RELATIVE SEA-LEVEL CHANGE IN BANGLADESH DURING THE HOLOCENE.

M. Shahidul Islam

A Thesis Submitted for the Degree of PhD
at the
University of St Andrews

1997

RELATIVE SEA-LEVEL CHANGES

IN BANGLADESH

DURING THE HOLOCENE

by

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Volume One

Thesis submitted for the degree of
Doctor of Philosophy

School of Geography and Geology
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Scotland, U.K.

May, 1996

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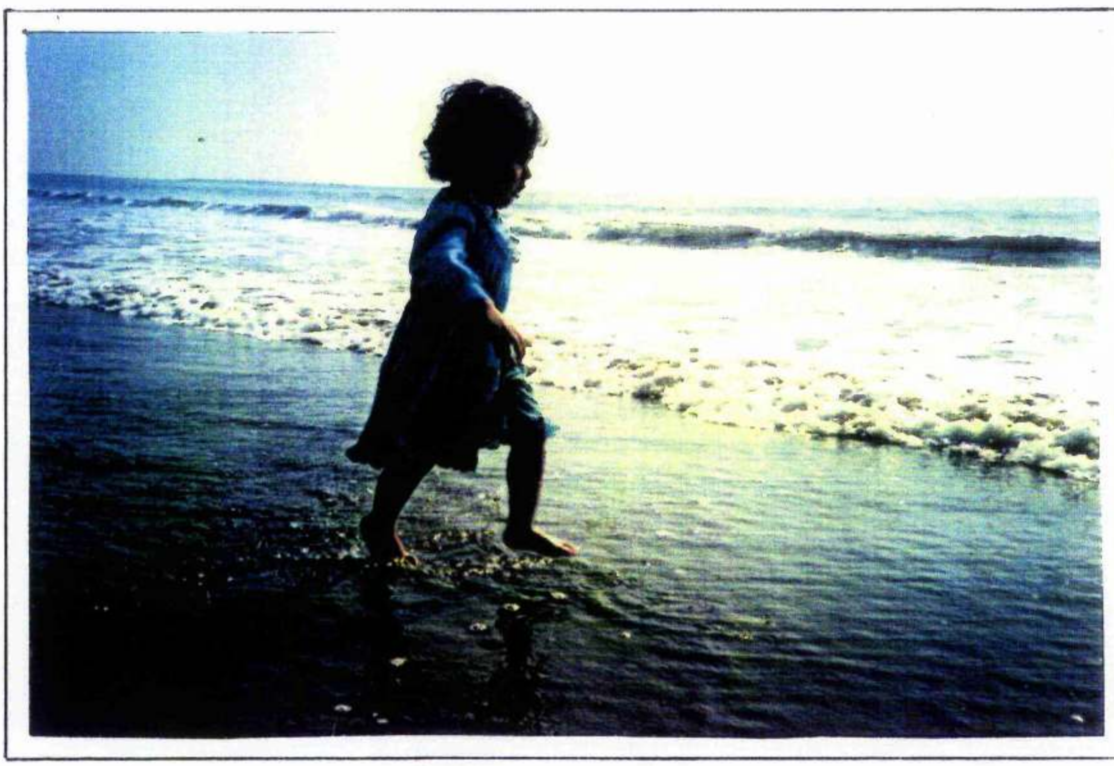

A Call from the Sea

for

Salma Islam, my wife

and

Shabrina Islam, my daughter

and

Shefatul Islam, my son.

DECLARATIONS

I, M. Shahidul Islam, hereby certify that this thesis, which is approximately 90,500 words in length, has been written by me, that is the record of work carried out by me and that it has not been submitted in any previous application for a higher degree.

Date. 22.05.96... Signature of Candidate......................

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Abstract

The thesis aims to reconstruct the Holocene sea-level history in Bangladesh. Detailed litho-, bio-, and chrono-stratigraphic techniques have been applied to elucidate the nature of sedimentary sequences in association with the events of the Holocene marine transgressions and regressions. Samples have been collected from two separate sites, one at Panigati near Khulna and another at Matuail near Dhaka.

The study shows evidence of five periods of marine transgression, each followed by a regression, during the Holocene. Each minerogenic sediment layer indicates a marine episode and these sediments were deposited under intertidal to estuarine conditions; each peat layer is in situ and indicates a retreat of the sea. It is difficult to separate the eustatic components contributing to these relative sea-level movements, although processes operating locally and regionally are clearly evident. Two separate sea-level curves, together with possible error ranges, have been proposed for Bangladesh; since the early mid-Holocene, an average relative sea-level rise of 1.07 mm yr^{-1} *has been estimated.*

The reconstructed sea-level curves show that during the early and mid-Holocene both sedimentation and subsidence rates were much lower than during the last millennium. Differential spatio-temporal progradation and coastline movements have also been evident. The Ganges and Brahmaputra rivers have provided a continuous sediment supply but their convergence is only of recent origin. A possible hypothesis of two separate estuarine systems for these two rivers has been put forward.

Acknowledgements

This work would not have been possible without the studentship from the Commonwealth Scholarship Commission. I would like to express my thanks to the Commission. I would also like to express my appreciation to the Department of Geography, University of Rajshahi, Bangladesh for granting me research leave for the period of this work.

I wish to express sincere acknowledgement to my supervisor Professor M.J. Tooley for his thoughtful supervision, valuable advice and continuous encouragement. I would also like to give him and his wife, Rosanna Mary Tooley, my deepest gratitude for their kindness in helping my family in many ways, particularly at difficult times.

I would like to thank my second supervisor Professor G. Whittington for his valuable advice and discussion, particularly on the pollen results and also for his comments for improvements to the text of the thesis.

My sincere thanks to Professor M. Banerjee and Dr. P.K. Sen of the Department of Botany, Calcutta University, for introducing me to mangrove pollen from the slides available at their laboratory. Dr. B.B. Mukherjee of Bose Institute, Calcutta kindly agreed to spend three weeks with me in Durham to discuss the mangrove pollen on my slides. My deepest gratitude to him. My thanks to Professor M. Umitsu for allowing me to use the core he collected from Daulatpur and now held at the University of Dhaka. Also, my sincere thanks to Professor G.V. Rajamanickam, Tamil University, Tanjavur, India, who kindly read the draft and made some positive comments.

Most of the work was done in the Department of Geography, University of Durham. I wish to acknowledge the help of Professor I. Shennan, Dr. Y. Zong and Dr. J.B. Innes at different stages of the work. Thanks are also due to Mr. D. Coates, Mr. B. Priestley, Mr. F. Davies, Mr. C. Mullaney, Mr. M. Scott, Miss. M. Johnson, Mr. A. Hudspeth and Mrs. S. Henderson for their technical supports. My sincere thanks to Dr. J.G. Townsend and Dr. P.J. Atkins for their support and encouragement.

In St. Andrews, I wish to express my thanks to Dr. M. Robinson for her valuable advice, particularly on diatom results and her encouragement. Thanks are also due to Mrs. L. Wood for her help, and to Dr. J. Walden, who restored my text after the computer crashed.

In Bangladesh, I wish to thank Professor Monirul Haque and Dr. M. Hussian Monsur of Dhaka University, Dr. Shah Alam of Chittagong University and Professor Sherajul Arephin of Rajshahi University for their help, support and encouragement. I tried to use all possible resources available in various institutions, such as SPARRSO, GSB, SoB, BIWTA and BWDB. I acknowledge the help I got from those places.

During the fieldwork, four young men, Abdul (1), Abdul (2), Monsur and Zahid from Chandanimohal village near Panigati shared with me the pain and pleasure of making boreholes and collecting samples. I wish to express my thanks to them. The support and help I got from local people and villagers was encouraging for my fieldwork. I wish to thank those people who were curious about to know what I was doing and who also enjoyed their participation.

Thanks are due to the Hebdomadar of the University of St. Andrews for his supports during the final stages of the work. Help and encouragement from many of my friends and well wishers, such as Mr. Gebril Ali, Mr. Alistair Kirk, Mr. Edward Twidy, Mrs. Margaret Donaldson, Mr. Onuonga Isaac, Mr. Harun S.M. Zin, Mr. Amir Hossain, Mr. Rabi Mallik, Mr. M.A. Zaman, Mr. A.Z.M. Shoeb and Mr. Mukbul Hossain will never be forgotten. My thanks to all of them.

I give my sincere acknowledgement to my family and my in-laws' family for their moral support and encouragement. Finally, I am deeply indebted to my wife and two little children who tolerated greatly during the work, and to whom I dedicate the thesis.

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GLOSSARY

BIWTA	Bangladesh Inland Transport Authority
BM	Bench Mark
BWDB	Bangladesh Water Development Board
cal.	Calibrated years
CEEHM	Committee of Experts on Earthquake Hazard Minimization
CPA	Chalna Port Authority
EPWDB	East-Pakistan Water Development Board
FAP	Flood Action Plan
FCD	Flood Control and Drainage
FPCO	Flood Plan Coordination Organization
GDP	Gross Domestic Product
GSB	Geological Survey of Bangladesh
GTS	Great Trigonometrical Survey
HAT	Highest Astronomical Tide
IGCP	International Geological Correlation Programme
IGU	International Geographical Union
INQUA	International Union for Quaternary Research
IPCC	Intergovernmental Panel on Climatic Change
MPA	Mongla Port Authority
MPO	Master Plan Organization
MSL	Meal Sea Level
MTL	Mean Tide Level
MXHWD	Maximum High Water Spring Tide During Dry Season
NRC	National Research Council
PWD	Public Works Department
SoB	Survey of Bangladesh
SPARRSO	Space Research and Remote Sensing Organization
UNDP	United Nation Development Programme
UNEP	United Nation Environmental Programme
WMO	World Metrological Organization

Chapter 1: INTRODUCTION

1.1. GENERAL INTRODUCTION

Bangladesh, located between 20°34'and 26°38' North, and between 88°01' and 92°41' East, is bounded in the west, north and east by India, in the south-east corner by Myanmar, and in the south by the Bay of Bengal (Fig. 1.1). This tropical lowlying country, covering 147,570 sq. km and supporting 111.4 million people (BBS, 1993) receives frequent international attention after being afflicted by natural disasters, such as catastrophic flooding, tidal surges and storm surges. Besides these aperiodic natural events, Bangladesh is also vulnerable to a few other environmental issues, such as saline water intrusion along the coastal belt, particularly in the south-west, rapid siltation of the river beds, river bank erosion, and drought and desertification in the north-west. Above all, the predicted sea level rise by the year AD 2050 (Milliman *et al.,* 1989) is a potential threat to the country.

The rise of global sea level (Houghton *et al.,* 1990) by the end of next century would mean that there is a high risk of coastal inundation by sea water. Barth and Titus (1984) indicated that one or two metres rise in sea level would result in the inundation of lowlying areas, erode shorelines by hundreds of metres, and raise the salinity of rivers, bays and aquifers. Rossiter (1962) reported that a sea-level rise of only 15 cm would double the probability of storm surge damage on the east coast and triple it on the west coast of Britain. In the case of Bangladesh, the projected 1.44 m rise of sea level by the year AD 2050 would inundate 16% of the populated land, displace 13% of the population and lose 10% of the GDP (Milliman *et al.,* 1989). The environmental issues associated with the so-called global warming and potential sea-level rise are of great concern to scientists, politicians and policy makers. However, how these future sea-level scenarios-global, regional and local- have been derived is still a matter of debate, and in need of further methodological refinement and explanation.

1.2. IDENTIFICATION OF THE RESEARCH PROBLEM

Sea level can be recorded either from the direct instrumental measurements or from indirect geological evidence (Tooley, 1992). At least a dozen attempts have so far been undertaken during the last 45 years to estimate the global sea-level rise based on tidal records. Gutenberg (1941) estimated an average rise of sea level of 1.1 $\pm$0.8 mm yr^{-1}. Mörner (1973) indicated that since 1840 the sea has risen at a rate of 1.1 mm yr^{-1}. Emery (1980) estimated a rise of 3 mm yr^{-1} based on data from selected stations in the worldwide tide gauge net. Gornitz *et al.* (1982) calculated a rate of 1.2 mm yr^{-1}. Barnett (1983, 1984) demonstrated a rise of about 1.5 mm yr^{-1}. Woodworth (1990) demonstrated a positive rate of 0.44 mm yr^{-1}. Warrick and Oerlemans (1990) estimated an average rise of 1-2 mm yr^{-1} over the last 100 years. The above estimated figures of global sea-level rise are based on only about one hundred years of tidal records; the longest tidal record is at Amsterdam, since 1682 (van de Plassche, 1986a). The distribution of many gauges is unsatisfactory, the highest station densities being in the United States, Western Europe and Japan. Moreover, the records are often discontinuous (Tooley, 1992) and the long-term records from the southern hemisphere also being few in number (Barnett, 1990). Hence, these sea-level data have numerous potential difficulties (Gornitz, 1995) and each estimated figure has its own drawback.

In Bangladesh, based on tidal records, few attempts have so far been made to estimate the sea-level changes during the last few decades and those that have been made are not only different but also confusing. For the site at Chittagong, Das (1992) estimated a 25 cm rise of sea level between 1944 and 1964 (a rate of 1.25 cm yr^{-1}) whereas Mahmood *et al.* (1992) demonstrated a fall at a rate of 2.24 mm yr^{-1} and Kabir (1993) considered the fall to be 1.11 mm yr^{-1}. Examination of relative sea-level changes of Mongla (Khulna) by Mahmood *et al.* (1992) and Kabir (1993) indicated a rise of 5.18 mm yr^{-1} and 4.65 mm yr^{-1}, respectively. Furthermore, all of these estimates have been based on records which refer to different periods. Das (1992) used records from Chittagong, the oldest in Bangladesh and dating from 1937; these records are, however, discontinuous. Mahmood *et al.* (1992) and Kabir (1993) also used data from Chittagong but only for the last 20 years when records are continuous. The data, therefore, are not adequate to allow the drawing of any conclusion on the long term changes of sea level. In addition, it is difficult to isolate and quantify the potential errors of tidal records which are induced by frequent inundation of tide gauges during tidal surges and floods, sediment compaction and the relocation of tidal stations to new sites as a result of river migration. Any projection and conclusion of sea-level changes based on such a data base, poor both in quantity and quality, and any planning measures to accommodate such sea level scenarios might not be sustainable; a view also suggested by Shennan (1993). Hence, an alternative approach to sea-level research is desirable.

The evidence of advance and retreat of sea level at any particular site is generally well preserved within the sedimentary records. The stratigraphy of the world's coastal lowlands is similar: there are alternating layers of marine, freshwater and terrestrial sediments. A clear understanding of these coastal sedimentary sequences reveals a precise sea-level history during the past, especially during the Holocene. It could also be used as an indication of possible future sea-level rise and coastline changes (Shennan, 1993).

Reconstruction of the Holocene sea-level history from geological evidence has successfully been applied to many coastal lowlands, such as the Netherlands (Jelgersma, 1961, 1966), England (Tooley, 1974, 1978a, 1982; Shennan, 1982a, 1986a, 1986b), Brazil (Ireland, 1987, 1989), Hawaii (Calhoun and Flatcher III, 1996), and many others.

Our current knowledge of the Holocene environmental history of Bangladesh is very limited and no systematic attempt to understand the sea-level changes during this period has yet been made. An understanding of the Holocene sea level history of Bangladesh from geological records would not only allow a new technique for possible application to future sea-level studies of the country but also provide a new dimension to the investigation of palaeoenvironmental issues. The present research is, therefore, focused as an endeavour in that direction.

1.3. OBJECTIVES OF THE STUDY

From the foregoing discussion, it is clear that work which attempts to investigate the environmental history of the large deltaic area of Bangladesh would have a very wide scope. The environmental history of any place is neither straightforward nor very simple; rather it involves a number of integrated natural processes. Reconstruction of the Holocene sea-level history must depend on a clear understanding of successive geological and biological sequences. Thus, the present research could have a large number of objectives. Considering the limitations under which it is undertaken, particularly the time constraint, only a few objectives could be considered here and they can be classified into primary and secondary objectives.

The primary objectives are:-

1. reconstruction of the Holocene sea-level history and drawing a sea-level curve for Bangladesh, and

2. implication of the reconstruction to understand the Holocene sedimentary sequences and depositional environment within the Bengal Basin.

The successful interpretation of these should expand our current understanding of the nature of river channel migration and coastline changes. The present study, therefore, also includes the following research problems as secondary objectives:-

1. **resolving the current controversy over the nature of origin of Bengal peat in relation to sea-level changes,**
2. **understanding the coastal mangal limits in relation to relative sea-level movements,**
3. **understanding the fluvial behaviour and shifting characteristics of the river system in the past,**
4. **understanding the palaeo-tides, -tidal range and -extreme tidal events along the coastal belt, and**
5. **understanding the nature of coastline changes and delta progradation during the Holocene.**

Above all, the main aim of this current research is to apply critically those techniques, which have already been successfully applied to many coastal areas of temperate regions, for the first time to Bangladesh, a tropical country, in order to reconstruct the Holocene sea level history.

1.4. SIGNIFICANCE OF THE STUDY

Bangladesh is affected by large scale natural disasters almost every year. Thirteen tropical cyclones struck coastal areas between 1960 and 1970 (Brammer, 1990a). An average of 1.5 severe cyclonic storms hit the country each year and the associated storm surges, driving water levels as much as 6 m higher than the present levels, can reach as far as 200 km inland (Mutry *et al.*, 1986). An estimated 300,000 people were killed during the cyclone and storm surge of November, 1970.

There was severe flooding in 1954, 1955, 1956, 1962, 1963, 1968, 1970, 1971, 1974, 1977, 1980, 1984, 1987 and 1988 (Hossain *et al.*, 1987; Miah, 1988; Brammer, 1990a). Soon after two consecutive unprecedented floods in 1954 and 1955 the then Pakistan Government adopted a policy to control flooding by constructing polders along the major rivers (Siddiqui, 1990). Since its creation, the Water Development Board has completed the construction of a total of 272 FCD projects. Such engineering works, in most cases, have failed to serve the purposes for which they were intended (Miah, 1988). Prolonged water logging of the polder of *Beel* Dakatia at Khulna is a man made ecological disaster due to faulty engineering measures (Adnan, 1991a). The engineering record displays recurrent and systematic operational failures of such physical constructions (Adnan, 1991b).

Following the disastrous floods of 1987 and 1988, the Government of Bangladesh undertook a comprehensive review of flood policy, which finally gave birth to the five year (1990-95), multimillion US dollars Flood Action Plan (FAP), funded by the donor countries and coordinated by the World Bank (World Bank, 1989). The FAP, which has initiated a fundamental debate on flood control issues (Task Force, 1991), consists of eleven components (engineering measures) and sixteen supporting activities (studies of different components). All of these proposed studies are being carried out based on instrumental records which rarely go beyond the 1950s. In some cases, the meteorological and hydrological data of Bangladesh are dubious and unreliable (Brammer, 1993).

Strategic or applied sea-level research concerns the projection of the future sea level scenario, be it rise or fall, for any geographical region on the scale of decades and centuries, and its consequences for coastal dwelling populations. Such strategic studies rely on the results of fundamental or academic research, based on the collection of basic data from the field (Tooley, 1987). Any Environmental Impact Assessment (EIA) and future policy, whether at a local or national scale, can only be developed from a good quality data collected over an extended period, preferably from the recent geological record. During the last two decades considerable advances have been made in systematic sea-level investigation at different time scales. The methodology (Tooley, 1978a, 1978b, 1982; Shennan, 1983a, 1986b;) is well established and needs to be applied over a wider range of geographical settings, particularly in the tropical coastal lowlands. A successful application, for the first time, in Bangladesh would not only reveal the Holocene sea-level history of the country but would also suggest further new palaeoenvironmental issues to be studied. The present work could initiate and establish a new approach in Bangladesh for the investigation of its palaeoenvironmental history. This would be a development which could have far reaching effects for archaeologists, geologists, geographers and other environmental scientists.

