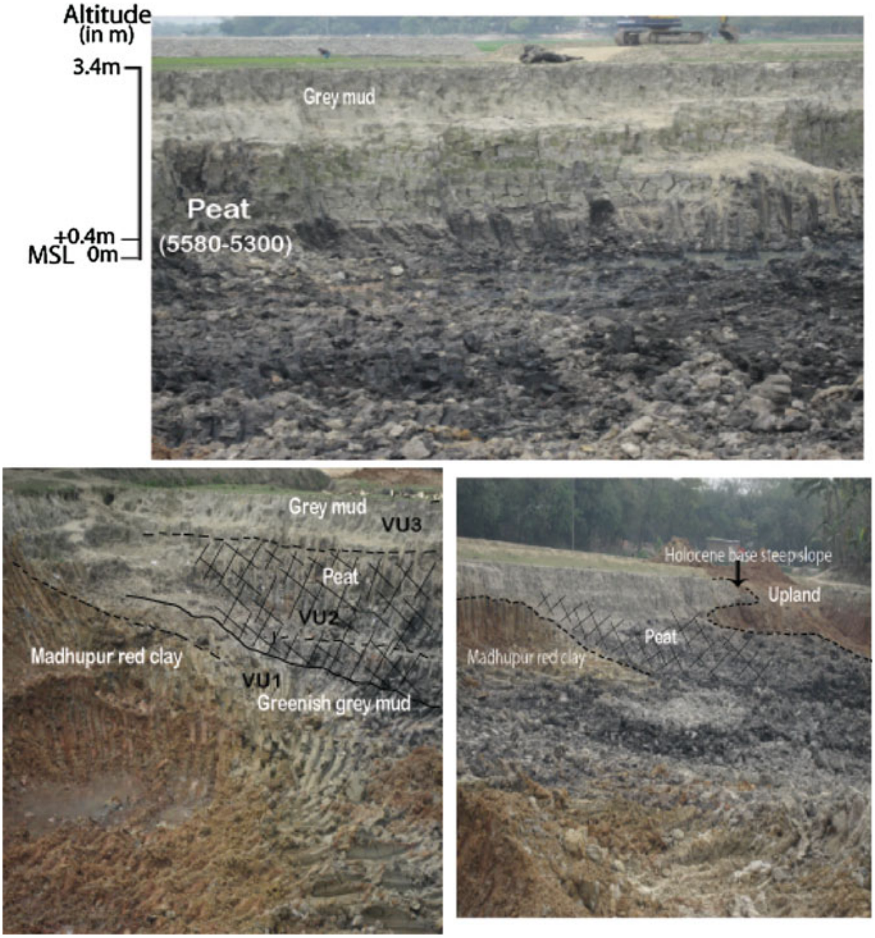


Fig. 2.6 Stratigraphic description at Vatpara

2009). The bottom of VU2 has a distinct, sharp boundary. Organic rich muddy lithofacies indicate the deposition of a marshy environment. Abundant occurrences of mangrove pollens and marine to brackish water diatoms suggest a salt marsh environment. The occurrence of rootlets supports the marshy environment. The abundant algae, spores and interlamination of very fine-grained sand reflect that the area was not permanently submerged and that it used to subject to a tidal effect.

Mud with interlaminated fine-grained sand or organic mud facies

A parallel lamination of fine-grained sand is developed in Chatbari site (Figs. 2.7, 2.8). It comprises an alternation of mud and organic mud. The mud beds are weakly laminated and a few thin (approximately 1 cm) sand beds are associated with them. The organic mud beds are composed of abundant plant fragments (including wood fragments) and mud. Channel structures are recognised at

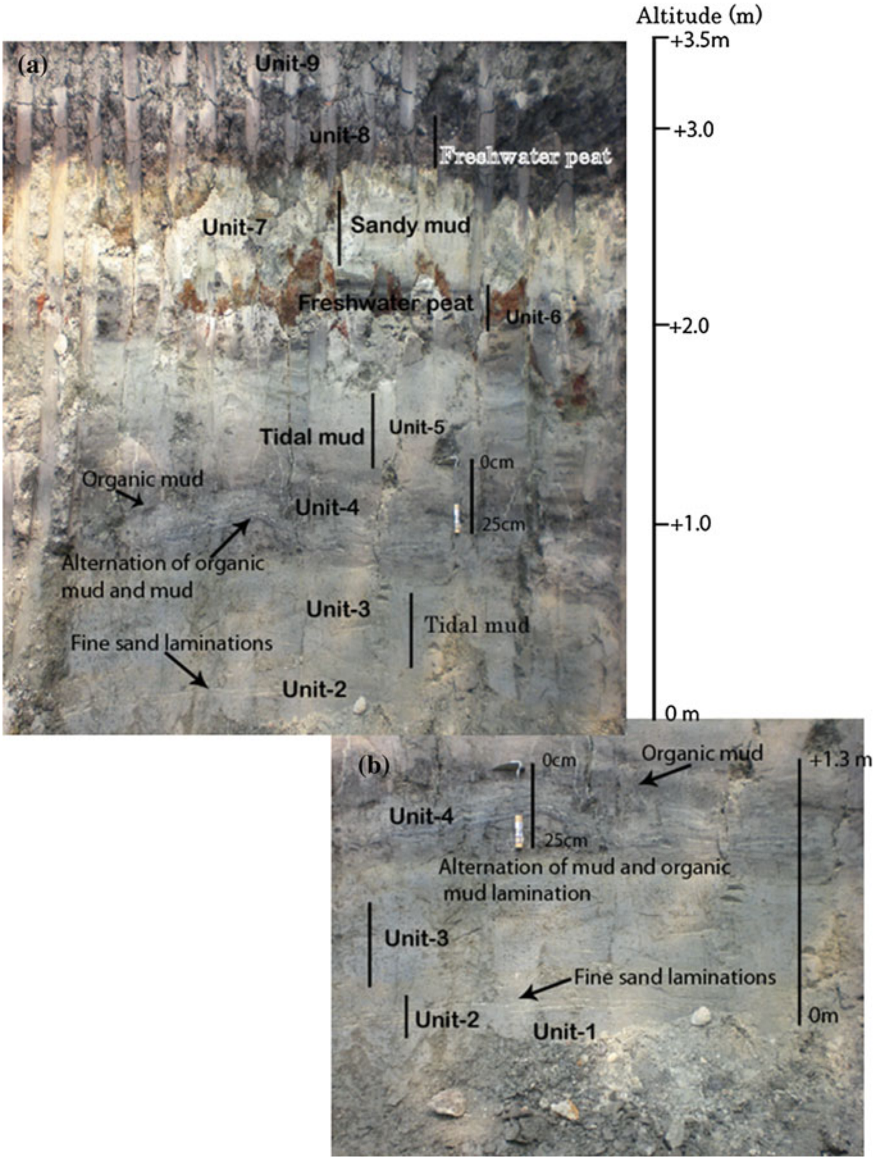


Fig. 2.7 Description of lithostratigraphy at Chatbari

the bottom of a few organic mud beds, which cut the lower bed. This facies is characterised by an occurrence of abundant diatom fossils. Under the microscope, fine-grained sand to silt clasts of quartz, mica (mainly biotite) with minor amounts of feldspar are observed in Chatbari (Rashid et al 2013). Feldspar clasts are not weathered. Soil structures such as sepic plasmic fabric are not developed in the