1.5. OPERATIONAL DEFINITIONS

i. Mean Sea Level

In broad terms, mean sea level (MSL) is the surface level which the oceans and seas of the world would adopt if tidal forces ceased to operate (Doodson and Warburg, 1941). In practice, MSL is the average level of the sea surface, relative to a permanent land-based bench mark, taken over a period long enough to eliminate the effect of waves and tides (Lewin, 1991). The reliability of the value of MSL will depend on the length of the period of observation and the best result can not be obtained from observations which do not exceed at least one cycle of the moon's nodes, 18.6 years (Jardine, 1986). For Bangladesh, MSL is the average of tidal readings observed between 1858 and 1909 at Chittagong (EPWDB, 1967).

ii. Tide

Tide is the regular movement of the oceans and seas, generated by the gravitational attraction of the moon and the sun (Pugh, 1991). The vertical range between tidal low water and high water varies between spring and neap tide over a period of about 14 days. The duration of tidal cycle varies semi-diurnally, diurnally, monthly and even yearly, as has been observed since the establishment of the first tide gauge station in 1682 in Amsterdam.

iii. Mean Tide Level

Mean tide level (MTL) at any given location is the average value of all the levels of high water and low water at that location over a long period. The value of MSL and MTL of any location would agree only if the tidal curve of that location is perfectly symmetrical;

in practice MTL differs either positively or negatively from the MSL at a constant value but this constant value varies from one location to another (Jardine, 1986). In sea-level investigations there are some advantages of using MTL as a reference level rather than MSL. Jardine (1982) stated that unlike MSL it may be possible to determine the MTL of any location from the sedimentary and geomorphological records of former high tide, low tide and tidal range values, and can be used to construct sea-level curves.

iv. Mean High Water Spring Tide

The tides recorded shortly after new and full moon, when the earth, sun and moon are in alignment, and have a combined gravitational effect, are relatively large, and are known as spring tides (Bird, 1969). Mean High Water Spring Tide (MHWST) is ecologically an important reference level rather than MTL and has been widely used in Holocene sea level research (Tooley, 1974, 1978a, 1982; Kidson and Heyworth, 1979; Heyworth and Kidson, 1982; Devoy, 1979, 1982; Shennan, 1986b). Many sea-level indicators are derived from saltmarsh plants which normally grow around or immediately above the MHWST and are overlain or underlain by marine clastic sediments (Zong, 1993). Heyworth and Kidson (1982) have suggested that the interface between saline and freshwater, which at present occurs between MHWST and HAT, gives the best point for determining the former sea levels at any location.

v. Datum Level

Datum level of any country is the reference level above or below which the altitude of any given point is measured (Jardine, 1986). It should be noted that a datum level is the most useful reference level for national surveying of any country. In practice, the datum level is commonly chosen to correspond as closely as possible with MSL at the location that has been selected as the national reference station. For Bangladesh the reference datum level, GTS datum, coincides with MSL calculated from hourly sea-level readings at Chittagong between 1858 and 1909 (EPWDB, 1967). Another widely used datum is the Public Works Department (PWD) datum which is 0.46 m above GTS datum.

vi. Transgression and Regression

Mörner (1976a) used the terms 'transgression' to indicate a positive vertical movement in sea level and 'regression' to indicate its fall. In sea-level literature usage of these two words in a variety of contexts has led to much confusion. The use of transgression and regression are totally unsuitable as formal chronostratigraphic terms (Shennan, 1980, 1982b; Tooley, 1982). They are not synonymous with a rise and fall in sea level (Shennan, 1982b) and this is made clear by adaptation of the terms into 'transgressive overlap' and 'regressive overlap' (Streif, 1979a; Shennan, 1982a; Tooley, 1982; Zong, 1993). Transgressive overlap is a term to describe the change of lithostratigraphy from a semi-terrestrial to a brackish or marine deposit, and conversely, a replacement of marine or brackish deposit by semi-terrestrial deposits is defined as a regressive overlap (Shennan, 1982a; Long, 1991). However, the interpretation of 'peat above clay' and 'clay above peat' as regressive and transgressive overlap, respectively (Streif, 1979a) is problematic, when applied to sea-level movement. Haggart (1986) suggested that a regressive overlap could form during a period of rising relative sea-level if, for instance, peat growth outstripped the sedimentation of the marine or estuarine deposits. Similarly, a transgressive overlap could form during a period of relative sea-level still stand or fall if, for instance, the coastal geography or sediment supply altered to reduce the effectiveness of a pre-existing barrier. Zong (1993), however, suggested that transgression and regression should be considered as the process of marine or terrestrial events, whereas transgressive and regressive overlaps should be emphasized as changes in sediment type, provided, there is evidence of marine sedimentation on land or the reverse.

vii. Geoid

The geoid is the equipotential surface of the earth's gravity field, determined by the attraction and rotation potential (Mörner, 1976a, 1980). Cook (1972) recognised the geoid as the particular surface of constant geopotential, which over the sea, coincides with the MSL. Mörner (1976a, 1977, 1980) argued that the present geoid configuration is not stable and must have changed, ranging from a period of 10^7 yrs to some decades, with variation of gravity and factors controlling it. He also showed that, in the real ocean, there are 'bumps' (near New Guinea) and 'depressions' (near the Maldives) showing sea level differences, with respect to the earth's centre or a satellite orbit, of as much as 180 metres.

viii. Eustasy

The term eustasy embraces a worldwide, simultaneous change in sea level which is thought to affect the ocean globally. The eustatic level is, therefore, assumed to be parallel to the earth's ellipsoid. A heavily irregular geoid configuration, recorded from satellite data, suggests rough and uneven geodetic sea level and causes new facts to be considered. The old concept of eustasy and its validity must be accordingly changed. The vertical changes of sea level are probably valid only locally or regionally, as suggested by Mörner (1980). He, however, redefined eustasy as vertical ocean level changes regardless of their causation and implying vertical- global and local- movement of the ocean surface at a particular point.

ix. Relative Sea-level Change

Sea-level change is the departure of MSL from a stable reference point, the centre of the earth in theory or the geoid in practice. Records of sea-level changes are based either on regular instrumental measurements (tidal records) or on the interpretation of field evidence (geological records). Given a stable geoid in the short-term, at least on a local scale, sea-level change can be considered to be the net vertical change of the wave-smoothed surface of the sea over a period of time at a given locality. For the long term, such as the Holocene, a similar definition can only be applied to the derived sea-level change, provided the sea-level indicators relate or can be converted to the same reference level obtained from the same locality (van de Plassche, 1986a). In a situation, where sea-level change is evident but cannot be expressed quantitatively, the above definition is of little value. In such a case, sea-level change would be expressed as either a positive or a negative direction of change from a given reference level. van de Plassche (1986a) indicated that recorded sea level, resulting entirely from land level movement is referred to as 'apparent', whereas it is called 'real' (absolute) where no land level changes are involved at the recording station. Modelling studies by Walcott (1972), Chappell (1974) and Clark *et al.* (1978) provide supporting evidence for crustal instability. It is, however, more convincing to use the term 'Relative Sea-level Change' as the resultant of simultaneously occurring real and apparent sea-level changes (van de Plassche, 1986a). Mörner (1980) stated that relative sea-level changes are the combined function of crustal and eustatic changes.

1.6. THESIS OUTLINE

The development of research background, the selection of appropriate methodology, the presentation of empirical evidence and the interpretation of results are the four distinctive features of the thesis. These have been discussed in nine separate chapters (Fig. 1.2).

Chapter One has introduced the current research problem and its potential significance for future strategic research. The immediate research objectives- both primary and secondary- are also explained in this chapter.

Chapter Two provides an extensive review of the relevant literature on Bangladesh and the investigated sites so as to provide an up-to-date statement on the regional physical geography.

The emergence of sea-level research, its methodological development and the current conceptual debate are reviewed in Chapter Three.

Chapter Four describes the field techniques used in data collection, with particular attention to Troels-Smith's (1955) scheme of sediment description. Different types of laboratory techniques used in the research are also discussed.

Lithostratigraphic data from 47 boreholes collected from two sample sites are presented in Chapters Five and Six (Chapter Five for Panigati and Chapter Six for Matuail). The results of the pollen analysis, diatom analysis and radiocarbon dating of each site are also presented in their respective chapter.

All types of evidence, field and laboratory, are used in Chapter Seven to reconstruct the Holocene sea level history of Bangladesh. Also considered are the sources of potential errors.

The implication of the relative sea-level movements on Holocene coastal sedimentation, coastal vegetation limits, palaeo-river system, coastal dynamics and coastline shifting are discussed in Chapter Eight.

Chapter Nine concludes the thesis by considering to what extent the initial research objectives outlined in section 1.3 have been met, and by proposing some research themes for future investigation.

Chapter 2: BANGLADESH AND THE STUDY AREAS: A REVIEW

2.1. INTRODUCTION

The aim of this chapter is to give a brief account of the physical geography and geology of Bangladesh with a view to synthesise current knowledge on the area. This brief review will also help to further critical discussion in later chapters.

2.2. THE BENGAL BASIN

The Bengal Basin is one of the largest geosynclines in the world. It is formed by subduction of the north-east part of the Indian plate which started in the early Cretaceous (Banerji, 1981). The Basin is bounded on the north by the Shillong Plateau, on the west by the Indian Peninsular Shield and on the east by the Lushai-Naga Folded Belt (Alam, 1972). The southern limit of the Basin is uncertain however, based on geophysical evidence, Sengupta (1966) suggested that it is open to the Bay of Bengal for a considerable distance.

i. Geometry of the Basin

Based on aeromagnetic survey and geophysical analysis such as, seismic and gravitational data of different oil companies, some attempts have been made to explain the geometry of the Basin (Bakhtine, 1966; Sengupta, 1966; Alam, 1972; Desikachar, 1974; Banerji, 1981; MPO, 1986). Bakhtine (1966) classified the Basin floor into three principal zones:-

a). Pre-Cambrian Indian Platform

b). Bengal Foredeep

c). Sub-Himalayan Foredeep

a). The Pre-Cambrian Indian Platform is the shallowest part of the Basin and serves as a concealed connection between the Deccan Shield in the west and the Shillong Plateau in the north. It consists of natural basement, at a depth of only about 294 m near Dinajpur town (Desikachar, 1974). This platform is also termed the 'Garo Rajmahal Gap' by Sengupta (1966) or the 'Stable Shelf' by Alam (1972). It gradually slopes northward and also southward forming, respectively the 'Dinajpur Slope' and 'Bogra Slope', separated by the 'Bogra Saddle' (MPO, 1986).

b). The Bengal Foredeep is the deepest part of the Basin which is separated from the Pre-Cambrian Indian Platform by a well defined 'Hinge Zone' (Fig. 2.1). This Hinge Zone is a zone of faulting that extends north-eastward from Calcutta to Mymensing across the Basin and played a major role in the tectonic and depositional history of the Basin (Sengupta, 1966). Bakhtine (1966) further subdivided the Foredeep into the north-western 'Platform Flank', the major part of the Basin, and the eastern 'Folded Flank'. The geophysical data indicate a heterogenous structure of the Platform Flank and it is characterised by a Southwest to Northeast extended zone of uplift which runs through Barisal town. This zone was called the 'Barisal-Chandpur Gravity High' by Alam (1972) but the 'East Bengal Ridge' by Banerji (1981). The natural basement of the Platform Flank is at a depth of about 8.5 km near Khulna (FPCO, 1993) and about 18 km in the area of the Meghna estuary (Anwar, 1989; in Warrick *et al,*. 1993b). The eastern Folded Flank comprises the hill ranges of Chittagong and Chittagong Hill Tract.

c). The north-western part of the Indian Platform, i.e., the Dinajpur Slope, passes into the Platform Slope of the narrow Sub-Himalayan foredeep which separates the Indian

Platform from the Himalayas. The negative and zero values of the magnetic field here indicates a deeper occurrence of the basement as compared to the Platform Slope (Bakhtine, 1966).

ii. Tectonic Activities

Tectonically the Basin is active and is characterised by a number of well defined faults. Geological and geophysical observations reveal that parts of the Basin have been uplifted and subsided as a result of neotectonic activities beginning in the Pliocene (MPO, 1986). There are some important faults (Fig. 2.2) which cross the Basin. These, described by several authors, are the Dauki fault (Desikachar, 1974), Karatoya fault (Khandoker, 1987), Echelon faults (Morgan and McIntire, 1959), Malda-Kishanganj fault (Krishnan, 1982), Padma fault (Nandy, 1980) and the Meghna fault (Chowdhury *et al.*, 1985). Some of these faults seem to control the major river courses. The Jamuna river approximately follows the course of the Dubri-Jamuna fault (Fig. 2.2) which represents the 'Zone of Weakness' caused by subsidence (Morgan and McIntire, 1959). Sesoren (1984) also suggested that the Meghna river followed a further 'Zone of Weakness', the Meghna fault. The Malda-Kishanganj fault seems to control the entire courses of the Mahananda river (Krishnan, 1982). Faults associated with the uplift of the Barind and Madhupur Tracts, and the subsidence of the zone of weakness along the Ganges-Jamuna-Meghna rivers and the Sylhet Trough are still active. This probably indicates that isostatic adjustment between different blocks of the Basin has not yet been attained (Khandoker, 1987).

iii. Basin Evolution

The evolution of the Basin is associated with the collision of two continental plates, the Indian Plate and the Eurasian Plate, which resulted from initial subsidence of the Basin in the early Cretaceous soon after the Gondwana tectonism (MPO, 1986). The extended rate of plate motion in the early Oligocene resulted in the formation of the Indo-Burma range to the east and the ancestral Himalayas to the north. The uplift of the ranges caused regression of the sea and thus, a deltaic system began to develop in the newly formed Basin. Three major Himalayan orogenic disturbances during the Late Cretaceous, the Eocene and the Miocene, and the associated marine transgressions on the Basin during each disturbance suggest that the Bengal Basin subsided, keeping pace with the Himalayan orogenies (Alam, 1972). During these periods a large volume of clastic sediments was supplied to fill the Basin. From the Miocene to the Pliocene the Basin represented a major deltaic progradation towards the south-west and south (MPO, 1986). Most parts of the Basin are floored with Quaternary sediments eroded from the highlands on three sides and deposited by the Ganges, Brahmaputra and Jamuna rivers, and their distributaries. Except for three exposed remnants of the Pleistocene landmass, deposited by the early Ganges-Brahmaputra river system, the whole of the Basin has been filled with the sediments of the recent epoch, brought by the present day river system and forming one of the largest deltaic landmasses of its kind, the Bengal delta.

2.3. PHYSIOGRAPHY OF BANGLADESH

Bangladesh has an average elevation of only 7.6 m and has a southward slope of less than 10 cm per km (Mafizuddin, 1992). Broadly, the country can be classified into three simplified physiographic units viz., Tertiary Hills, Pleistocene Terraces and Holocene

Plains (Fig. 2.3).

i. Tertiary Hills

The Tertiary Hills (shown in dark-brown colour in Fig. 2.3) occupy the eastern and north-eastern hilly areas and cover 12 percent of Bangladesh (Brammer, 1996). The high hills (300 to 1000 m) of Chittagong and Chittagong Hill Tract regions are oriented in a north-south direction and have a series of parallel ranges. The synclines of these ranges are occupied by river valleys. The alignment of the rocks of these ranges indicates that the steep slope has a folded, faulted and dissected pattern (Mafizuddin, 1992). The lower hills of Chittagong, Comilla and Sylhet districts are less than 75 m high. These are highly dissected and manifested with sharp or rounded summits (MPO, 1986).

ii. Pleistocene Terraces

Three distinct blocks of Pleistocene Terraces, which cover about 8 percent of the territory (Brammer, 1996), are the characteristic features of Bangladesh's physiography. The Barind Tract, located in the mid-western part of Bangladesh, covers an area of about 7770 sq. km (Khan, 1991); its elevation is 22-43 m (Morgan and McIntire, 1959). The Tract represents an uplifted and locally tilted series of flat blocks (MPO, 1986) and the faulted area is occupied by streams. The landscape is rolling in the west and at its western edge, the Tract has been tilted upwards to stand 15-30 m above the adjoining Purnabhaba and Mahananda floodplains. The oval shaped Madhupur Tract, with an elevation of about 15 m (Khan, 1991), occupies an area of about 2558 sq. km (Rashid, 1991). Morgan and McIntire (1959) considered the Tract to be the ancient flood plain of the Ganges and Brahmaputra rivers. Islam (1978) stated that this landmass was deposited in a fresh water, shallow basin. Miah and Bazlee (1967) and Miah (1972) suggested that the Tract was deposited as the delta of the Brahmaputra which was later uplifted; they called it an 'Uplifted Delta'. The Tract is finely dissected, broken by faults, shows a dendritic drainage pattern and is still being actively tilted in a south-east direction (Khandoker, 1987; Mafizuddin, 1992). A remarkable characteristics of the Madhupur Tract is its abrupt western margin which separates the adjacent flood plain by a series of six echelon faults (Morgan and McIntire, 1959). Lalmai Hill, the third Pleistocene landmass, covering about 13 sq. km and with an altitude of about 55 m, is located near Comilla town (Morgan and McIntire, 1959). A detailed geomorphological description of the Hill is available in Hassan (1986). In Figure 2.3, the Barind and Madhupur Tracts are shown in pink colour.

iii. Holocene Plains

Apart from the above units, the entire country, about 80% (Brammer, 1996), has been formed by sediments of recent geological age. At the foot of the Himalayas, the extreme northern district of Dinajpur, parts of Rangpur, and north of Mymensing and Jamalpur districts, comprise the piedmont plain. It is composed mainly of sand, and river pebbles and cobbles, coarsely textured, slightly oxidized (Morgan and McIntire, 1959) and free from annual flooding. The flood plains of the Ganges-Brahmaputra-Jamuna-Meghna river systems cover approximately 40% of the country (Khan, 1991) and are seasonally inundated. The plain is characterized by curved ridges, saucer shaped basins (*haors*), swamps (*beels*), abandoned channels, ox-bow lakes, meander scars and cut-offs (Coleman, 1969). Natural levées are the distinctive geomorphic features along the river courses (Oya, 1977; Umitsu, 1985). Generally, the sandy and silty sediments are deposited on the levées and fine particles in the basins. The region south of the Ganges and west of the Arial Khan rivers (light green in colour, Fig. 2.3) is the mature delta. It is drained by the distributaries of the Ganges. The western half of the region is known as the moribund delta (Bagchi, 1944) and is characterized by rivers choked with sand, and unable to carry much water except when the Ganges has a high flow (Rashid, 1991). Bagchi (1944) argued that this moribund tract had been mostly built up by the spill water of the Bhagirathi and Padma (Ganges) rivers. The coastal belt along the southern regions, called the tidal floodplain, is under the direct influence of diurnal tides. The elevation of this tidal belt, which is further discussed in section 2.5, is within 3 m of the sea surface.

2.4. DRAINAGE SYSTEM AND HYDROLOGY

The Ganges, Brahmaputra-Jamuna and Meghna, and their numerous tributaries and distributaries have developed a complex drainage network within the delta, and are the arteries of the drainage system of Bangladesh. Out of about 1.56 million sq. km of these rivers' catchment, only 7.5 % lies within Bangladesh (Pramanik, 1983), the remainder being outside in countries like India, Nepal, Bhutan and China.

The mighty river Ganges originating on the south slope of the Himalayas and travelling about 2400 km through Indian territory enters Bangladesh near Rajshahi. At Gualando, the river joins the Brahmaputra-Jamuna (Fig. 2.3), another of the world's large rivers, which originates on the north slope of the Himalayas and travels about 2575 km within Tibet, China and India. The width of the Ganges varies from about 5 to 7 km (Islam, 1990) and that of the Brahmaputra-Jamuna from 9 to 16 km (Islam, 1989a); the average annual discharge of the Brahmaputra-Jamuna is 678,000 cusec or nearly twice than that of the Ganges (Coleman, 1969). The combined flow is called the Padma which has a confluence with the Meghna, the third largest river of the country, about 40 km to the south at Chandpur and the combined water flows into one of the largest river estuaries of the world, the Meghna estuary, about 20 km wide (Khan, 1991). There are several estimates of the sediment being carried by these three rivers annually to the Bay of Bengal; one such estimate is of 2.4 billion tons (Tarafder, 1975).

The rivers of Bangladesh often change their courses. Bagchi (1944) argued that the Bhagirathi, at present the westernmost distributary of the Ganges, was the earliest course of the main flow until the sixteenth century. He argued that the Mahananda and the other rivers of North Bengal used to meet the sea by flowing longitudinally from the Himalayas to the Bay prior to the eastern swing of the Ganges. Coleman (1969) stated that some 200 years ago, the Brahmaputra river flowed along the course which is now that of the old Brahmaputra river. Fergusson (1863), Hirst (1916), and Morgan and McIntire (1959) suggested that the diversion of the Brahmaputra into a new course, now called the Brahmaputra-Jamuna, was geologically controlled due to the uplift and tilting of the Madhupur Tract. LaTouche (1919) offered a different explanation and suggested that the diversion of the river course was hydrologically controlled due to severe flooding in 1787, a view accepted by Majumder (1941) and Rashid (1966). Situated at the lowermost reaches of these three large rivers, the catchments of which have a heavy monsoon rainfall means that floods, occasionally devastating in nature, are common annual events in Bangladesh.

2.5. THE COASTAL BELT

The coastal belt is a 'zone of varying width and includes the shore and the landward limit of penetration of marine influence whether that is the foot of a cliff, the head of a tidal estuary or the solid ground that lies beyond coastal dunes, lagoon and swamp' (Bird, 1969). The land-sea interface is composed of a series of boundaries or gradients which are not constant but change in time and space, sometime slowly, sometime rapidly (Boaden and Seed, 1993). The 654 km long (Sned, 1985) coastal belt of Bangladesh (Fig. 2.4), from the Indian border in the west to that of Myanmar in the east, includes a number of important features, such as two of the country's major port cities in Chittagong and Khulna, the major tourist beach at Cox's Bazaar, the world's biggest mangroves forest- the Sundarbans (see section 2.6), numerous islands including a coral island- St. Martin, and extensive shrimp farms and agricultural areas. The exact landward limit of the coastal belt is difficult to define. The Study of Multiple Cycle Shelter Programme (SMCSP) by UNDP (1992) has considered approximately the 3 m contour line as the northern limit of the belt which occupies about one quarter of the national territory and 30 million people (Broadus, 1993). This area is of great concern to the scientists and policy makers.

i. Coastal Regions and Their Geomorphology

The coastal geomorphology of Bangladesh is characterized by its funnel shaped, vast network of rivers, strong tidal and wind action and enormous river discharge laden with bed, and suspended sediments. During the last fifteen years, the application of remote sensing technique (Pramanik, 1983; Jabber, 1979, 1992; SPARRSO, 1987) has facilitated the understanding of coastal geomorphology and coastal processes. Most of the information regarding the coastal zone can be found in the files of the former Land Reclamation Project of BWDB. Based on the available information, Pramanik (1983) has divided the coastal belt of Bangladesh into three distinct regions namely, the Eastern Region, the Central Region and the Western Region (Fig. 2.4).

a). The Eastern Region

This region comprises a narrow strip of plainland between the Chittagong Hills and the Sea, together with the flood plains of the Halda, the Karnafully and the Sangu rivers. This coast is regular, unbroken and not very susceptible to erosion (Mafizuddin, 1992), and is protected along the sea by mudflats and submerged sands. Important geomorphic landforms are sandy beaches, coastal dunes and mud flats. A continuous strip of sand has formed a long sand beach, one of the tourist attraction of the country, the Cox's Bazaar beach.

b). The Central Region

The central region occupies the tidal plains of the Meghna estuary covering the districts of Patuakhali, Barisal, Bhola and Noakhali. The coastline is most irregular, highly broken and consists of a series of islands (*char*) formed by the deposition of sediment. Some of these *char* are less than 30 years old; the older parts of Sandwip, Hatia and Ramgati *char* are in parts as much as 200 years old (FAO, 1988).

c). The Western Region

This region consists of the district of greater Khulna and part of Patuakhali. The coastline in general, is transverse to the structure of the continental margin. The area is relatively stable, mostly covered by mangroves forest and is characterised by a criss-crossed pattern of tidal rivers and tidal creeks. The significant geomorphic features are tidal flats, mangrove swamps, natural levées, sandy beaches, dunes and beach ridges (Khan, 1990).

ii. Tides on the Bangladesh Coast

BIWTA has established a network of 48 tide gauge stations along the coastal belt and is solely responsible for preparing the annual Tide Tables for Bangladesh. In addition, BWDB, CPA and MPA also have tide gauges within their own jurisdiction for specific projects. Records from these coastal tide gauges allow to a certain degree, an understanding of the tidal behaviour along the coastal belt.

Tides along the Bangladesh coast originate in the Indian Ocean but the funnel shape of the Bay of Bengal increases their speed and height. The tides travel very quickly through the two submarine canyons, the 'Swatch of No Ground' and the 'Burma Trench', and arrive at Hiron point, the southwest extremity of the Sundarbans and at Cox's Bazaar, the southeast coast, at the same time (Miah, 1989; Khan, 1986). In Bangladesh tides are semidiurnal in character, having a periodicity of 12 hours 25 minutes. The tidal range shows roughly an increase from the west towards the Meghna estuary where it achieves its maximum and then decreases south-eastward (Table 2.1).

iii. Coastal Dynamics

Tides play an important role in coastal sedimentation by producing a region of reduced turbulence or standstill water where they meet a river current. This provides conditions favourable for sediment settling (Pramanik, 1983).

Table 2.1:

Mean Tidal Range on the Bangladesh Coast (m)

Stations	Mean Spring Tide	Mean Neap Tide	Mean
Hiron point	2.41	1.01	1.71
Mongla	2.65	1.28	1.97
Khepupara	2.36	1.05	1.71
Barisal	1.14	0.62	0.88
Ramadaspur	2.38	1.23	1.81
Charchinga	2.92	1.31	2.12
Chandpur	1.14	0.67	0.91
Sandwip	5.03	2.31	3.67
Chittagong	3.51	2.07	2.79
Cox's Bazaar	3.05	1.22	2.14
St. Martin	2.68	0.98	1.83
Average	2.66	1.25	1.96

(Sources: Pramanik, 1983; Khan, 1986)

The central coastal region is very dynamic. Through the Meghna mouth about 2.4 billion tons of sediments (Tarafder, 1975) of the combined Ganges-Brahmaputra-Meghna river system are flowing on to the continental shelf. Miah (1975) studied the coastal dynamics of the estuary and concluded that here both erosion and accretion rates were significantly high. Similar conclusions were also derived by Jabber (1979) and Pramanik (1980). Alam and Rahman (1982) indicated a high sediment discharge at the estuary which had greatly been influenced by the ocean and the tidal current, particularly the ebb tide. Jabber (1992) reviewed all available maps, aerial photographs, landsat images and published-unpublished reports. He concluded that the processes of major accretion and erosion remain confined to the Meghna estuary and during the last 200 years the coastline has not extended significantly towards the Bay as it should have, despite the huge supply of sediment.

The eastern and western coastal regions are comparatively less dynamic. In the south-east, along the Chittagong coastal belt, Mafizuddin (1992) indicated that deposition took place only to a limited extent. In the western region, the rivers are mostly tidal and get little fresh water discharge from upstream, particularly during the dry season. Due to reduced water discharge from the Ganges, after the installation of the Farakka barrage in India, the western coastal region is under the threat of saline water intrusion (Islam, 1989b). There the interface between fresh and saline water already appears to lie about 120-160 km inland (Fig. 2.5) whereas in the east (Miah, 1989) it is in close proximity to the shore. In this western part, accretion does not occur much, being mostly concentrated at a few points. For example Khan (1990) reported a considerable progradation of the delta plain in Barguna district. He argued that the width of the tidal channel plays an important role in the process of accretion and erosion in this area.

iv. Storm and Tidal Surges

After devastating floods in 1987 and 1988, Bangladesh again received international attention and sympathy when an 8 m storm surge crossed the Bangladesh coast on 29 April, 1991 and killed 138,000 people (Haider *et al.*, 1991) in just a few hours. In a similar way, on 12 November, 1970, more than 200,000 people were killed by a 9 m storm surge (Flierl and Robinson, 1972).

The Bay of Bengal is the breeding ground for tropical storms and depressions. An average of 1.5 severe cyclonic storms hit the country each year and associated storm surges as much as six metres higher than normal, can reach as far as 200 km inland along the water ways (Murty *et al.*, 1986). In Bangladesh alone, about 40% of the total number of global storm surges are recorded (Murty, 1984).

A storm surge is generated in the Bay of Bengal, either during pre-monsoon or post-monsoon seasons, due to variations in atmospheric pressure. When such a surge approaches the continental shelf bordering the Bay, the main contribution, acting over shallow water, comes directly from the wind (Murty *et al.*, 1986). The wind speeds rarely exceed 160 km hr^{-1} but the highest recorded was 225 km hr^{-1} during the storm surge of 1970 (Stoddart and Pethick, 1984). The interaction of storm surges and high tides heightens the danger of damage from the surge, as was the case in 1970 and 1991. The funnel shaped configuration of the coastline amplifies the tides and surges at the head of the Bay, especially on the Meghna estuary. Some common cyclonic paths are shown in Figure 2.5.

2.6. MANGROVES FOREST

Mangrove formations are described as 'Mangal' (MacNae, 1968; Chapman, 1976) leaving the term mangrove for the individual species (Chapman, 1977; Grindrod, 1988). In Bangladesh, mangroves provide the coastal tropical formation found along the border of the sea reaching as far up the rivers banks to the point where the water is still saline, growing in swampy soils and covered by the sea during high tides (Blasco, 1975).

Frequency and duration of flooding, the nature of the soil as to whether it consists of sandy or clayey mud deposits, and the degree of admixture of saline and fresh water at the river mouth are the three environmental factors which determine mangroves growth, development and zonation (Walter, 1971). MacNae (1968) argued that mangroves would occur only along protected sedimentary shores. Wakushima *et al.,* (1994a, 1994b) suggested that the growth and zonation of mangroves are regulated by salinity and pH. Local topography and high precipitation are also favourable for the extensive growth of mangroves formation (Boaden and Seed, 1993). A high wave energy and a dynamic coast is not favourable for germination and survival of mangroves vegetation (MacNae, 1968).

Extensive mangrove ecosystems occur in areas on the west coast of Florida, the Ganges-Brahmaputra delta, Andaman and Nicobar Islands, the coast of Sumatra, Borneo and Papua New Guinea, and the deltas and estuaries of Queensland and the Northern Territory of Australia, and similar locations in east and west Africa. Chapman (1977) has classified the Bengal mangroves as the 'Indo-Malesian Mangal Group'.

i. The Sundarbans

The southwestern part of the Bengal delta is covered by a belt of extensive and dense mangroves forest, the Sundarbans (Fig. 2.4). One of the earliest description of the forest was made by Rainey (1891). Prain in 1903 made a detailed account of the forest and reported from the Sundarbans and adjoining areas a total of 334 species, belonging to 245 genera of Spermatophytes and Pteridophytes. Other significant attempts have been made to describe the ecology of the forest (e.g. Champion, 1936; Blasco, 1975, 1977; Chapman, 1976; Chaffey and Sandom, 1985; Mukherjee, 1992; and Karim, 1988, 1994).

The Sundarbans forest cover a coastal belt with dimensions of about 175 km in length and 60 km in width (Blasco, 1975). They belong to two countries, with about 6000 sq. km in Bangladesh and about 2000 sq. km in India (Blasco, 1977). The major vegetation types of the present day Sundarbans forest are *Heritiera fomes* (sundari)[1], *Excoecaria agallocha* (gengwa), *Sonneratia apetala* (keora), *Rhizophora mucronata* (big goran), *Xylocarpus mekongensis* (passur), *Avicennia marina* (baen), *Bruguiera gymnorhiza* (kankra), *Xylocarpus granatum* (dhundol), *Amoora cucullata* (amur), *Aegiceras corniculatum* (khalshi), *Ceriops decandra* (goran), *Acanthus ilicifolius* (Hargoza), *Nypa fruticans* (golpata), *Phoenix paludosa* (hetal) *Pandanus foetidus* (kewa) and *Acrostichum aureum* (udoban).

Heritiera is the dominant tree followed by *Excoecaria* (Chapman, 1976; Mukherjee, 1992). Chaffey *et al.* (1985) stated that *Heritiera-Excoecaria* forest type covers the largest

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[1] The names within the parentheses are the vernacular names of the mangroves of Bengal (Chaffey and Sandom, 1985)

area (29.4%), followed by pure *Heritiera* (21%), *Excoecaria-Heritiera* forest type (14.8%) and *Ceriops-Excoecaria* (14.6%), respectively.

ii. Mangroves Zonation

Unlike many other mangroves forest (Boaden and Seed, 1993), the mangroves of the Sundarbans are not apparently in zones but, when the entire forest is considered (Mukherjee, 1992), it forms a mosaic which is related to the local topography. Karim (1988) divided the forest from east to westward into three horizontal salinity zones (Fig. 2.6), oligohaline, mesohaline and polyhaline. Each zone is delineated by distinctive physiographic units viz., mudflat, backswamp, and levées (Blasco, 1975, 1977; Karim, 1994), each characterized by inundation and water supply of differential salinity. There is, as a result, a very complex vegetation composition.

iii. Vegetation Patterns

Mudflats are formed along the estuaries or along the river banks and are subjected to direct wave action, flow and turbulence of the river current, and daily tidal inundation. This geomorphic unit is dominated by *Nypa fruticans, Phragmites karka, Porteresio coarctata, Acanthus ilicifolius, Sonneratia apetala* with sparsely distributed *Excoecaria agallocha* and *Ceriops decandra*. The levées along the river courses are 5-15 m wide (Karim, 1994) with a steep gradient towards the channel side. Characteristic vegetation types are *Nypa fruticans, Saccharum sponteneum, Pandanus foetidus, Sonneratia apetala, Avicennia officinalis, Rhizophora mucronata* with associated *Excoecaria agallocha, Amoora cucullate* and *Xylocarpus*. Backswamp, the low lying and saucer-shaped depression in between tidal creeks, are dominated by *Heritiera fomes, Excoecaria* *agallocha, Amoora cucullata, Bruguiera gymnorhiza,* and *Ceriops decandra*. A physical description and habitat of each mangrove species is given in Appendix-1, and its salinity tolerance in Figure 2.7.

iv. Vegetation Succession

Chapman (1976) suggested that on newly created land at the mouth of the tidal river *Sonneratia apetala* is the primary colonist followed by *Avicennia marina* and later *Excoecaria agallocha*. *Heritiera fomes* is the climax of the succession stages. The model proposed by Karim (1994) shows an approximately similar succession in different saline regimes: it also relates the vegetation succession of the Sundarbans to tidal height (Fig. 2.8). The *Heritiera-Excoecaria* forest type precisely shows its relation to the maximum high water mark during the dry season (MHWD) or 20 cm inundation during MHWST. The vertical range of this tidal level may vary in different geomorphic units (Fig. 2.9) but careful examination of all proposed vegetation profiles given by Karim (1994) suggests that the *Heritiera-Excoecaria* forest type can be used as a precise indicator to locate the MHWST at ± 10 cm error limit.

2.7. THE CONTINENTAL SHELF

The continental shelf of the Bay of Bengal is rather narrow except south of the Bengal delta where it can be as much as 150 km wide (LaFond, 1966). Sounding data show that the continental slope starts at about 80 m datum line in the estuary (BIWTA, 1982). The area up to 12 metres depth covers about 18,000 sq. km (Jabber, 1979) and about 41,000 sq. km when the area up to 100 fathom (182 m) depth is considered (Islam, 1975).

i. The Swatch of No Ground: A Submarine Canyon

One of the characteristic topographic feature of the continental shelf is the presence of a submarine canyon, the 'Swatch of No Ground'(SNG) (Fig. 2.1). It crosses the continental shelf diagonally in a south westerly direction and has a seaward continuation up to 2000 km into the Bay of Bengal. At the head, the SNG appears to have a depth of 80 m, cut the shelf to a depth of as much as 910 m below the adjacent sea floor and has, on average, a wide of 16 km (Chowdhury *et al.*, 1985). The origin of the SNG is not yet fully understood. It is suggested that it was created by turbidity current (Fergusson, 1863: Lloyds, 1938). Chowdhury (1959) argued that the SNG had been the estuary of the Ganges-Brahmaputra river system during the lowest sea-level of the Pleistocene glaciation; the formation is structurally controlled and is related to the Barisal-Chandpur gravity high (Chowdhury, *et al.*, 1985). The tidal current, sediment movement, deposition and other hydromorphological processes along the shelf region of Bangladesh are greatly influenced by this SNG.

2.8. SITES INVESTIGATED

After initial reconnaissance sampling at 8 sites in the country, discussed in section 4.2, two sites, at Panigati and Matuail were selected for further study.In this section, a brief account of the geological background and the nature of the physical and social geography of the two investigated sites will be given.

i. Site One: Panigati

The site at Panigati, about 12 km north-east of Khulna city, is situated about 100 km inland and located in between two tidal rivers, the Bhairab and Atai (Fig. 2.10).

Geologically the site has never been recorded. Some unpublished (Khan, 1957; Khalequzzaman, 1968; Hasan *et al.*, 1984; Ali *et al.*, 1992; Khan, 1993) and one published report (Zaher, 1962) of GSB[1] on surrounding regions give some account of geological mapping. A significant contribution to the study of the Quaternary history of the region has been made by Umitsu (1987, 1993).

Alam *et al.* (1990) have mapped the area at the interface between the tidal deltaic deposits on the south and the deltaic silt on the north. East of the site, immediately east of the Atai river, is the grey or bluish-grey clay and black herbaceous peat bogs. Tectonically the area is within the north-western part of the Faridpur Trough (gravity low) of the Bengal Basin (Fig. 2.1). In the seismic zoning map of Bangladesh the site falls within Zone-III (Fig. 2.2), the Low Risk Zone (CEEHM, 1979). This part of the Basin is thought to be constantly subsiding due to crustal downwarping and the compaction of recent sediments. The regional surface topography is very gentle; the southward slope varies from 1:6000 to 1:10000 (FPCO, 1993).

The studied area can be characterized into three geomorphic units, natural levées, flood plain, and backswamp. Natural levées are well developed along the river banks (Umitsu, 1985). The surface of these levées is about 2-3 m above than the backswamp and mostly occupied by human settlement. The flood basin is relatively broad, a more or less flat to trough like plain, fringing the natural levées and extending up to the backswamp. The backswamp is the lowest part of the area characterized by nearly flat topography, poorly

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[1] It is surprisingly very difficult to get access to GSB unpublished reports; the author thanks those who helped him to get the copies and requests the authority to change their policy.

drained and has a longer period of water logging than the flood basin. The general topography of the investigated area is like a saucer and is only about 2.0 m above the present MSL. The entire area is seasonally inundated during the monsoon period and becomes dry during the winter.

The area is characterized by a typical tropical monsoon climate with high temperature, heavy precipitation and excessive humidity. At Khulna the temperature ranges from about 8°C in winter to 37°C in summer and the average annual rainfall is 1734 mm (BBS, 1993).

The area is densely populated and is typically rural in nature. Panigati and Pir Hazirgram are the two villages immediately southwest and southeast of the site. The villages are connected to each other by unmetalled roads, made high enough to be above the seasonal flooding level (see Fig. 5.1). Two canals (*Khal*), the Kachubeel *khal* and the Mathabhanga *khal*, cross the site northwest to southeast and east-west, respectively. The entire area is within the Barakpur-Digholia FCD project, operated by BWDB which includes 20 km embankment, 19 km excavated *khal* and 4 drainage regulators (BWDB, 1984).

ii. Site two: Matuail

The site at Matuail, about 3 km east of Dhaka city, is located about 200 km inland and is in between the Balu-Lakhya river on the east and the Buriganga river on the southwest (Fig. 2.11). The Dholai *khal* provides an important drainage along the western side of the area.