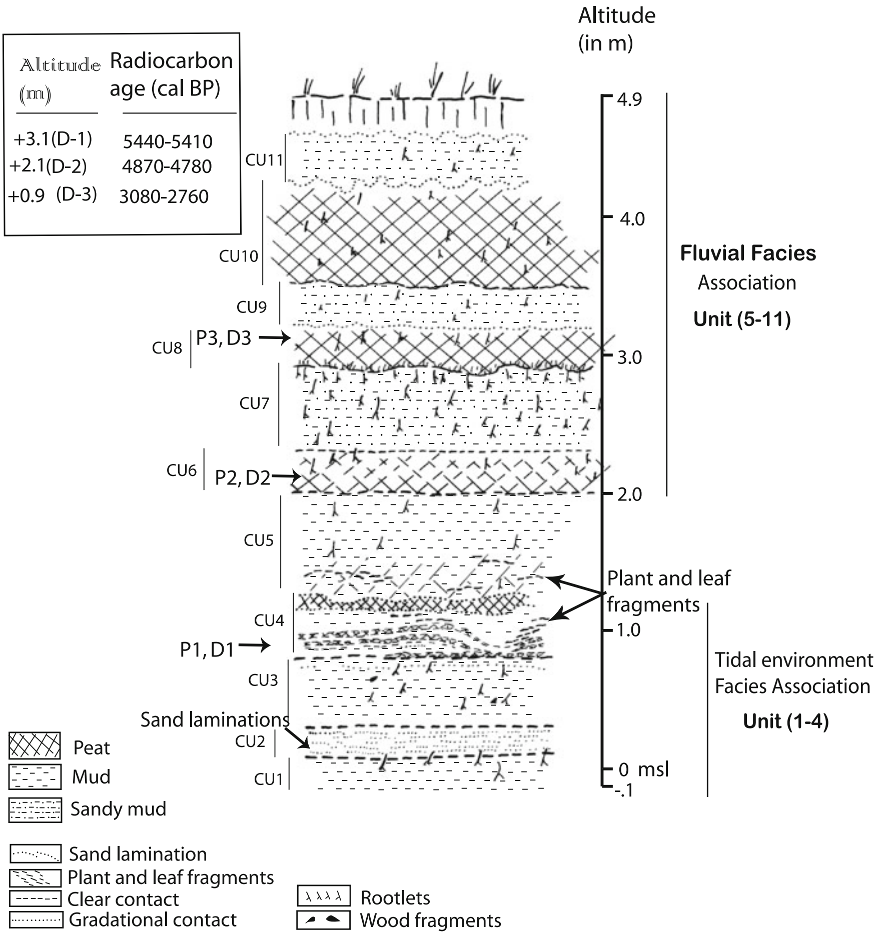


Fig. 2.8 Lithostratigraphic and sedimentary description at Chatbari

clay portion. This facies contains a few mangrove palm pollens, such as *Phoenix paludosa*. Abundant diatom fossils, such as marine planktonic diatoms (*Cyclotella striata*, *Actinocyclus octonarius* and 5 species), brackish planktonic diatoms (*Thalassiosira bramaputrae*, *Actinocyclus normanii* and 1 species) and freshwater planktonic diatoms (*Aulacoseira ambigua*, *A. granulata* and 3 species), are observed (Rashid et al 2013). A small number of haptobenthic diatom fossils, but with many species (3 species of marine haptobenthic diatoms, seven species of brackish haptobenthic diatoms and 21 species of freshwater haptobenthic diatoms), were also collected. It yields abundant freshwater diatoms, such as *Aulacoseira ambigua*, *Eunotia formica*, *Aulacoseira granulata*, *Aulacoseira granulate,* with two species of marine diatoms, such as *Cyclotella striata* and *Cyclotella stylorum* (Rashid et al 2013).

The general lithology of mud (silt with clay) with fine sand beds and organic mud indicates a low energy environment. The associated mangrove pollen and diatom fossils reveal a brackish water environment. The alternation of mud and organic mud beds indicates that the succession at Chatbari might have been affected by repeated flooding or tidal currents at the final stage of the deposition of this facies. The pollen fossils indicate that the organic matter was transported from nearby mangrove vegetation coverage, which might have been slightly more elevated than the deposition site. The Chatbari site is located in the valley of the Turag River and is situated at the border of the Madhupur Tract and a recent fluvial plain.

Considering the geographical setting, this facies is interpreted as the deposition of an estuarine environment. The predominance of the planktonic diatoms (marine, brackish and freshwater) indicates a lagoonal environment. The central basin of an estuary (Dalrymple et al. 1992) is thought to be reconstructed for a sedimentary environment.

Fluvial facies association

The fluvial facies association is subdivided into facies E: non-marine mud and facies F: peat, which are described and interpreted below.

Non-marine mud facies

The structureless ill-sorted sandy mud with abundant rootlets characterises the facies. Under a microscope, the pores of rootlets, coated with orange to deep red iron oxides, and clay skin are observed. In the mud matrix, clinobimasepic microfabrics (Retallack 1997) with highly birefringent streaks are developed.

This facies indicates that the sediments were formed by a mud flow. Abundant rootlets and soil structures reveal that the deposits were affected under a subaerial environment. The facies is interpreted to be deposited by flooding in a fluvial plain.