Khan *et al.* (1990) have mapped the area. It consists of marshy clay and a peaty layer, and is bounded by medium to dark grey silt and clay on the north, light to medium grey alluvial silt on the east and south, and light brown Madhupur clay residual on the west. Some attempts (Morgan and McIntire, 1959; Miah and Bazlee, 1967; Alam and Aurangzeb, 1975; Khandoker, 1987; Alam, 1988; Monsur, 1990; Khan *et al.*, 1991; Rashid, 1993) have been made to describe the regional geology.

The site being located at the southern fringe of the Madhupur Tract is tectonically influenced. The emergence of the Madhupur Tract is associated with faulting and uplifting (Morgan and McIntire, 1959; Miah and Bazlee, 1967; Alam, 1988). On the southeast, the Tract is delineated by a basement controlled fault zone (Chowdhury *et al.*, 1985), a 'zone of weakness' passing between the Madhupur Tract and Tippera surface through the Meghna river at the northeast and Ganges tidal floodplain at the southwest (Sesoren, 1984). A number of faults with N-S, E-W, NE-SW and NW-SE trends control the courses of both major and minor rivers (see Alam and Aurangzeb, 1975; Alam, 1988; Rashid, 1993). The northern blocks defined by the Pagla and Buriganga faults form an upthrown area while the zone south is downthrown. Similarly, the west block of the Balu fault along the Balu river is the upthrown area and the eastern, the downthrown, suggesting that the investigated site lies within the uplifted blocks of the Madhupur Tract.

The surface physiography of the site is slightly undulating due to the underlying Madhupur Tract which is exposed in some places adjacent to the sample site. This lowlying flood plain of the Buriganga-Lakhya rivers is poorly drained, remaining water logged and marshy over a considerable period of the year. Being located outside the DND (Dhaka-Narayanganj-Demra) FCD project, the area is deeply flooded during the monsoon season. The regional temperature varies from 10°C in winter to 39°C during summer and the annual precipitation is about 1850 mm (BBS, 1993). Despite its proximity to the capital city and its location within the Dhaka Metropolitan Area, the urban zone gives way very abruptly to a rural land use immediately to the west and south of the site.

Chapter 3: SEA-LEVEL RESEARCH: A REVIEW

3.1. INTRODUCTION

Present concepts, theories and methodologies of sea-level research have evolved due to the combined efforts made by many sea-level scientists. Sea-level literature, theoretical and empirical, has been increasing rapidly, both in quality and quantity, in recent years. The aim of this chapter is to provide a brief review of the history of sea-level research up to the present.

3.2. PROCESSES OF RELATIVE SEA-LEVEL CHANGES

The processes of relative sea-level changes over time are complex and the nature and magnitude are directed by a number of interdependent variables which operate globally, as well as regionally and locally. Some of these variables are geologically and astronomically induced and some are introduced or at least accelerated by human beings (Gornitz, 1995).

i. Geological Components of Sea-level Movement

a). Glacial Components

It is held that, after the retreat of the ice-sheet following the last glacial maximum, the melt water increased the volume of the global oceans- the eustatic sea-level rise. This climatically controlled movement of water from land to the oceans, under the condition of glaciation and deglaciation, has been described by Daly (1920) and defined as glacio-eustasy by Fairbridge (1961). The sea-level was 121 ± 5 m below the present (Fairbanks, 1989) at the last glacial maximum, but it began to rise rapidly at a rate of 20-34 mm yr^{-1}

(Tooley, 1978a) between 10000 and 7000 BP[1]: the major contributor was the meltwater. Clark *et al.* (1978) concluded that during the last 5000 years there has been very little change of eustatic sea-level, perhaps less than 0.50 m, suggesting less significance of glacial components in present day eustatic sea-level movement (also see in section c.).

b). Isostatic Components

Globally uniform rise of sea-level would have only be possible on a rigid earth. The glacio-eustatic components indicate non-uniform sea-level movements relative to the land (Walcott, 1972; Clark *et al.*, 1978); this is based on the fact that the earth is not a rigid mass. After deglaciation, areas once depressed by glaciation began to undergo rebound to the position before glaciation. The process of re-equilibrium and equilibrium of the earth crust is termed iso-eustasy (Mörner, 1987). The consequences of isostatic components on sea-level movement would be expected even at a large distance from the deglaciated areas. Walcott (1972) demonstrated submergence of areas, peripheral to the ice-sheets, as resulting from isostatic adjustment. Flemming (1982) and Shennan (1989) have recorded post-glacial crustal downwarping throughout south and southeast England and isostatic uplift in northern England and mainland Scotland. Mass transfer from land to ocean not only distorts the solid surface of the earth; the depth of the ocean floors would also be deformed due to the addition of meltwater: the process termed as hydro-isostasy (Bloom, 1967; Pirazzoli, 1991). Clark *et al.* (1978) demonstrated the problem of ice unloading and ocean loading, and divided the oceans into six predicted zones (Fig. 3.1), as the result of the deformation of the earth surface. Four zones (I, III, V and VI) have been considered to be emergent and two zones (II and IV) submergent.

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[1] The 0 BP (Before Present) starts from AD 1950

c). Geodetic Components

Walcott (1972) suggested that the earth behaves as an elastic and viscous material to applied stress. As the ice melts on the surface of the earth and matter within the earth flows to compensate for the changing surface-mass distribution, the confined mass transfer affects the geoid (Clark *et al.*, 1978). Mörner (1976a, 1980) has recognised the variation of the geoid in space and time, and suggested that the combined effect of the horizontal and vertical movement of the geoid would produce significant variation on sea-level movement. In simple terms, eustasy means 'ocean level changes' which are, in fact, nothing other than geoidal changes. Mörner (1976a) used the term geoidal-eustasy as the ocean water distribution or geoid relief deformation. The acceptance of the concept of deformed geoid configuration would mean that eustasy as a world-wide phenomenon could no longer be valid and there must have been significant regional differences (Kidson, 1982). Mörner (1987) concluded that no sea-level could strictly be global and each region needs to define its own 'eustatic' curve which could then be used for comparison with other regions to solve the problems related to the behaviour of the crust and mantle (Tooley, 1993).

d). Tectonic Components

Tectonic components comprise all crustal deformations of endogenic origin which may result in subsidence and uplift of wide areas. Jelgersma (1961) recognized tectonic movement as an important variate to land/sea movement particularly in mobile belts and in areas recovering from isostatic downwarping. Fairbridge (1961) identified tectonic activities as a component of sea-level change which he defined as tectono-eustasy: it may have local, linear, regional and even ocean wide implications. Pirazzoli (1991) stated that important vertical movements of land can be due to tectonic phenomena, at a time scale varying from a few seconds to several million years.

e). Oceanic Components

Ocean basin volume, controlled by vertical and horizontal earth materials movement and ocean water volume, determined by climatically-induced glaciation and deglaciation, are two significant variables in eustasy (Mörner, 1976a). The volume of the ocean can be modified because of changes in plate divergence, plate emergence, volcanic activities, marine sedimentation and isostatic adjustment of the earth's crust. Fairbridge (1961) believed that the addition of sediment, which reduces the ocean volume, causes upward displacement of water; a positive movement which he termed 'sedimento-eustasy'. Sediment loading, particularly in coastal lowlands and deltas, not only causes sediment-isostatic readjustment and subsidence but also creates an equilibrium between land-level and sea-level movements. Some minor additional factors such as the addition of juvenile water from volcanoes and changes of water volume of the ocean following upon the expansion and contraction of water mass due to temperature and salinity, as suggested by Fairbridge (1961), may also make a contribution to sea-level movement.

ii. Astronomical Components of Sea-level Movement

Astronomical components operate in the sea-level movement, particularly on a geological time scale, and so need to be fully understood. Material transfer between land and sea, and the deformation of the geodetic configuration have the potential to change the earth's motion and shape as a whole, and those in turn, may be related to gravitational and rotational variations (Fairbridge, 1961). Such variations include changes in the earth's rate of rotation and the tilt of the rotational axis (Barnett, 1983; Mörner, 1988; Sabadini *et al.*, 1990). Peltier (1987, 1990) argued that the duration of a variation of the tilt would have the equivalence of palaeoclimatic change. Fairbridge (1961) suggested that any changes in the angular velocity and rotation of the earth would result in differential sea-level change between the equatorial belt and the poles. Munk and Revelle (1952) argued that changes in the post-glacial ice-sheets would result in changes to the length of day and the position of the pole, producing a variation in sea-level movement. They concluded that an increase of the length of day by 0.06 milliseconds per century would raise the sea-level of 10 cm due to ice melting. Fairbridge (1961) also recognized the effect of the variation of length of day on sea-level oscillations. A small change of position in the earth's instantaneous pole of rotation is highly sensitive to the changes in the amount of polar ice and its position (Barnett, 1983, 1990). Munk and Revelle (1952) concluded that a 10 cm rise in sea-level, if added to by melt-water from Greenland and Antarctica, would displace the pole of rotation towards 60°W: the pole of rotation is, therefore, a remarkably sensitive indicator of the process of melt-water induced sea-level movements.

iii. Oceanographic Components of Sea-level Movement

Sea-level movement, on a short time scale, is primarily the function of oceanographic, meteorological and hydrological factors, such as wind stress, atmospheric pressure, ocean current, temperature, salinity, precipitation, river discharge and tidal forces (van de Plassche, 1986a; Matin and Hossain, 1992). The operation of such components is clearly observed in instrumental records, such as come from tide gauges and satellites (SEASAT and GEOS 3), and also from physical and oceanographic studies. Deep atmospheric depressions, strong winds and local hydrodynamic phenomena can cause a local relative rise of sea-level (van de Plassche, 1986a; Pirazzoli, 1991). Variation in atmospheric pressure, ocean temperature and water density can change the ocean surface by 2-3 m in confined epicontinental seas (Mörner, 1984). Stress derived from wind, depending upon the local direction to coast, may induce either a rise or a fall of relative sea level depending on whether the winds are onshore or offshore, respectively (Peltier, 1987). This may have an eustatic significance if it is associated with climatological components over a longer time scale. Barnett (1990) suggested that in the northern hemisphere sea level would be higher in the central part of the ocean's gyres because of the general geotropic balance of the clockwise circulation of the current system with the opposite effect in the case of a counter-clockwise circulation: in the southern hemisphere the mechanism would be the opposite. The El Nino-Southern Oscillation (ENSO) phenomenon, over several years timescale, is extremely important in climatic variation (Thompson, 1995) and contributes to sea-level change significantly. Such fluctuation is baroclinic (Peltier, 1990), derived from steric effects, due to the incursion of equatorial warm water into the cooler water of oceans at higher latitudes. This can induce a variation in the ocean surface by 50 to 150 mm (NRC, 1990). Rare events, such as storms, cyclones and more particularly storm surges (Lisitzin, 1974; Rossiter, 1962) can raise sea level several metres higher than their normal. Possibly the most dramatic changes of relative sea-level are associated with tsunamis, the water waves generated by earthquakes (Shi *et al.*, 1995). These waves can vary in amplitude from 1 cm in the open ocean to tens of metres in shallow seas surrounding distant islands and coastal sites (Peltier, 1987).

iv. Greenhouse Components of Sea-level Movement

Watson *et al.* (1990) stated that since the industrial revolution the atmospheric concentration of greenhouse gasses, such as CO_2 (carbon dioxide), CH_4 (methane), N_2O (nitric oxide), O_3 (tropospheric ozone), H_2O vapour and aerosol, has been increasing, primarily due to human activities, such as fossil fuel burning and changes in land use as a result of deforestation and the expansion of agriculture. CO_2 concentration of 280 parts per million by volume (ppmv) in 1880 has risen to 354 ppmv in 1990, an increase of about 25%, and currently rising at a rate of about 1.8 ppmv per year (0.5%) due to anthropogenic emission (Watson *et al.*, 1990). Sundquist (1990) assumes that the CO_2 content of the air would be 800 ppmv around AD 2160 which would only be possible if the current production of 6 billion tons of carbon per year is increased to 9 billion tons, 50% higher than present rate (NRC, 1990). An increase of atmospheric CO_2 would affect the earth's radiation budget and thus, lead to global warming (Bolin *et al.*, 1986a). The current atmospheric CH_4 concentration is 1.72 ppmv, more than double that of the pre-industrial period (Watson *et al.*, 1990), and is currently increasing at a rate of 0.6 to 0.8% per annum (Warrick *et al.*, 1993a). Similarly, other greenhouse gasses have been increasing since the mid-eighteenth century (Table 3.1) and that it is believed to be the result of human activities, such as solid waste disposal and agricultural practice. Since increased concentrations of CO_2 and other greenhouse gasses lead to global warming, they would have consequences for sea-level change. The connection between global atmospheric warming and the behaviour of the ocean surface would mean an increase in ocean water volume due to the acceleration of the ice melting process in Greenland and Antarctic (Clark and Primus, 1987), and also by thermal (steric) expansion of ocean water (Gornitz *et al.*, 1982; Warrick and Oerlemans, 1990). Wigley (1989) has

Table 3.1:

Pre-industrial and 1990 Concentrations of Major Greenhouse Gases and Their Recent Annual Growth

	Carbon Dioxide	Methane	Nitrous Oxide	CFCs
Pre-industrial Concentration	280 ppmv	800 ppbv	288 ppbv	nil
Concentration in 1990	354 ppmv	1720 ppbv	310 ppbv	CFC11=280 pptv CFC12=484 pptv
Recent Annual Growth rate	0.5%	0.6-0.8%	0.2-0.3%	CFC11=4% CFC12=4%

Source: Warrick *et al.*, 1993a

ppmv= Parts per million by volume, ppbv= Parts per billion by volume, pptv= Parts per trillion by volume demonstrated a trend in global temperature rise by at least 0.5°C between 1958 and 1989 and that coincides with the increase of CO_2 by about 8% between 1958 and 1984 (Bolin *et al.*, 1986b). The IPCC (Houghton *et al.*, 1990) scenario of greenhouse gas emissions indicates that global temperature would be 3.3°C higher by the end of next century, with a range of uncertainty of 2.2 to 4.9°C. Frei *et al.* (1988) estimated that the rise in sea level caused by the steric effect would be 10 to 50 cm during the next century and from ice-melt water- the most likely scenario- it would be 55 cm (NRC, 1990): together they could subsequently raise the global sea-level to 1 m (Houghton *et al.*, 1990) or in between 1.44 and 2.17 m (Hoffman *et al.*, 1983). It must be borne in mind, however, that the very 'noisy' instrumental records upon which such interpretations and projections are based need to be very carefully and critically considered.

The understanding of sea-level movement, whether caused by natural processes or induced by human interference, is neither easy nor straight forward. The processes which are responsible for causing variations in sea level- globally, regionally or locally- are clearly related to the timescale over which the change occurs. Understanding the time-space variables operating in the sea-land relationship should, therefore, be based upon sound empirical and theoretical investigations.

3.3. EMERGENCE OF SEA-LEVEL RESEARCH

The occurrence of variations in sea level has been recognised over a long period; the cumulative evidence in early Indian literature, Tamil and Sanskrit, bear witness to it (Panikkar and Srinivasan, 1971). Changes of land level to sea level, and *vice-versa*, were documented as early as the eighth and ninth centuries in China (Zong, 1993). In historic time, such events began to be noted and collected, and sea-level change emerged as a distinct research focus.

The earliest attempts to understand the cause of sea-level change derive, in the main, from areas where the land emergence had occurred. The Fennoscandian uplift, perceived as either a sea-level fall or land-level rise, provided ammunition for an animated debate between the so called 'neptunist' and 'plutonist' during the eighteenth century (Mörner, 1987). In the middle of that century, Celsius and Linné noticed the gradual drying up and emergence of the Swedish coast which they considered to be due to lowering of sea level; so was born the 'Desiccation Theory' which gave rise to further controversy. In 1785, Frizi (in Devoy, 1987) introduced the 'Theory of Earth's Rotation' to explain the fall in sea-level in Fennoscandia and its rise in the Mediterranean. Runeberg, in the period 1765-69, suggested that small movement of the earth's crust were responsible for many of the observed land-level changes (Devoy, 1987). This 'Elevation Theory of Crustal Changes' gained general acceptance during the early nineteenth century and was extended to explain sea-level change.

More field evidence became available in the mid-nineteenth century to aid the explanation of the land/sea-level relationship. The observation of rock-burrowing bivalves, an organism of intertidal habitat, in the marble columns of a market place, at 4.9 m above the floor, of Serapis at Pozzuoli in Italy, discovered by Lyell in 1832, clearly proves submergence to that level and subsequent re-emergence. The upward growth of coral atolls in the Pacific was suggested by Darwin (1842) as due to the sinking of the ocean floor. Diastrophism was perhaps the popular explanation of sea-level changes during this century (Tooley, 1985a).

With the adaptation of the concept of 'Eustasy' and 'Glacio-isostasy' sea-level research moved into a new era. Suess in 1888 (see Mörner, 1987) suggested that the origin of the eustatic changes is due to the formation of ocean-basins and in the infill of sediments; he denied the concept of vertical crustal movement. The theory of 'Glacio-eustasy' introduced by Maclaren (1842) was illustrated by Daly (1920, 1925) and until the twentieth century this concept was widely accepted.

3.4. SEA-LEVEL RESEARCH: METHODOLOGICAL DEVELOPMENT

During the twentieth century sea-level research gained attention from more and more scientists in various disciplines. During the 1920s and 1930s the concept of sea-level research proceeded apace with the development of analytical techniques such as 'Shoreline Relation Diagram' and 'Time/altitude Graph' (Devoy, 1987). During the sixties and seventies sea-level literature dealt primarily with the issue of method and the quality of analysis, and this ultimately divided the sea-level workers into different schools (see section 3.5).

i. Search for Evidence

The evidence for post-glacial sea-level movement can be found both above and below the present sea surface. Before the discovery of the ^{14}C dating technique by Libby in 1955, geomorphological features had been used to make the link between land-level and sea-level movement. The formation of coral reefs, common features in the Pacific, regardless of whether they are seen as proof of the subsidence theory (Darwin, 1842) or the glacial controlled theory (Daly, 1925), postulates a post-glacial sea-level change. The observation of numerous island terraces and raised reefs in the Pacific suggested to several workers (Wentworth and Palmer, 1925; Stearns, 1935) that there was a higher sea level in the post-glacial period. Baulig (1935, in Tooley 1987) explained coastal geomorphic features, such as wave-cut platforms and barrier beaches as evidence of a former sea surface. The presence of older beach features in the gulf coasts, at the same elevation as the modern beach, led to the idea by LeBlanc and Bernard (1954) of a still stand sea-level during the last few thousand years . The evidence of beach ridges and intertidal flats in a chenier plain were used as sea-level indicators by Schofield (1960) in New Zealand. A coastal erosional feature, such as a notch, as suggested by Guilcher (1958) in North Spain, has a relationship to tidal events and can be used as sea-level indicator.

Chatterjee (1961) suggested the existence of 7 marine terraces along Indian coasts as being records of sea-level changes. He also suggested that a submerged reef, the Adam's bridge, which is hardly 4 m below the sea-level, is evidence of a post-glacial sea level rise which caused the submergence of this connecting link between India and Ceylon. Rajamanickam and Loveson (1990) recognised large number of coastal features, such as 5 beach ridges and 7 marine terraces as evidence of post-glacial sea-level variations along Tamilnadu coast, India. Sewell (1935) considered the presence of raised coral reefs and marine conglomerates, well above the level of present day high water mark, to be clear evidence of relative sea-level fall in the Andaman and Nicobar Islands. Katupotha and Fujiwara (1988) used coral evidence from southwest and south coast of SriLanka as record of post-glacial higher sea level. Coulson (1940) explained the presence of peat beds near Calcutta as either due to subsidence or a relative sea-level rise. Records of submerged mangrove trees in the Bengal delta by Fergusson (1863), Bagchi (1944), and Morgan and McIntire (1959) suggested evidence of land subsidence.

Prior to the 1960s, sea-level workers, regardless of the type of geomorphological features they were investigating, concentrated on obtaining field evidence and it was from this that the theories already discussed were developed. This stage in the systematic study of sea-level movement could be regarded as the *juvenile phase*, the phase of recording evidence, in the development of sea-level methodology.

ii. Search for New Techniques

The discovery of the ^{14}C dating technique brought a revolution to sea-level research methodology. This technique allowed the generation of a time/depth graph of relative sea-level change which has subsequently been utilised by a number of workers (Shepard and Suess, 1956; Godwin *et al.*, 1958; Shepard, 1960, 1961; Schofield, 1960, Curray, 1960, 1961; Jelgersma, 1961; and Fairbridge, 1961). Godwin *et al.* (1958), Fairbridge (1961), Shepard and Suess (1956), and Shepard (1961) used a variety of samples for dating from different parts of the world to plot their own time/altitude graph with the aim of drawing the so-called eustatic sea-level curve. Such ambiguous use of different material as sea-level index points is undesirable and does not satisfy the basic criteria proposed by Tooley (1978b, 1985b). 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 (e.g. Andrews *et al.,* 1973).

Palynology is another powerful tool employed by sea-level researchers. The technique was originally used for investigating the Quaternary vegetational history but was also applied by Godwin (1940b) to sea-level investigation. He brought together sedimentary, archaeological and biostratigraphic data to establish the history of relative sea-level changes in the Fenland, U.K. (see Tooley, 1986).

The nature of sea-level movement, whether positive or negative, is well registered in sediment layers. The introduction of Troels-Smith Scheme (1955) to describe unconsolidated sediments provided another advance in sea-level methodology. Tooley (1974) drew this scheme together with biostratigraphic (pollen and diatoms) and radiometric data from North-west England to reconstruct the post-glacial sea-level history. His subsequent publications (e.g. 1976, 1978b, 1982) were influential on his students (e.g. Shennan, 1980; Haggart, 1982; Ireland, 1989; Long, 1991; Zong, 1993 and the author himself) who used an integrated approach of litho-bio-and chrono-stratigraphic techniques for sea-level investigation. Such an approach is now widely used within the UK (e.g. Devoy, 1979, 1982; Heyworth and Kidson, 1982; Shennan, 1986a, 1986b).

From the mid 1950s up until mid 1970s, sea-level workers were not only registering field records of sea-level changes but also to exploring results acquired from laboratory works. This period of sea-level research could be regarded as the *expanding phase*, the phase of technical innovation.

iii. Search for New Explanations

Since mid 1970s, sea-level workers have become more critical of sea-level methodology.

Mörner's (1976a) paper brought a revolutionary change of attitude to the whole concept of eustasy. This greatly influenced other scholars, such as Tooley (1985a, 1993) and Devoy (1987). The highly dynamic model (Mörner 1976a, 1980, 1984, 1987, 1995) of a deformed geoid surface and its topographic relief, which occurs as compensation for horizontal asthenospheric flow, provides an explanation of relative sea-level variation, both for the long- and the short-term. The uneven distribution of geoid relief is associated with global patterns of positive and negative gravity anomalies, related to the dense and light materials in the earth's crust and mantle, and shows geoidal highs and lows, respectively (Tooley, 1993).

The visco-elastic model (Clark *et al.*, 1978) suggests that the earth responds as an elastic material for applied stress of short duration and as a fluid for stress of long duration. Establishment of the elastic and viscous behaviour of the earth have undermined the concept of rigid and stable earth surface (also mentioned earlier) which would have allowed the eustatic sea-level movement to be measured. This 'super-isostatic' loading model (Mörner, 1987), operating differentially in six regions (Clark *et al.*, 1978) each of which is characterized by unique sea-level behaviour, might have played a dominant role in the differentiation of eustatic sea-level changes.

Significant progress has also been made recently in testing models (Allen, 1995) of local sea-level movement. These models of sea-level changes and coastal evolution, registered in coastal stratigraphy, can be illuminated by the model of vegetational succession (Long and Shennan, 1994). The earthquake deformation cycle model (Savage, 1983; Thather, 1984; Savage *et al.*, 1991) could provide an explanation for any missing stage in the coastal sediment sequences. Long and Shennan (1994) argued that the tendency model (see section 3.6) could make possible a thorough testing of the earthquake deformation cycle.

During the last 20 years significant efforts have been made to scrutinise sea-level data, develop new models and testing them in sea-level research methodology. This period could be regarded as the *explanatory phase*, the phase of careful explanation in sea-level research methodology, preferably at both local and regional scale.

3.5. SCHOOLS OF THOUGHT

Jelgersma (1966) considered that agreement on the movement of the early Holocene sea level had been achieved, but the changes during the last 6000 years remain much disputed. From the 1960s onwards, sea-level workers have been grouped into three controversial schools. These are outlined below.

i. Sea-level Oscillations

Fairbridge (1961) argued that the Holocene sea-level changes were fluctuating in nature and that during the last 6000 years there were a number of stands of sea level, at up to 3.7 m (12 ft) above the present level, at about 5700, 4900, 3700, 2400 and 1000 BP. This concept was followed by Gill (1961), Mörner (1969), Hopley (1971), Gill and Hopley (1972), Tooley (1974), and Katupotha (1992) among others. They produced evidence of higher post-glacial fluctuating sea-level from their respective regions. This group is regarded as the 'School of Oscillating Sea Levels'. Evidence supporting the concept of 'higher than present' sea-level comes mainly from the coral islands of the

Indian and Pacific oceans, and from the coasts around New Zealand, Australia and the Mediterranean.

ii. Continuous Sea-level Rise

Shepard and Suess (1956), on the other hand, found no indications of a post-glacial sea-level higher than that of present. Shepard (1960, 1961) and Jelgersma (1961) suggested that the post-glacial sea-level rise is a continuous one, at a rate diminishing over time but going on to the present day. This concept of 'smooth exponential sea-level rise' has been supported by Bloom and Stuiver (1963), Scholl (1964), Bloom (1967), Scholl and Stuiver (1967), Thom *et al.* (1969), and Kidson and Heyworth (1973) among many others. This group is known as the 'School of Continuous Rising Sea Level'. Initial data supporting this concept come primarily from low-lying long-term depositional coastlines.

iii. Still Stand Sea Level

The third group favours the concept of still stand sea level and is known as the 'School of Steady Sea Level'. This school suggests a steady rising sea-level during the Holocene reaching its present level between 5000 and 3600 BP, since which it remains at still stand. This concept was demonstrated by Fisk (1951), Godwin *et al.* (1958), Gould and McFarlan (1959), McFarlan (1961), and Coleman and Smith (1964) among other. Data in support of this view come primarily from the gulf coast of the USA.

Disagreements among the followers of the different schools are not only primarily based on the field evidence but also on the interpretation of raw data. For example, the alternating minerogenic and biogenic sediment layers recorded from the coastal zone are inferred by the oscillating group as evidence of marine transgression and regression resulting from positive and negative changes of sea level. The continuous sea-level rise group, on the other hand, suggests that such coastal sequences are a natural consequence of continuous sea-level rise; the alternating facies being the result of climatically induced coastal processes and differential sedimentation rates. These differences in the interpretation of the raw data have significant implications not only for correlation of marine events but also for inferring other global events, such as climatic change (Tooley, 1978b). Despite these controversial opinions sea-level curves continue to be published by workers from each group; a situation which, may be misleading and creating problems for attempts at correlation.

3.6. CURRENT CONCEPTS OF SEA-LEVEL INVESTIGATION

i. Concept of Potential Errors

Almost from the inception of the modern phase of sea-level studies, all the potential sources of errors, whether naturally derived from eustatic or local components, or anthropogenically derived from human activities and careless field survey, have been recognized as a fundamental problem in sea-level research. A full account of possible potential sources of errors, which can give a false sense of accuracy to resulting sea-level curves, is available in Heyworth and Kidson (1982), Kidson (1982) and Shennan (1986b).

Besides eustatic, isostatic, and tectonic deforming components, a wide range of potential errors resulting from tidal origin, those arising from the choice of sea-level indicators, those related to coastal processes and finally, those stemming from age determination have to be taken into account (Kidson, 1982; van de Plassche, 1986a). Proper assessment of the quality and limitations of field data (Tooley, 1985b) relating to the determination of the altitude of the sample in relation to national datum level can reduce the potential errors considerably. Shennan (1980, 1982b) estimated the possible sources affecting the measurement of the altitudes of stratigraphic boundaries.

Heyworth and Kidson (1982) argued that the potential error sources can reduce the quality of the published data considerably. Kidson (1982) suggested that sea-level data coming from an area of large variation of tidal range over a small distance have to be adjusted before plotting on a graph. Errors resulting from sediment compaction could produce only an unreliable sea-level history (van de Plassche, 1986a). Rare events would accumulate sea-level events well above the actual indicative mark and could suggest a sea-level higher than the actual (Kidson, 1982). Only carefully screened data, to eliminate or at least to reduce the error range, should be used to construct the time/altitude graph of relative sea-level changes.

ii. Concept of Sea-level Index Point

The central question of past sea-level research is the identification of former sea-level index points precisely. Evidence of relative sea-level changes is preserved either as geomorphic features or as biogenic materials or both. Every marine feature or organism which has a quantifiable vertical relationship to a 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, beachrock, notches, slope breaks, shells, coral reefs, and archaeological features. The use of such a wide range of indicators as former sea-level indices has led to enormous ambiguity in the published sea-level data. It is clearly undesirable to use different materials with different indicative meanings, as practised by Fairbridge (1961), as sea-level indicators (Tooley, 1985a). Erosional features, such as shore platforms and notches can only rarely be used as precise indicators of former sea level (Kidson, 1982). The most reliable indicators are considered to be organic remains in their growth position, preferably *in situ* peat. In the British Isles, the common and reliable sea-level indicators are saltmarsh peats. Mangrove peats, which indicate the former sea-level very precisely, have been applied in some studies (Geyh *et al.*, 1979; Woodroffe, 1981; Woodroffe *et al.*, 1985; Grindrod, 1985, 1988) as sea-level indicators.

iii. Concept of Sea-level Band

The use of ^{14}C to date various types of index points from different parts of the world in a single time/altitude graph was discussed above. Tooley (1978b, 1985a, 1993), repeatedly argued that sea-level index points must come from a small homogeneous area, unlike those employed by some other workers (e.g. Godwin *et al.*, 1958; Fairbridge, 1961; and Shepard, 1961), who drew their evidence from world wide sources. With the greater understanding of the nature of sea-level change and a fuller recognition of possible sources of errors, sea-level workers will aim to establish local relative sea-level curves ((Jelgersma, 1961; Kidson and Heyworth, 1973; Tooley, 1974, 1978a; Heyworth and Kidson, 1982; Devoy, 1979). Reconstruction of such time/altitude graphs simply by scrutinising the index points by eye, regardless of whether they are oscillatory or smooth, is not the way to understand the rate and direction of sea-level movement. Kidson (1982) recognized that such a presentation of data is misleading in sea-level investigations. Sea level did not change in a linear way as was graphically illustrated in the past: rather each index point on a sea-level graph has been affected by a change in altitude due to uplift or subsidence, variation in tidal range, sediment compaction and sediment influx (Tooley, 1993). Problems are also encountered in the dating of each index point which is given as BP, with ±2Õ (two standard error). The indicative meaning of each index point is only acceptable with the recognition of possible errors in altitude and dating. Recognition of such time/altitudinal errors associated with each index point has led to the use of error boxes (van Straaten, 1954; Akeroyd, 1972; Shennan, 1982a; Devoy, 1982) or ellipses (Kidson, 1982; Heyworth and Kidson, 1882). Tooley (1993) estimated that in cool-temperate humid latitudes, the altitude of past sea-level can vary within a band of ~1 m; Gehrels (1994), for example, recorded up to 1.2 m variation at Wells, USA. The potential error, therefore, could be greater than that of possible sea-level fluctuation: the recognition of minor oscillations of sea level, in such cases, is obscure and, therefore, not feasible (Kidson, 1982).

iv. Concept of Sea-level Tendency

Neither the concept of the time/altitude graph nor the concept of error boxes, ellipses or bands can provide the perfect description of sea-level movement and directions during the geological past. Shennan (1982b) argued that the sea-level band suffers from numerous errors and can only be used as the last and unreliable resort in analysis. With the limitation of present research methods, the simple plotting of data with the associated errors in a time/altitude graph, cannot be used with any confidence.

An alternative approach, the concept of sea-level tendency, was introduced by Streif

(1979a) and put forward by Tooley (1982), Shennan (1982b, 1986b), Haggart (1986) and Long (1991). Shennan (1982b) argued that each sea-level index point would reflect a tendency of sea-level movement, either positive or negative: each indicator is site dependent but indicators from a wider area show a general tendency of regional sea-level movement (Tooley, 1985a). A positive tendency of sea-level movement indicates an apparent increase in marine influence and a negative tendency the opposite (Shennan, 1987). Shennan (1983a) further argued that it is possible to determine the tendency of sea-level movement operating on a wider scale when all variables such as radiometric dating of sea-level index points, lithological changes, archaeological records and palaeobotanical evidence are taken into consideration. Haggart (1986) suggested that the gap between the description of coastal sequences and the interpretation of sea-level movement can be bridged by adopting the sea-level tendency concept. However, the transition, between each tendency, positive to negative or negative to positive, has not been properly addressed and clearly demands attention.

v. Concept of Correlation

Shennan (1982a) stated that due to the lack of any accepted methodology, a meaningful comparison of sea-level data is not yet possible. He (1982b) demonstrated the difficulties in published sea-level diagrams of determining the 'goodness-of-fit' between various sea-level chronologies. van de Plassche (1986a) argued that the comparability of sea-level data with respect to time and space is a function of definition of terms, representation of sea-level indicators and evaluation of uncertainties, which, as suggested by Shennan (1987), require a correct research design. Shennan *et al.* (1983) proposed an alternative approach to the correlation scheme, based on the sea-level tendency concept and demonstrated that correlation, using data from the Fenland, North-west England, and Tay estuary, of marine sequences between uplifting and subsiding areas is possible (Fig. 3.2). Such an approach to correlating marine events, over a wider scale, for example between and within different temperate and topical regions, needs further testing.

vi. Concept of Uniform Methodology

Tooley (1985a) noticed the problem of recording, analysis, interpretation and correlation of marine events due to the fact that sea-level investigators had not employed a unified methodology and a homogeneous data base. Jelgersma and Tooley (1995) reiterated Tooley's (1978b) original suggestions that sea-level data should come from a small homogenous area, that the sea-level indicators should have similar indicative meaning and that the radiometric dating should be capable of independent corroboration by some other techniques, and that these are the basic requirements for establishing a uniform methodology. Inconsistencies remain among the sea-level workers about the method of collection, extraction and interpretation of sea-level data. Some investigators have considered morphological features, such as coral reef and terraces, others have taken stratigraphic, altitude and age data whilst a third group has used palaeotological evidence to investigate the sea-level history. van de Plassche's (1986b) edited manual of 'sea-level data collection and evaluation' makes a remarkable contribution to the minimising of the divergent methodological approaches towards a uniform goal.

Prior to about 1980, workers mostly followed the inductive approach (Hervay, 1969) in sea-level investigation, as summarised by Shennan (1983b) into an eight-stepped traditional model. This is no more than the development of a local sea-level curve. The basic problems of interpretation of sea-level data and the problems of correlation still remain. Shennan (1983b) proposed an expanded model of sea-level research methodology (Fig. 3.3) which shows wide scope for its applicability on a wider regional scale. He has quantified some of the errors that affect the time/altitude presentation of the sea-level data base. This methodology based on the tendency concept of sea-level movements has already given convincing results in correlating the sea-level sequences within the Fenland, North-west England and the Tay estuary (Shennan *et al.*, 1983). Shennan (1983b) acknowledges that some problems still remain before it is possible to reconstruct the altitudinal parameters of both sea-level and crustal movement with any accuracy. The availability of a large number of data sets, at various regional scales, collected in a consistent manner, would increase the potential of this methodology as an approach to be applied uniformly by sea-level investigators.

3.7. INTERNATIONAL PARTICIPATION IN SEA-LEVEL RESEARCH

i. IPCC

The Intergovernmental Panel on Climatic Change (IPCC), established in 1988, and sponsored by WMO and UNEP, is responsible for assessing the scientific information related to climatic changes and the formulating of response strategies. The Working Group-I is primarily responsible for studying the scientific information associated with the global climatic change, particularly the emission of greenhouse gasses and global sea-level rises (Houghton *et al.*, 1990). The IPCC scenario of global sea-level rise, mostly based upon the short-term instrumental records, has been put forward by this IPCC working group and has now become of great concern to the policy makers of many nations.

ii. INQUA

The International Union for Quaternary Research (INQUA) was established in 1928. The INQUA Commission on Shorelines, established in 1953, is concerned with changes in land and sea level around the world's coastlines (Tooley, 1987). It acts as a major coordinator and initiator of many aspects of sea-level research and also interacts with many other international organizations working on sea-level studies (Devoy, 1987). Scientists all over the world, as a result of from its six Sub-commissions[1], are now more promotive and collaborative than ever before.

iii. IGCP

The International Geological Correlation Programme (IGCP), established in 1973, was designed to encourage international research on geological problems. Holocene sea-level research has gained much stimulation from two IPCC projects- project 61 and project 200. The main aim of the IGCP 61 project (1974-1982), led by A.L. Bloom, was to establish a sea-level graph for the last deglacial hemicycle (about 15000 yrs) based on records collected from all over the world. The creation of computer-storage global sea-level data, identification of key areas with deficient data, and mathematical modelling, were also goals of the projects. It become apparent from the investigations of 31 countries (Tooley, 1985a) that the concept of uniform global sea-level change could no longer be accepted. Project 61 was succeeded by IGCP 200. The aims of this project (1983-1987), led by P.A. Pirazzoli, were to quantify late-Quaternary local sea-level processes, to produce local sea-level history and to provide a basis for predicting future

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[1] Bangladesh has been elected as the secretary for the INQUA Shoreline Indian Ocean Sub-commission for 1995-1999.

coastal problems, particularly for densely populated low-lying areas. The shift towards a more process oriented approach and the establishing of local sea-level history is a reflection of the priorities established by the sea-level scientists, participating from 63 countries (Devoy, 1987), as a result of the findings from the previous project (Tooley, 1985a). IGCP 274 project (1988-1992), led by O. van de Plassche, entitled 'Coastal Evolution in the Quaternary' was launched to establish a link between climatic change and sea-level with regard to coastal responses to various coastal processes. Such a shift towards more applied approach in sea-level investigation is a current concern among the sea-level investigators. The sea-level Atlas (Pirazzoli, 1991) is a contribution to the IGCP 274 project, in which 800 local relative sea-level curves from all parts of the world, have been assembled. The on going Project 367 (1994-1998) on 'Late Quaternary Coastal Records of Rapid Change', led by D.B. Scott, aims to document and explain the rapid fluctuations of climate and sea-level events in coastal zones, with the projection to future scenario. Recently, the IGCP Project 396 on 'Continental Shelves in the Quaternary' (1996-2000) has been approved by the IGCP Board which will formally be launched in November, 1996, at Sydney, Australia.

iv. IGU

The International Geographical Union (IGU) promotes collaborative research on sea-level and coastal changes through its Commission on the Coastal Environment, begun in 1976. Projects on coastal landforms and processes, pursued by the Commission, were influential in establishing an International Geological Correlation Programme (IGCP) and determining its aims (Tooley, 1987). During the last 20 years many sea-level problems, both fundamental and strategic, and at different time scales, have been systematically attacked under the promotion of the INQUA Commissions and Sub-commissions and the IGU.

Sea-level research now varies over a wide range of temporal and spatial scales, and to which scientists from various disciplines have been contributing. Sporadic data collection and difficulties in correlating marine events, are the major methodological problems sea-level scientists now face. With the adoption of a correct research design and a common methodology, it should be possible to solve some of those problems.

Chapter 4: METHODS AND TECHNIQUES APPLIED

4.1. INTRODUCTION

Techniques used in the current study to reconstruct the Holocene sea-level changes are well established and have been applied successfully elsewhere (Tooley, 1978a; Shennan, 1980; Ireland, 1989). These are levelling, study of sediment profiles, sampling, stratigraphic analysis, pollen analysis, diatoms analysis and radiometric analysis. In this chapter these techniques are discussed under two major headings- fieldwork and laboratory work.