Peat facies

The facies is characterised by black massive peat, which is composed of mud and a large quantity of loose and undecomposed organic materials with small rootlets (Fig. 2.9). Abundant terrestrial plant pollen fossils are contained. The palynological data give evidence of freshwater sequences at Sony (Rashid et al. 2009). The pollen fossils from Dobadia are dominated by terrestrial tree elements such as Podocarpaceae and Geraniaceae. Podocarpaceae indicates a forest in moist conditions (Rashid et al 2013). DU2 is also characterised by pteridophytic and fungal spores. CU6, CU8, CU10 (Chatbari) and NU2 and NU4 (Nayamipara) contain terrestrial pollens and some pteridophytic and fungal spores. Under the microscopic observation of CU6 and CU8, some rootlet pores were coated with iron oxide. The lithofacies indicates that the facies was deposited in a marshy environment in a fluvial plane (Rashid et al 2013). The pollen results and the occurrence of pteridophytic and fungal spores support the hypothesis that the site was surrounded with a moist freshwater environment and that a forest was developed in the Madhupur tract. The ferric concentration of the walls of roots

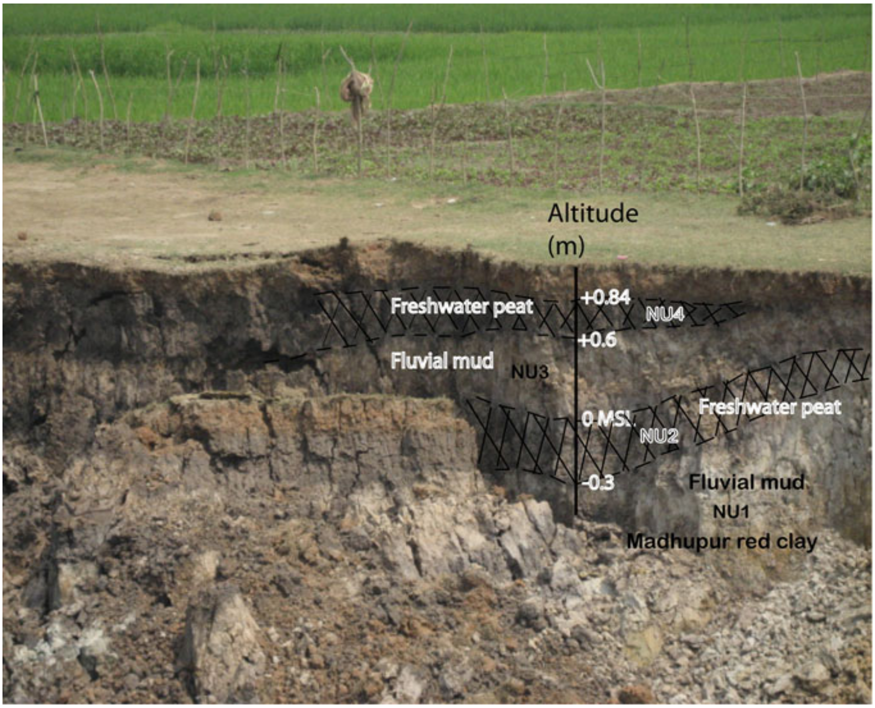


Fig. 2.9 Stratigraphic description at Nayanipara

may reveal that the weathering acted upon the succession and that it experienced wet and dry weather.

2.3 Sea Level Changes from Tide Gauge Data

Tide gauge record refers to continuous record of height of tide, accurately observed at fixed interval of time and referred to a stable bench mark. First tide gauge was established in 1682 in Amsterdam. Only 122 stations have recorded from before 1900. Global sea-level change has been relatively well studied by making use of the coastal tide gauge data that are available (Woodworth and Player 2003) through the Permanent Service for Mean Sea Level (PSMSL). Tide-gauge records have been used extensively during this century to estimate sea level changes (Gornitz; Pugh 1987; Emery 1980; Barnet 1984; Aubrey and Emery 1993). At least a dozen attempts have so far been under taken during last 50 years to estimate the global sea level change based on tidal records. Tide-gauge records have been used extensively during this century to estimate sea level changes (Gornitz 1991; Emery 1980; Barnet 1984; Aubrey and Emery 1993). Studies of global mean sea level changes over the last 100 years based upon tide-gauge data yield values ranging between 0.5 and 3 mm/yr; most estimates lie within 1.0–2.0 mm/yr (Warrick and Oerlemans 1990).

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