4.2. FIELDWORK

Extensive fieldwork which included reconnaissance sampling, levelling, the study of sediment profiles and borehole sampling was carried out during the six months period between October 1993 and April 1994. A considerable part of the fieldwork was monitored by the supervisor, during training.

i. Reconnaissance Sampling

Considering the aims of the research, attempts were made to locate suitable sites for sampling. For an ideal site to be chosen, many variables are involved. In a large deltaic region, despite its potentiality for work of a similar kind to that undertaken in this study, little systematic work has been attempted. Thus, there were no extant guidelines and given the limited resources and time available, selecting the site for research was a complicated task.

After a field visit to some areas of the country, eight different sites in four separate regions were isolated for preliminary investigations. These were, Bakal and Binirputa at Satkhira, Panigati and Pir Hazirgram at Khulna, Chakuria and Cox's Bazaar at Cox's Bazaar, and Matuail and Sanirakhra at Dhaka (see Fig. 1.1). Except at Chakuria, two reconnaissance boreholes were put down at each site to obtain a generalized stratigraphy for the region. At Chakuria, six boreholes were put in three geomorphic units, delta apex, delta plain and tidal plain (Alam *et al.,* 1991). After a consideration of the stratigraphic records, Panigati and Matuail were finally selected for detailed investigations because:-

i). at Panigati alternating peat and minerogenic layers are well developed; the site is located in between two tidal rivers where sediment layers are undisturbed; and, finally, easy to reach deeper sampling depth using hand operated gouge sampler than other places, and

ii). at Matuail an ongoing excavation enabled to detail recording of sediment properties; the lithology covers the entire sequences of the Holocene, overlying the Pleistocene sediment; the Pleistocene/Holocene boundary is well visible; and finally, alternating organic and inorganic layers are well developed.

ii. Levelling

Precise levelling was undertaken of the location and altitude of all the boreholes, using a Kern Automatic Level, GK1-AC. The transect was closed and the closing errors were within 15 cm for Panigati and 10 cm for Matuail. Bench marks (BM) within two kilometres for both sampling sites were available and used. The position and altitude of these BM were obtained from the Survey of Bangladesh.

A temporary BM for each site was set-up and all the boreholes were levelled to it. This BM was then connected and levelled to the nearest local PWD bench mark. In the case of Panigati, the local PWD bench mark is located on the north-west wall of the sluice gate, across a *khal* on the east bank of the Atai river, which is about 1.5 km from the sampling site. For Matuail, the PWD bench mark is on the north-west corner of a bridge parapet on the Dhaka-Chittagong highway (old), about 1 km from the site.

Levelling was carried out in a good sunny weather with only a gentle breeze and with good visibility. The temperature was around 20° C. To keep the error as small as possible, the distances between the reading points and staff points were kept within 100 metres.

iii. Study of Sediment Profiles

To resettle several hundred shelterless people at Matuail above the flood levels, a major project, which involved excavation of material and the raising of an area up to 7.3 m above the MSL, was planned by the Dhaka Municipal Corporation with the financial support of the World Bank. Fortunately, excavations were in progress during the period of fieldwork and the opportunity was capitalised upon. An ideal site was selected with an exposed face, about 2.5 m high, from which to draw sediment profiles and to describe the lithology. Three exposed faces were cleaned by spade, trowel and spatula so as to be as perpendicular as possible. Lithological boundaries were carefully incised on the face of the excavation, and then match sticks[1] were used and their positions were transferred to graph paper to draw the profile. The detailed stratigraphy of each layer was recorded and a complete photographic record was also made (also see section 6.4).

iv. Sampling

Selection of appropriate types of sampling techniques and equipment depends upon the problem under investigation, distance to the field site, transport to reach the site, personnel, time and other available resources. In the present research, equipment and associates were transported from England to Bangladesh by air and this limited the chance of using heavy equipment like a piston corer or a vibrator.

Three different types of samplers were used. The type most commonly used was the gouge sampler. It comprises a metre-long and 2.5 cm wide tube, split longitudinally and sharpened at the lower end. The upper end is fixed to a T-shaped handle. After obtaining the first metre of sediment, metre long rod can be added to the gouge so as to sample to the desired depth. First, it is pushed vertically into the ground to the required depth and then rotated 360° clockwise. The sediment is pushed into the chamber, giving a core one metre long and 2.5 cm in diameter. The gouge sampler consolidates the core slightly but is the most efficient, robust and reliable sampler for reconnaissance survey and routine analysis (Tooley, 1981). In the field, boreholes of up to 10.1 m were achieved with the help of four field assistants. Shennan (1980) measured some common types of errors arising from the angle of the boreholes, the curvature of the rods, the identification of the

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[1] The match stick technique includes the demarcation of every intersecting points between each boundary line and perpendicular lines drawn at regular intervals. It gives a clear visual expression of the lithology of the profile.

lithological boundary, measurements of depth and compaction. The present investigation is also not free from such errors but effort has been made to minimise these, especially those arising from the angle of the boreholes and the consequences for the depth measurements.

A Russian-type sampler is very useful for retrieving a semi-circular half core, 50 cm long and 5 cm wide, without disturbing the stratigraphy. The chamber is rotated 180° clockwise against a plate which acts as an anchor at the sampling level. On retrieval from depth, the sampler is opened by a reversed rotational procedure. The samples are collected alternatively from two adjacent boreholes. The design of the sampler is suitable for a peaty sediment but not good for penetrating clastic sediments, and this was experienced during the fieldwork. The sampled cores were transferred to pvc pipes, sealed in polythene tubes and returned to the UK for laboratory analyses.

A Dacknowski sampler was also used; it provided a core 25 cm long and 2 cm diameter. On reaching the sampling depth the closed end of the sampler is opened by pulling the handle 25 cm upwards and the rotating it 90° clockwise which locks the rods. The corer is then pushed 25 cm into the sediment. This was very useful for sampling where alternating layers of organic and inorganic sediments occurred. The sampled cores were removed from the sampler by pushing them from the upper end into half-diameter pvc tubes before transporting them for laboratory analyses. One of the disadvantages of this corer is that the collected samples can be compacted during extraction which leads to incorrect depths in the sampling. Attempts were made to correct for this compaction.

Besides the above three types of samplers, monolith tins (25x10x10 cm) were also used to collect samples from the exposed face. Before sampling, the selected face was first straightened as vertically as possible, using a spatula and a trowel. The monolith tin was then placed vertically on the sediment face, pushed in by hand and then with a hammer, the depth recorded on the tin, dug out, sealed in polythene, and taken for sub-sampling in the laboratory.

v. Stratigraphic Analysis

Lithostratigraphic data were collected employing a gouge sampler. After the sampler was brought to the surface from the sampling depth, the sediment was cleaned with a spatula, and each stratigraphic boundary was marked and measured very carefully. The stratigraphic descriptions were made in a standard format, following Tooley (1978a); each stratum is numbered from the base upwards, and its altitude was measured from the PWD Bench Mark which later was corrected to GTS datum. The depth below the ground surface is given in centimetres. The description of the sediments sampled and the symbols used in the diagrams employed the Troels-Smith Scheme (1955), which is being used here for the first time to describe the unconsolidated sediments of the Bengal basin. A brief description of the scheme is, therefore, given here.

In lithostratigraphic analysis, an universally accepted and used scheme is essential. Until 1955, there had been no consistency among the workers in stratigraphic description and different people used different symbols for the same type of deposits (Tooley, 1981). Troels-Smith (1955) attempted to overcome these difficulties by devising a scheme for recording the physical characteristics of an unconsolidated sediment. In this scheme, three elements- the components, the degree of humification and the physical properties, of a sediment layer can be specified.

The composition of a layer is recorded on the basis on a scale of 1 to 4, where 1 indicates 25% and 4 indicates 100% of the component. The trace amounts of any component in a stratum are represented by the plus (+) sign where one plus (+) indicates 1% of the total components in addition to the major components. A layer may contain one or more components. The main components are *turfa, detritus, limus, argilla* and *grana.*

Turfa is defined as the roots of woody and herbaceous plants, and the stumps, trunks, branches, and stems if connected to the roots. It also includes mosses. *Turfa* is, therefore, the material which has commonly been deposited *in situ*. Only one type of the *turfa,* the *T. herbacea* (Th) was found in the studied sediments. *Detritus* is composed of fragments of leaves, wood, stems, bark, branches and trunk which are unconnected to a root system. All of these have either been rained down onto the forest floor or have been washed into the site, then deposited. Three types of *detritus, D. lignosus* (Dl), *D. herbosus* (Dh), and *D. granosus* (Dg) were recorded in this study. *Limus* is a mudlike, homogenous, non-plastic deposit made up essentially of small organic particles arising from the productivity of microorganisms in lakes and swamps. The type *Limus detrituosus* (Ld) was recorded in the field. *L. detrituosus* is a homogeneous organic material, elastic, non-greasy and is the product of more or less complete disintegration of the organic material. *Substantia humosa* (Sh) consists of completely decomposed organic material, dark or blackish in colour, greasy and without any macroscopic structure. In the field, sometimes when it is well humified, *Limus detrituosus* (Ld) is too difficult to distinguish from the *Substantia humosa* (Sh). It may, however be distinguished by inspection of the pollen and diatom assemblage as because the Ld sediment usually displays a greater numbers of pollen and diatoms than does the Sh sediment (Zong, 1993) and the pollen is not as corroded. *Argilla* consists of minerogenic sediments (silt, clay) and is characteristically sticky and plastic. Two types of *argilla* were recognised in the field, *A. steatodes* (As) with grain sizes <0.002 mm (clay), and *A. granosa* (Ag) with grain sizes 0.06-0.002 mm (silt). *Grana* is the sediment of macroscopic particles (sand, gravel).

The degree of humification indicates the degree of decomposition of the macrofossils that can be observed. It is estimated on a five points scale where 0 on the scale indicates that the plant structure is unhumified and 4 indicates more or less complete humification. The number of the scale is labelled on the upper-right corner of the identified component.

The physical properties of any layer include the degree of darkness (nig. = *nigror*), stratification (strf. = *stratificatio*), elasticity (elas. = *elasticitas*), dryness (sicc. = *siccitas*), and the sharpness of the upper boundary (l.s. = *limes superior*) which are all also estimated on a five point scale. In the case of boundaries, the scale l.s.0 indicates diffused and l.s.4 indicates a very acute boundary. Detailed discussion of the scheme is available in Tooley (1981).

In the present research, the lithostratigraphic records (depth, altitude, components, degree of humification and physical properties) for each layer were recorded in an abbreviated form with a short written description (See Appendix 2 for symbols). An example of a complete description of strata 1 to 5 of the core P-0 is shown as follows:

Borehole No. P-0

Stratum	Altitude (m)	Depth (cm)	Description
05	-2.31 to -2.44	395 to 408	Th[1]3, Sh1, Ag++; nig.3+, strf.0, sicc.2, elas.2, l.s.1 Brown organic turfa with rare silt; fibrous
04	-2.44 to -2.82	408 to 446	Ld[2]3, Th[2]1, Dl++, anth+; nig.2+, strf.1, sicc.2, elas.2, l.s.0 Brown limus with rootlets and rare charcoal and woody detritus; coarsely laminated
03	-2.82 to -3.12	446 to 476	As2, Ag2, Th[2]+, Sh+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with are rootlets and herbaceous detritus; coarsely laminated
02	-3.12 to -3.38	476 to 502	Ld[3]4, Th[2]++, Dl+; nig.2++, strf.2, sicc.2, elas.1, l.s.0 Dark-brown limus with frequent rootlets and rare woody detritus; laminated
01	-3.38 to -3.95	502 to 559	Ag2, As2, Th[2]+, Dh+, Dl+; nig.2, strf.1, sicc.2, elas.+, l.s.0 Battleship grey clayey silt with rare woody and herbaceous detritus and rootlets;

Some problems, however, with the application of the scheme were faced during the present research and stated as follows:-

i. When the sediment components change gradually, the identification of the stratum boundary is, practically, impossible or difficult.

ii. Proper identification of sediment components, especially in case of *argilla* is not very accurate. The distinction between *Argilla steatodes* (As) and *Argilla granosa* (Ag) by means of the naked eye is very arbitrary. It is necessarily inaccurate when there are equal parts of three elements, because of the four point based scale of the scheme.

iii. Furthermore, percentage identification of trace elements by a plus (+) sign is not very accurate and indeed lesser amounts are not represented, and plus (+) elements can not be shown on the diagrams.

Despite these problems, the Troels-Smith scheme for characterizing the unconsolidated sediments has gained increasing acceptances as a descriptive technique and has been successfully applied by many workers (e.g. Tooley, 1978a, Shennan, 1980, Ireland, 1989, Long, 1991, Zong, 1993). It was also recommended in 1974 for use in IGCP Project 61.

4.3 LABORATORY WORK

i. Pollen Analysis

A pollen grain is a microscopic structure (5-100μ) produced within the anthers of an angiosperm or the male cones of a gymnosperm. A spore on the other hand is the structure of similar size which functions in the reproduction and dispersal of cryptogams (pteridophytes, bryophytes, algae and fungi).

Palynology is the study of pollen grains and spores, and is the principal technique to reconstruct the Quaternary environment (Birks and Birks, 1980). Pollen[1] is the most abundant microfossil preserved in peats, organic sediments and lake muds. The identification, counting and statistical representation of pollen data in a pollen graph is the common practice by palaeontologists, botanists and geographers to reconstruct the palaeoenvironment of a site.

The technique of quantitative pollen analysis was initiated by the Swedish geologist Lennart von Post in 1916 (in Birks and Birks, 1980) which was later taken up and continued by his students (Faegri and Iversen, 1989). Erdtman (1943, 1952) also made similar contribution to pollen analysis and pollen taxonomy. Since then, the technique has widely been in use all over the world, particularly in temperate countries. The technique has also been applied in sea-level research (e.g. Godwin, 1940b; Jelgersma, 1961; Tooley, 1974 and many others).

In the present study the technique of pollen analysis has been applied for the first time in

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[1] Here and hereafter, the term pollen means pollen grains or spores or both.

the Bangladeshi part of the Bengal Basin, with the following aims:-

i. to establish the local vegetational (mangroves) history of the basin,

ii. to identify the nature of sedimentary change and sediment influx rate associated with each transgressive and regressive episode, and

iii. to determine the sea-level index points so as to establish the Holocene history of relative sea-level movements.

Pollen analyses were carried out on samples collected from Panigati and Matuail. Samples were taken from the cores collected either by Russian sampler, Dacknowski corer, monolith tins or gouge sampler and prepared according to well established techniques (Appendix 3). Counting was carried out on a Zeiss photomicroscope, with magnification up to 600 times; most photographs were taken at a magnification of 1000 times (see Appendix 21).

At the beginning, the major problem faced during the laboratory work, due to the lack of any pollen key, was the certain identification of pollen taxa. A short period of instruction by Prof. Manju Banerjee (see photograph k in Appendix 22) at her laboratory in the Department of Botany, University of Calcutta, Calcutta, and also demonstrations by Dr. B.B. Mukherjee, in the microscope room of the Geography Department, Durham University, for a few weeks, allowed the author to gain experience of tropical pollen. Some type-slides were also made by the author himself from the flowers collected from the Sundarbans forest[1], and also from the herbarium of the Royal Botanic Garden Edinburgh. Pollen photographs, available in different articles (e.g. Muller, 1964, 1969;

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[1] One forest officer within the Sundarbans was kind enough to collect flower samples for the author and sent those to him by post. This great help by that forest officer who does not wish to disclose his name, is warmly acknowledged.

Mukherjee, 1972; Sen and Banerjee, 1990) and in a report (Thanikaimoni, 1987), have also been used in identification.

Detailed pollen counts are available in Chapter five and six. However, some discussions are also made here. Given that the pollen of *Chenopodium* and *Amaranthus* are not separable, they were counted together as Cheno-amaranthaceae. *Phragmites* pollen was included in the Gramineae. Grass pollen were not possible to differentiate from cereals on the basis of size differences. Sub-samples for pollen analysis were taken at 10 cm intervals. For percentage diagrams at least 150 land pollen were counted for each level and in some cases the identification was confined to the genus level. A similar sum had been adopted by Shennan (1980), Haggart (1982), Sutherland (1984) and Long (1991). The pollen concentration technique using Lycopodium tablets (Stockmarr, 1971) to a known volume of sediment was also employed.

Pollen diagrams were produced using the computer program **TILIA**. All diagrams were divided into a series of Local Pollen Assemblage Zones (LPAZs). Zone boundaries were drawn by computer from conventional relative frequency diagrams, where the frequency of taxa rise or fall, sharply. All pollen taxa were arranged in groups, with trees on the far left, followed by shrubs, herbs, aquatics, and ferns and spores. Taxa are listed alphabetically on the diagrams (also see section 5.10)

ii. Diatom Analysis

Diatoms are microscopic unicellular plants which vary in size; the smallest one may be 4 or 5 μ in diameter or length while the largest exceeds 500 μ (Barber and Haworth, 1994). They are useful for sea-level study. One of the earliest systematic diatom analyses used to trace sea-level changes was done by Halden in 1929 (in Palmer and Abbott, 1986). Since then, the application of diatoms as Holocene sea-level indicators has been used by Tooley (1978a), Devoy (1979), Shennan (1980), Cullingford *et. al.* (1980) and Ireland (1989) among other.

In the present study, as with pollen analysis, the technique of diatoms analysis has also been used for the first time in Bangladesh to reconstruct the Holocene sea-level history with the following aims:-

i. to identify the nature of sedimentary sequences and sediment influx rates associated with each transgressive and regressive episode,

ii. to determine the land/sea interface and depositional environment, whether marine, brackish or fresh, and

iii. to determine the sea-level index points and to establish the Holocene history of relative sea-level movements.

Diatom analyses were carried out on the sediments taken from the same cores as those used for pollen analysis and samples were prepared according to well established techniques (Appendix 4). Counting was carried out on the same microscope and at the same magnification as pollen identification. Diatom identification was made with reference to the texts of van der Werff and Huls (1958-74), and Hendey (1964). At least two hundred valves were counted at each level. A similar sum had been adopted by Shennan (1980), Haggart (1982), Sutherland (1984), Ireland (1989), Long (1991) and Zong (1993).

Diatoms may be classified according to a number of different salinity and life-form groupings, and there is no general agreement on such classification. The ecological code proposed by H. de Wolf (1982) has been followed for this study. He (1982) classified diatoms into five salinity groups, polyhalobous, mesohalobous, oligohalobous-halophile, oligohalobous-indifferent and halophobous[1].

Diatom diagrams, like the pollen diagrams, were produced by using the computer program **TILIA** and all the diagrams were divided into a series of Local Diatoms Assemblage Zones (LDAZs). Zone boundaries were drawn by computer from conventional relative frequency diagrams and mark where the frequency of diatoms of above salinity groups rises or falls, sharply (also see section 6.12).

iii. Particle Size Analysis

Particle size analysis is an important technique that has been widely used to interpret sedimentary environments. Textural parameters can give useful information about an environment because they are related to dynamic conditions of transportation and deposition. Identification of past environments on the basis of grain size analysis has been undertaken by many workers (e.g. Inman, 1952; Folk and Ward, 1957; Friedman, 1961, 1967; Sahu, 1964, 1982; Hassan, 1986; Rajamanickam and Gujar, 1988; Monsur, 1990; Jahan *et al.*, 1990; Rajamanickam and Muthukrishnan, 1995), during the last 50 years. Unfortunately these workers have extrapolated their results to other depositional basins, and these have their own physical, chemical and biological characteristics which may be unique to a particular basin.

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[1] Conventionally Polyhalobous, Mesohalobous, and Oligohalobous and Halophobous diatoms are used as synonymous of Marine, Brackish and Freshwater diatoms, respectively.

The Particle size analysis, together with the Troels-Smith scheme, has been applied to investigate sea-level changes by Tooley (1978a), Shennan (1980), Haggart (1982) and Long (1991) among other. In the present research, the technique has not been used as a technique to extrapolate the results (see above) and no statistical measure has been undertaken. Here, it is applied with the following aims:-

i. to validate the field records based on the Troels-Smith scheme,

ii. to determine the nature of sediments and their vertical sequences, and

iii. to correlate different layers of sediment.

Samples for analysis were taken at different intervals covering each sediment stratum, identified in the field, and from the same cores used for pollen and diatom analysis. The sampling intervals, therefore, varied from 20 cm to 50 cm. The pipette method (see Appendix 5) was applied to analyze particle size. Sediment from the same sample was also used for Loss-on-Ignition measurement (see Appendix 6). Samples from the core collected by Prof. Umitsu[1] were also used.

iv. Radiocarbon Dating

Radiocarbon dating is a method of determining the age of an organic material by measuring the proportion of the ^{14}C isotope contained within its carbon content. This method has seen considerable development since its inception about 45 years ago. The radioactive ^{14}C isotope of carbon is continuously produced in the atmosphere and it enters

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[1]Prof. Umitsu, Department of Geography, Nagoya University, Japan, donated some of the cores he collected in 1987 to a depth of 70 m at Daulatpur, about 3 km south-west of Panigati, to the Geology Department, University of Dhaka, Bangladesh. Some of those sediments were collected and analyzed by the author with due permission from Prof. Umitsu.

the living organisms, both plants and animals, being incorporated by them until the organism dies and is buried under the sediments. Once carbon has become fixed in the plant or animal tissue, at death, the radioactive decay of ^{14}C begins at a known rate. The half-life of ^{14}C is 5568 years (Mook and van de Plassche, 1986) which makes it useful for dating materials up to at least 45,000 years but the accuracy diminishes beyond 30,000 years.

Radiocarbon dating is a well established and powerful technique to provide dating of sea-level index points, and to determine the chronology for the sea-level changes. In the present research the technique has been used:-

i. to establish an absolute chronology for the sea-level changes by dating the transgressive and regressive contacts, and

ii. to measure the sediment influx rate and the nature of sedimentation of different layers.

Samples were taken from the same core used for pollen, diatoms and particle size analyses.

Before materials were collected from the core, each core was carefully cleaned to make each organic/inorganic contact clearly visible. These organic/inorganic boundaries have indicative meaning in sea-level research (Ireland, 1989). About 50-75 gm of material were selected for ^{14}C dating from immediately above or below each organic/inorganic contact. All the samples were submitted to the Beta Analytic Inc, Miami, USA for radiometric dating.

A number of errors are involved in the radiocarbon dating technique. Some of those errors have been widely discussed by Olsson (1986), and Mook and van de Plassche (1986). A brief discussion is given below.

The radiocarbon dating technique conventionally assumes that the ^{14}C activity of carbon containing material during its formation have been the same during geological time. However, this assumption has been proven incorrect due to the so called 'Suess effect' (Suess, 1955). High-precision data, now available for dendrochronologically dated wood samples (Stuiver and Pearson, 1993; Becker, 1993), show that the relationship between ^{14}C and calender years has varied significantly through time. For example, the ^{14}C age of 8210 $\pm$60BP (the oldest date used in this research) shows 985 years younger than its calibrated age of 9195 yrs BP (see table 5.2).

The sample selected for dating may be contaminated when other associated components were not formed together with it. Contamination, therefore, can occur with either older organic materials during sediment accumulation or younger organic materials following deposition. Hard water error, resistant organic debris (Schoute *et. al.*, 1981) and other forms of old carbon contamination can occur as a result of the incorporation of allochthonous organic materials in the sample materials.

Contamination by younger materials may occur due to infiltration of organic (humic) carbon by rain water to the layer to be dated. Another major younging type of contamination is associated with the penetration of roots. This may result in the contamination of materials by up to 845 $\pm$ 210 C^{14} years (Streif, 1972), while van de

Plassche (1980) has noted a similar younging effect of *ca.* 400 years.

4.4. STRENGTHS AND WEAKNESSES OF THE TECHNIQUES APPLIED

Selection of any suitable technique for sea-level study largely depend upon the availability of evidence in the field. Subsequent works, such as laboratory analysis and interpretation of results are also important. It has already been mentioned earlier that some sea-level workers consider geomorphic evidence, such as notches, terraces, beach rocks and beach ridges as sea-level indicator. The most common danger to use these evidence in sea-level research is that they do not precisely indicate the former sea level position. There is always a great possibility to include an altitudinal error in using such evidence.

On the other hand, fossils (both macrofossil and microfossil) can be used with more confidence because their buried position in relation to the former sea level is largely known. Fossils, such as coral reef, ostracod, foraminifera, shell, beetles, molluscs, fruits and seeds, vertebrates, and plant macrofossils are widely in use in palaeoenvironmental studies, including sea-level research (see van de Plassche, 1986b and Berglund, 1986). These techniques provide more accurate evidence for past environment and sea-level changes than those field based geomorphic records. However, studies of such fossils require a large exposure of sediment face and several kilogram of sediments. Most of these fossils (except foraminifera) are not enough in number in a core collected by Gouge, Russian-type or Dacknowski samplers.

Pollen and diatom are two powerful tools for reconstructing the environmental conditions during the recent geological past. These two techniques have more advantages than other fossil studies which are as follows:-

1. Both require only a small amount of sediment for analysis in contrast to other fossil studies.

2. Because of their abundant occurrence in the sediment, counting of a significant number of pollen or diatom under a microscope, can be applicable as a relative proportion to represent the environment in which the sediment was deposited.

3. Both the pollen and diatoms can be identifiable at various taxonomic levels with confidence.

4. In case of pollen, during the fossilization, intine substances are easily destroyed (Faegri and Iversen, 1989) whereas the sporopollenin-containing exine is resistant to decay and it carries all the morphological characters necessary for pollen recognition (Moore *at al.*, 1991). If they are examined from several levels through a sediment column, they provide a record of the history of vegetational and environmental changes over time.

5. 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 (Moser *et al.*, 1996), 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). If they are examined from several levels through a sediment column, they provide a record of the history of sedimentation, water quality

and environmental changes over time.

However, these techniques also suffer from some limitations. The successful application of these techniques as proxy data largely depends upon the representation of the environment dealt with and many uncertainties remain with such representation. Pollen analysis is based on the assumption that before reaching the ground pollen is well mixed by atmospheric turbulence, uniformly distributed over an area and statistically represents the vegetation coverage at a particular period. Similarly, diatom analysis is based on the assumption that diatom species are autochthonous in origin, before buried they are uniformly distributed within the watermass, and statistically represent the water quality and sedimentary sequences when they are deposited. It is difficult to say whether the pollen and diatoms counted under the microscope satisfy these above assumptions. However, repeated application of these techniques can make it easier to understand many of these potential problems. Palynology and diatom analysis are now two powerful methods and are widely being used by scholars to investigate many palaeoenvironmental issues, including the study of Holocene sea-level movements.

Chapter 5: PRESENTATION OF DATA: PANIGATI

5.1. INTRODUCTION

The aim of this chapter is to present empirical data from the site at Panigati, Khulna.

5.2. LITHOSTRATIGRAPHY

At Panigati, 23 boreholes were put down in two transects (Fig. 5.1) covering an area of one square kilometre. Three preliminary boreholes (P-0, P-30N and P-30S) were first sunk at 30 metres intervals; these did not show significant variations in lithology. The borehole interval was then increased to 100 metres; they were put down in a north-south, east-west intersect with borehole P-0. To avoid any disturbance to the sediments covered by the digging of the Kachu beel *khal*, one hole (P-208W) was sunk at 208 metres west of P-0. The selection of the interval between boreholes is site dependent. In an area where lithology changes very sharply over a short distance, a high resolution sampling interval is required. At the present site, where the surface topography and the lithology do not show significant changes over a short distance, a lower resolution is acceptable.

5.3. BOREHOLE RECORDS

Field records have been compiled following the Troels-Smith (1955) scheme (discussed in section 4.2.v) covering a total core length of 163.3 m. The cores vary in length from 5.6 m to 10.1 m. Borehole P-200E shows the maximum number (23) of strata, whereas the minimum number, only 10, have been recorded in cores P-30N and P-300N (see Appendix 7).

From the 23 boreholes, core P-208W provided most of the major sedimentary sequences found in the area. The whole core from P-208W and part of the core from P-500W have been utilised for laboratory analyses. Figures 5.2 and 5.3 provide their respective lithological description. Although many individual strata are identified in the borehole records, it is possible to aggregate some of the strata into larger, informal, sedimentary units (phases) in order to simplify description of vertical sequence of deposits. Careful scrutiny of all the borehole records (Fig. 5.4) reveals 12 distinct sedimentary phases within the investigated area. Each phase is discussed below, with particular attention to the principle core P-208W. Records of all these boreholes are presented in Appendix 7.

i. Phase-I (Clayey-silt)

This battleship-grey, minerogenic sediment consists of silt and clay with some woody fragments. The deposit is coarsely stratified and some herbaceous detritus is embedded within the laminations. The upper part of the phase has an admixture of sand particles (P-500W and P-400W). Some rootlets of herbaceous plants and traces of decomposed organic matter have also been observed. The phase shows a diffuse upper boundary and is overlain by the lowermost peat bed. In core P-100N, the phase includes up to ~50% fine sand.

ii. Phase-II (Peat-1)

This is the lowermost peat (peat-1) which has been recorded in six boreholes (P-500W, P-400W, P-208W, P-100W, P-200N, and P-100N). The layer is dark brown in colour, becoming slightly lighter at P-200N and P-100N due to incorporation of some clay particles. Organic components in core P-400W, P-100W and P-100N are partly decomposed, forming a mud-like organic substance and plastic. In other cores the peat is elastic, crumbly, shows no stratification and brittle. This ~ 15 cm thick peat layer is overlain by inorganic sediments; the upper boundary is difficult to discern, except in core P-208W where it is sharp and perhaps an erosional contact.

iii. Phase-III (Silty-clay)

This battleship-grey, silty-clay sediment becomes browner when it contains more decomposed organic matter (P-300W and P-208W). Some woody detritus and herbaceous rootlets are also present in this sediment. Apart from the middle section of core P-500W, this layer includes frequent sandy particles. Sand particles are also present in cores P-500E, P-300N, P-100S, P-400S, and P-500S. In cores P-100W and P-200E, the phase shows an upward change from a sandy-clayey-silty to a silty-clayey texture with rare herbaceous detritus. The sediments are coarsely to well laminated, the phase is about 1 m thick, and is overlain by a peat bed (peat-2). The upper boundary of the phase is diffuse which indicates a gradual change to the next sedimentary phase.

iv. Phase-IV (Peat-2)

Except in cores P-500W and P-500S, this dark-brown peat layer (peat-2) has been recorded in all boreholes. The layer is composed of herbaceous fragments and many wood particles from mangrove species. *In situ* herbaceous rootlets are also present (P-208W, P-0, P-30S, P-200S, and P-300S). In some cores (P-200S, P-300S, and P-400S) the peat is found mixed with some minerogenic sediment and becomes plastic. Except in cores P-400W, P-208W, and P-0, the peat bed overlies a brown, organic, peaty sub-layer at its base which is mixed with some clay particles. In cores P-500N, P-400E, and P-

500E, the peat bed interdigitates one or more brown-grey, organic-clay layers. This ~40 cm thick peat bed is coarsely laminated and shows a diffuse upper boundary. In cores P-100E and P-300N, the upper boundary has possibly been eroded by the overlying sandy-clayey-silty sediments.

v. Phase-V (Organic silty-clay)

This organic, silty-clay is light grey to battleship-grey in colour and is composed of some herbaceous detritus, and rare rootlets of herbaceous plants. The layer is well developed in cores P-100W and P-400E; the thickness is up to about 150 cm. In cores P-0 and P-100E, rare organic components are present. A 15 cm thick peaty-clay sub-layer is intruded into this sediment phase in core P-200E; this sub-layer has a diffuse lower boundary and an indistinguishable upper boundary which indicates a gradual change of sedimentary sequence without any sign of erosion. In cores P-200N and P-100N, this sediment phase is associated with some fibrous *limus* components. The sediment varying between plasticity and extreme coarseness in structure, is overlain by a peat layer (peat-3) and shows a diffuse to nearly absent upper boundary.

vi. Phase-VI (Peat-3)

This peat bed is dark brown to brown in colour, stratified, and in some cases crumbly (P-500W, P-300W, P-400E, P-500E, P-200S, P-300S). Some pink woody fragments of mangrove plants and some mangrove tree barks are present. Many herbaceous fragments, possibly of *Phragmites karka* are embedded along the laminations. *In situ* rootlets of herbaceous plants are also found. Particularly in core P-0, these rootlets constitute a significant proportion of the layer's composition. This peat is well developed and is about

1 m thick in cores P-500W, P-200N and P-100N; in the principle core (P-208W), it is 55 cm thick. In cores P-100E and P-300E, an organic-peaty sub-stratum mixed with some minerogenic particles has developed at the base of the peat, without developing any clear visible boundary and any sign of erosion at its contact. In 4 cores (P-100S to P-400S) the peat layer directly overlies peat-2 without any separating minerogenic layer in between; the presence of a diffuse boundary between them confirms their development as two separate peat sequences. The upper boundary of the peat is also diffuse and is overlain by an organic silty-clay layer.

vii. Phase-VII (Organic silty-clay)

This organic silty-clay sediment is brown-grey in colour and includes frequent herbaceous detritus. Rare woody fragments are also found. The colour becomes slightly darker when the sediment is mixed with *limus* and other organic materials. Some rootlets of herbaceous plants are also present, particularly in core P-0. In some cores (P-200N, P-100S, and P-300S) *limus* components are also present and take on proportions such that the identification of this layer as a separate bed is difficult, unless the stratum boundary is considered. In core P-30N, this layer is totally absent; rather a 120 cm thick peat layer overlies Phase-V deposits. Whether the peat layer at this borehole has been developed as peat-3 or as the next peat bed (peat-4), is not clear. Confusion also arises about the lithological sequences in core P-400N and P-500N. Possibly, the stratum-3 of P-400N and stratum-9 of P-500N is the continuation of Phase-VI. In core P-300N, a 3 m thick minerogenic bed without any decomposed organic matter has been formed. Whether this layer was deposited as Phase-VII or as a separate localized sediment sequence, is difficult to say. The sediment of Phase-VII varies in plasticity and becomes coarsely laminated.

Its upper contact is diffuse and poorly traceable (except in P-500E) which indicates a gradual change to the next sequence (peat-4).

viii. Phase-VIII (Peat-4)

This peat layer is light brown to brown in colour and sometimes becomes dark brown to blackish depending upon the degree of decomposition and oxidation. For example, at P-208W the lower part of the peat is more decomposed and darker than that of the upper two-thirds; a diffuse boundary has developed between these two sub-phases of the same peat. Pink to light brown woody fragments are more frequent in this peat than its predecessor (peat-3). Some of these wood fragments are from the mangrove plants, while at least some being from *Heritiera fomes*. Some other macro-fossils, such as buds, bark and fruits have been recorded. *In situ* monocot. rootlets are also present. The peat layer is well developed in most of the cores and in core P-208 it is 76 cm thick; the maximum thickness is about 1 m in core P-100S. The peat is well stratified and along the laminations, stems and leaves of herbaceous plants, and some dicot. leaves are embedded. In core P-300W the peat is mixed with some clay particles. A sub-stratum of organic clayey-limus-peat has been developed in the upper end of cores P-200E and P-500E, and also at both ends of cores P-300E, P-500N and P-400N. In cores, P-400E and P-100S, a thin sub-layer with frequent clay particles is intruded into the peat bed. The upper boundary of the peat is diffuse and shows a gradual change to the next sequence which is of minerogenic nature.

ix. Phase-IX (Organic Clayey-silt)

This layer is light grey to brown grey in colour and composed of silt particles together with clay and decomposed organic matter. Rare herbaceous detritus and woody fragments are present. Some *turfa* of herbaceous plants is also found, particularly in core P-100S. In cores, P-208W, P-100W and P-100S, a large proportion of *limus* particles are present. A battleship-grey, coarsely laminated sub-layer with frequent sand has been developed between this bed and peat-4 in cores P-200E and P-300E. The sediment of this phase is plastic and sticky, the upper boundary is diffuse to nearly untraceable and shows no sign of any erosional contact.

x. Phase-X (Peat-5)

This is the uppermost peat. It is well developed on the western and southern parts of the site and has a maximum thickness of 73 cm (P-400W); in the principle core (P-208W), it is 34 cm thick. A coarsely laminated, light brown and organic clayey-limus sub-layer, about 15 cm thick, has been developed (in most cores) over this peat bed; a diffuse boundary exists between this sub-layer and the peat. In core P-300S, a peat layer of 132 cm thick has been formed and whether this peat is a continuation of peat-4 or whether peat-5 is completely missing, it is difficult to say. The upper boundary of the peat in this core does not show any sign of erosion. The peat is dark brown in colour and well laminated. Some pink wood fragments of *Heritiera fomes*, some dicot. leaves, *turfa* from herbaceous plants and stems, possibly *Phragmites karka*, are embedded within the laminations. In cores P-300N, P-400N and P-500N, this peat lies nearly at the level of the present MSL. In some cores (P-30N to P-300N), the peat contains some clayey particles and lies directly on top of peat-4 without any intervening inorganic layer. This uppermost peat layer is overlain by inorganic sediments which were deposited in a fluvial environmental system. The change of sediment sequences from peat to fluvial system is gradual and does not show any major erosional evidence.

xi. Phase-XI (Silty-clay)

This battleship-grey, silty-clay phase with rare sand inclusions has covered the uppermost peat. The phase is well developed in the middle of the site and in cores P-0, P-30S, P-200S and P-500N, it continues up to the surface. In some cores (P-100W, P-300W to P-500W, P-30N and P-100N) it is intruded by some sand or sandy-silty-clay layers. Near the surface, the layer is buff-grey in colour, includes more silty particles, frequent sand, and traces of diffuse iron staining. Some rootlets of living herbaceous plants, possibly cultivated crops, are also present near the surface.

xii. Phase-XII (Sand)

The layer is well developed in the north-eastern part of the site, overlying the Phase-XI. The layer is mostly composed of light-grey to battleship-grey, sub-rounded, medium to fine sand particles which are coarsely to well-laminated and becoming buff-grey in colour near the surface (P-200E to P-500E) due to the presence of diffuse iron components. Some fragments of wood, bark, leaves and remnants of herbaceous plants are also present. This sandy layer is interfingered by occasional sandy-silty-clay (P-400E) or silty-clayey layers (P-100N, P-100S). At the western part of the site, the sandy layer is overlain first by the silty-clayey layer and then by the sandy-clayey-silty layer. The contact boundary between such interfingering does not show any major sign of disturbance, except in cores P-100E, P-400E and P-100N where the sharp contacts might suggest some erosional activity.

5.4. TRANSECTS

The progradation of the Bengal delta during the recent geological past is unequivocally accepted among scholars. Whether the coastline has been moving southward or south-eastward, can be understood from detailed sedimentological work of high resolution borehole intervals covering a wider area and a repetition of a similar kind of work at several sites. A grided sampling network could give a clear three dimensional view of the lithology of the sites. Such an attempt to achieve a systematic conclusion, however, requires intensive and lengthy team-work. Two right angle transects, therefore, can be considered as an acceptable sampling approach to provide a three dimensional lithological view of the site. At Panigati, this approach has been employed; an east-west and a north-south transect have, therefore, been considered. Despite the discussion of lithological sequences of boreholes in the previous section, some salient features from these transects are discussed below.

i. East-west Transect

The one kilometre long east-west transect (Fig. 5.4.I.a) shows clear sequences of peats and minerogenic sediment layers. Most of the peat beds are more or less parallel and have a horizontal to sub-horizontal alignment. The uppermost peat is about 1 m and the lowermost peat is 5 to 6.5 m below the MSL. Most of the peat beds are well developed and persistent along the transect; the uppermost peat is better developed in the western part. The changes in lithology from one sequence to another are gradual and are indicated by the diffuse and undisturbed stratum boundaries. The sub-stratum of clayey peat, overlying peat-5, is well developed in the western part. In the middle part of the transect (P-100E), the development of a sandy-silty-clayey layer on top of peat-2 shows some interdigitation of layers which could be the result of some localized process; the contact between peat-2 and that of the overlying minerogenic layers is very sharp and possibly erosional. This sandy sediment is overlain by a silty-clay layer which does not show any sign of disturbance, rather it has an uniform lithology and indicates the same sequence as that of Phase-V. Records of possible localized sedimentation have also been found at the western end of the transect (P-500W) on top of peat-1 where alternating sandy-clayey-silty and silty-clayey sediment layers are interfingering each other forming three separate sub-stratum. Overlying the uppermost peat, particularly in the eastern part, thick sandy beds have been deposited; in the western part, the sandy layers become thinner and shows some interfingering of silty-clay layers.

ii. North-south Transect

This transect intersects the east-west transect at right angles at core position P-0 and divides the site into quadrants (NW, SW, NE, and SE). The lithology of the north-south transect is rather complicated; sequences of sediments are not as well developed as those of the east-west transect. The peat beds are mostly well developed in the central and southern parts of the section, although the separating minerogenic layer between two subsequent peat layers is not well formed. The minerogenic sediment layer (sandy-silty-clay) overlying peat-3 in the south-central (P-300S) part of the section was perhaps deposited by some local process and is possibly the same layer as recorded in the east-west transect in core P-100E (stratum-IV). Similarly, the interfingering of alternating peats and organic silty-clay at the northern most part (P-500N) may be the same sequences as observed in the eastern-most part (P-500E) of the east-west transect. In the north of the section, thick layers of minerogenic sediments (P-500N and P-300N) have been developed on top of peat-2 which is totally absent in P-400N; in this core, rather, a continuous thick peat layer has been deposited. This may suggest the possibilities of some simultaneous occurrence of two different localized process of sedimentation operations, on either side of core P-400N and overlying peat-2. The uppermost peat bed (peat-5) has been developed more or less at present MSL on the northern part of the transect, but displays a marked change in altitude (about 1.5 m) in the central part; it may suggest differential compaction and subsidence within the area, or formation within a depression.

If the site is divided into two parts by drawing a NW to SE line through core site P-0, then, a three dimensional projection of the lithology at the site can be produced. This would suggest that different sedimentary environments existed to the north and east of the area compared with the south and west. The sub-layer overlying peat-5 has been developed well only on the south-west side. On the north-east side of the line, peat-3 is poorly developed, interfingering lithology is more significant and there is a thick deposit with sand particles. On the south-western side, the sedimentary sequences are well developed and the lithology possibly, preserves complete records of environmental history since the mid-Holocene at the site. The principle cores, P-208W and P-500W, are located in this part of the area. The only evidence of a major localized sedimentary event in this part is the deposition of a minerogenic sediment layer in between peat-2 and peat-3. The pattern of inorganic sediment layers overlying peat-5 suggests that the eastern and north-eastern parts of the area have been deposited under strong fluvial activities.

5.5. PEAT LAYERS AT PANIGATI

Five peat layers at Panigati have already been discussed in the preceding section. The lowermost peat (peat-1) is recorded only in six boreholes. This layer is only about 15 cm thick, includes some decomposed organic matter mixed with some clay particles. Occasional signs of erosion are present at both the upper and lower boundaries.

The second peat layer is thicker than peat-1; it is separated by a minerogenic layer with traces of decomposed organic matter. Virtually, all the other peats (peat-3, peat-4, and peat-5) are thick, well-developed, separated from each other by organic silty-clayey sediment and does not include any mixing of minerogenic sediments. In some cases, a sub-stratum, mixed with clay particles, is developed at the top and bottom of each peat. The boundaries between the peat and minerogenic layers are very diffuse, indicating a gradual change from one depositional environment to the other.

The major components of these peat beds are the remnants of herbaceous plants, *in situ* herbaceous rootlets (*turfa*) and wood fragments (*Detritus lignosus*) of mangrove species. Some of the wood fragments are pink in colour and become dark when exposed to the air. Possibly these are the wood fragments of *Heritiera fomes* because they are fibrous and pink in colour. Most of the peat beds are laminated. Some dicot. leaves and monocot. stems are embedded within these laminations. Sometimes, the peat becomes crumbly when it includes more fibrous components and plastic when it is mixed with inorganic sediments.

Both the upper and lower boundaries of each peat layer are diffuse to absent. In some cases sharp boundary contacts are also present which might be the result of localised erosion. Such an example is found at the upper boundary of peat-2 in core P-100E.

It has been demonstrated that the sediment deposited above the upper peat (peat-5) has no direct relationship to relative sea-level changes since they were deposited in a fluvial deltaic environment (section 5.3.x). However, sediments deposited below this uppermost peat and, the development of underlying alternative peat and minerogenic layers could have been related to relative sea-level changes. Further discussion on this possibilities will be made in section 7.2.i.

5.6. RECORDS OF CHARCOAL

No systematic attempt has so far been undertaken to record charcoal evidence from the sediments of the Bengal Basin. During the field work at panigati, a large number of macroscopic charcoal fragments were recorded. They were found from almost every peat layers; only in peat-1 do they appear to be absent. This peat was reached only in 6 boreholes; therefore, it could not be claimed that this peat layer is devoid of any charcoal record.

Peat-4 and peat-5 show charcoal evidence more frequently than other peat layers. The central part of the investigated area had the highest charcoal concentration. Except for P-400E and P-500E, charcoal were recorded in all the boreholes, either in every peat layer or at least one of them. An example, charred particles contained more than 2% (anth++) of the composition in stratum-4 of core P-300W, and shows a calibrated age of *ca.* 6000 yrs BP.

The origin of this macroscopic charcoal remains is not clear. It would be very unusual for it to have been derived from natural fires in this tropical environment; that would have demanded very different climatic conditions from those which obtain today. Domestic fires are the more likely explanation. That would suggest widespread human activity in the area over a long period during the mid-Holocene, but it requires more supporting archaeological evidence to argue for that.

Further work in the Bengal Basin requires the application of charcoal counts and quantification (Clark, 1982) as part of any palynological investigation. It would then be possible to explore another research tool for the understanding of environmental events in the Bengal Basin.

5.7. PARTICLE SIZE ANALYSIS AND LOSS-ON-IGNITION

21 samples from P-208W and 7 samples from P-500W were analyzed for particle size. At least one sample was taken from each separate minerogenic sediment layer. It was mentioned earlier (section 4.3.iii) that the aim of such an analysis is to secure the accuracy of the field records of the sediments. Some differences between the laboratory and field analyses have been observed (Appendix 9). For example, at depth 280 cm of stratum 16 (P-208W), the field record is As2,Ag1,Ga1 which means a composition of 50% clay, 25% silt and 25% sand, whereas the laboratory analysis shows 4% clay, about 77% silt and 18.6 % sand. Therefore, the possibility exists that inaccurate estimation of the clay-silt proportion occurred. Shennan (1986a) also had a similar experience. In his sample from Cowbit Wash area in the Fenland, he described the sample at depth of 745-750 cm of stratum 11 as Ag2,As2 which means 50% silt and 50% clay; his laboratory

analysis shows only 10% clay, about 90% silt and <1% sand. The exact identification of silt-clay proportion in the field is a matter of experience; as a worker becomes more experienced such discrepancies can be reduced. Besides, the application of the four-scaled description technique of Troels-Smith (1955) scheme to describe 7 categories of inorganic particles is likely to induce confusion over the various proportions present.

Loss-on-Ignition measurements were also carried out on those samples (Fig. 5.5). The organic content of most of the samples is less than 10%. Where samples have >10% organic content, the organic matter has been removed before the particle size analysis was undertaken. Results of particle size analysis are presented in Figure 5.6. Each minerogenic layer below peat-5 shows a more or less similar pattern whereas above it, the pattern is quite different. This might suggest two different depositional phases within the area, namely estuarine and fluvial, respectively, although additional evidence is required to support this assertion.

5.8. UMITSU'S BOREHOLE RECORD

It was mentioned earlier that Professor Umitsu of Nagoya University, Japan had collected a 70 m long core at Daulatpur, about 3 km south-west of Panigati, in 1987. He has given permission for the present author to re-assess the nature of the sediment in his core. A total of 43 samples between 25 and 70 m of his core have been reused for particle size analysis (Appendix 10). The aim in re-examining the data was to get a possible correlation with the borehole records collected for the present investigation. Umitsu's (1987) core covers the deposition sequences of the Bengal Basin since the late-Pleistocene. His core (Fig. 5.7.a) has a ^{14}C date of 7640 ± 100 (NUT) at a depth of 27 m, which is about the same age as the sediment at the base (1010 cm) of core P-500W. It was possible to recognise a larger number of sediment facies than he originally observed. Eight different facies (zone 7 to 14 in Fig. 5.7.b) were identified only between 47 and 25 m depth with an age range between 12000 to 7600 BP; Umitsu (1987, 1993) suggested only 5 sedimentary units (in the whole core) since the late Quaternary. Radiocarbon dates 7600 $\pm$100BP at Daulatpur and 8210 $\pm$60BP at Panigati, at a depth of 27 m and 10 m, respectively and the particle size data from two sites suggest that a possible correlation of the base of core P-500W (10.1 m) can be made at some point in between 27 m and 30 m of the Umitsu's core. The 20 m depth difference between the cores obtained from these two sites (Panigati and Daulatpur) may not be usual due to only their altitudinal difference. It is possible that his single core was taken from some deep localized sub-surface basin or buried channel where thicker sediment layers had developed in each depositional phase as compared with Panigati. If records had been obtained from a large number of boreholes, as at Panigati (23 boreholes), more confident conclusions could be drawn. Furthermore, Umitsu's (1987) core was not properly levelled to any reference datum. However, his 1987 and 1993 works provide the foundation for further investigations in this area.

5.9. CORRELATION OF THE LITHOLOGY

Correlation of different sedimentary layers recorded from the borehole data is a complex and complicated task in lithological analysis. The simple connection of a stratum boundary by a straight or dotted line could give rise to a false correlation. It can be achieved with greater accuracy if it has been based upon a good quality and repeated palynological record, provided the pollen assemblage indicates a simultaneous sedimentary sequence of the layers to be correlated. A large number of radiometric dates could also be used and with greater confidence, but this is a very expensive practice.

The present investigation suffers from such problems. No previous pollen data exist and the number of published ^{14}C dates is very limited. Despite such drawbacks, another approach to correlation could be proposed, using the colour, physical composition and stratum boundary of different sediment layers; such a practice would still produce very tentative results. Figure 5.4.II. shows such an attempt.

5.10. BIOSTRATIGRAPHIC RECORD: POLLEN

Pollen records have been used as evidence of palaeoenvironmental changes at the site. The technique of palynology has been discussed in Chapter-4 (section 4.3.i). From the two cores (P-208W and P-500W), collected for laboratory analyses, 58 samples, 45 from core P-208W (340 cm to 810 cm) and 13 from the core P-500W (830 cm to 1000 cm), have been used for pollen analysis. Generally, a minimum of 150 land pollen have been counted from each level. Any level, having less than 100 grains, has not been included in the percentage frequency analysis and as a result, pollen data from 13 levels have not been graphically presented. A full record of pollen counts for each level is given in Appendix 12 (P-208W) and Appendix 13 (P-500W).

Pollen are counted and recorded within five categories- trees, shrubs, herbs, and aquatics and fern spores, of which the first three are grouped together as the land pollen and life form classes, and the remaining two as their own separate groups. Aquatic taxa are a unique life form class, and it is generally regarded that the pollen of aquatic taxa are local. Data are presented in pollen diagrams (Fig. 5.8 and Fig. 5.9) and the counts are expressed as percentage of the total count of the land pollen and that of the respective category. For example, pollen counts at every level for each taxon of tree, shrub or herb is expressed as a percentage of the total land pollen count at that level; similarly, that of aquatic taxa are expressed as a percentage of land pollen plus aquatic pollen and similarly for fern spores (see Tooley, 1981). The main part of the pollen diagram shows the percentage frequencies of each species and the right hand side provides a summary result, the cumulative percentage of the pollen of trees, shrubs, herbs and aquatics.

5.11. LOCAL POLLEN ASSEMBLAGE ZONES

The pollen diagram for P-208W (Fig. 5.8) shows 13 pollen zones and that for P-500W (Fig. 5.9) three. From the lithostratigraphic records, it has already been argued that the peat layer of P-208W (between 692 cm and 705 cm) and P-500W (between 830 cm and 842 cm) is the same stratum (peat-1). As a result, the pollen records from these two cores could be described as coming from a single sampling site. Fourteen local pollen assemblage zones (LPAZs) have, therefore, been proposed as coming from the investigated site. The evidence of the pollen assemblages combined with the lithostratigraphy of the zone and the evidence of proceeding zones has enabled the ecosystem trends of the zone to be evaluated.

i. LPAZ-I: (*Excoecaria-Heritiera-Sonneratia*)

Depth: 1010-985 cm (core P-500W)
Lithology: Organic Silty-clay

The zone (Fig. 5.9) is characterized by a high frequency (~70 %) of the pollen of mangrove trees; *Excoecaria* (~21%), *Heritiera* (~12%), *Sonneratia* (~8%) and *Xylocarpus* (~7%) are the major species. The zone also includes *Rhizophora* (~5%), *Avicennia* (~4.5%), *Bruguiera* (~4%) and *Ceriops* (~3%) pollen. A large number (~27%) of herbaceous, such as *Cucumis* (~10.5%), Gramineae (up to 10.6 %) together with some (~3.4%) shrubs pollen and fern spores are also found. The zone shows a gradual upward decrease of mangrove tree and an increase of herbaceous pollen frequencies indicating a declining mangal ecosystem.

Ecosystem: A declining mangroves forest environment indicating an increasing marine influence.

ii. LPAZ-II: (Infrequent Pollen)

Depth: 985-855 cm (core P-500W) and 820-725 cm (core P-208W)
Lithology: Organic Silty-clay

The zone (Fig. 5.8 and 5.9) is characterized by a sporadic occurrence of pollen grains; a total count of only about 40 land pollen is available from each level, and hence, is not shown on the pollen diagram. Most of the pollen is from the mangrove trees, predominantly *Excoecaria* and *Heritiera*. Some *Sonneratia, Rhizophora, Ceriops, Bruguiera* and *Amoora* have also been identified and counted. Pollen of herbaceous plants are mainly from Gramineae and *Cucumis*. Some pollen from *Suaeda* and Cheno-amaranthaceae have also been found. Except for a few *Typha*, aquatic pollens are virtually absent as is also the case for shrub pollen. Sporadic fern spores occur. Due to low pollen counts, data from this zone have not been used for percentage frequency analysis and graphical representation.

Ecosystem: The mangal ecosystem probably continued to decline as the site became progressively under marine condition.

iii. LPAZ-III: (*Excoecaria-Heritiera-Ceriops*)

Depth: 855-825 cm (P-500W) and 725-690 cm (P-208W)
Lithology: Organic silty-clay (lower) and peat (upper).

The LPAZ between 855 cm and 825 cm in core P-500W and that of between 725 cm and 690 cm in core P-208W shows a similar pollen assemblage which suggests that they were deposited in a similar environmental condition and under a similar phase of sedimentation. These two zones is, therefore, nothing but the same zone, where Figure 5.9 and Figure 5.8 are linked together as LPAZ-III. The zone (Fig. 5.9 and Fig. 5.8) includes a high frequency of land pollen of which about 75% are from mangrove trees; *Excoecaria* (~30%) and *Heritiera* (~20%) are the two dominant species. It is also characterized by the occurrence of *Sonneratia* (~7%), *Typha* (~5%), *Bruguiera* (~2.5), *Rhizophora* (~2.4%) and *Avicennia* (~2.2%) pollen. Following the lithological boundary between the peat and underlying inorganic sediment, the lower part of the zone includes higher frequencies of *Ceriops* (~10%) pollen. It is also characterized by the occurrence of *Nypa* (~2%) and higher percentage of *Bruguiera*, and *Avicennia* pollen than to occur in the upper part. This part shows a fall in the frequencies of tree pollen, including *Excoecaria* and *Heritiera* (except *Rhizophora, Amoora* and *Aegiceras*) and a rise of (up to 50%) those from herbaceous plants, such as *Cucumis* (up to 14%), Gramineae (up to 20%), Cyperaceae (up to 4%), and ferns spores (up to 20%). Some pollen grains of *Phoenix, Potamogeton, Acacia* and Cheno-amaranthaceae have also been found in this part. The middle part of the zone is characterized by a relative decline of *Sonneratia*, and the occurrence of some *Xylocarpus* ($\sim 1\%$) pollen.

Ecosystem: The lower part of the zone (organic silty-clay) predominantly represents dense mangroves vegetation and the upper part (peat) represent mangroves but associated with a large number of herbaceous plants and ferns species indicating increasing freshwater influence and terrestrial ecosystem.

iv. LPAZ-IV: (Infrequent Pollen)

Depth: 690-675 cm
Lithology: Organic silty-clay

Like LPAZ-II, this zone also has a low pollen content (Fig. 5.8). Only about 30 land pollen have been counted from each level of which about 25 (83%) are from mangrove trees, and these data have not been used for percentage frequency analysis and graphical presentation. Most pollen in this zone are from *Excoecaria, Heritiera, Sonneratia* and *Typha*. In addition, pollen from shrub, herb and aquatic plants are sporadically present; some monolete, verrucate and psilate ferns spores have also been found, but have not been identified.

Ecosystem: Mangroves disappeared and the site came under a short period of marine influence.

v. LPAZ-V: (*Excoecaria-Heritiera-Sonneratia*)

Depth: 675-645 cm
Lithology: Organic silt-clay (lower) and peat (upper)

This zone is characterized by a high frequency of pollen from mangrove trees (67%) of which *Excoecaria* (~22%), *Heritiera* (~15%), and *Sonneratia* (~12%) are the three main species. In addition, pollens of other mangrove trees, such as *Rhizophora* (~5.3%), *Avicennia* (~2.7%), *Bruguiera* (~2.6%), *Ceriops* (~2.6%), *Aegiceras* (~2%) and *Amoora* (~1%) have been recorded. This zone is also characterized by the occurrence of *Cucumis* (~8.5%), *Phoenix* (~1.6%), Cheno-amaranthaceae (~1%) and *Aster* type (~1.2%) pollen, and some trilete and monolete ferns spores. Following the lithological boundary between the peat and underlying inorganic sediment, the lower part of the zone is characterized by a higher occurrence of *Sonneratia* (up to 19.2%), *Avicennia* (up to 6.6%), *Aegiceras* (up to 2.7%), *Xylocarpus* (up to 2.7%), *Potamogeton* (up to 3.1%) and *Phoenix* (up to 3.3%) pollen than those of the upper part. This lower part also shows some occurrences of *Barringtonia* (~1%), Umbelliferae (~2%) and *Anacardium* (~1%) pollen. The upper part has an increasing frequency of pollen from herbaceous plants (up to 41%), such as Gramineae (up to 25%) and Cyperaceae (up to 3.6%), and a decrease in the frequencies of pollen of most of the mangrove trees. Low frequencies of *Nypa, Plantago* and *Amoora* pollen and spores of *Acrostichum aureum* have also been found. The middle part of the zone is marked by a significant increase of *Excoecaria* (up to 30.6%) and *Heritiera* (up to 23%), and a decrease of *Sonneratia* (up to 7.1%) and *Cucumis* (up to 5.1%) pollen.

Ecosystem: A dense mangroves forest with some herbaceous plants and the site became under brackish to freshwater influence.

vi. LPAZ-VI: (*Excoecaria-Heritiera-Sonneratia-Avicennia*)

Depth: 645-625 cm
Lithology: Organic silty-clay

In this zone, the pollen frequency of mangrove shows an increasing value of up to 80%, of which *Excoecaria* (~28%), *Heritiera* (~14%), *Sonneratia* (~10%) and *Avicennia* (~7%) are the major species. It also reveals an increase of *Amoora* (up to 4%), *Barringtonia* (up to 3.5%), *Bruguiera* (up to 5.1%), *Ceriops* (up to 4.5) and a decrease of *Rhizophora* (up to 3.5%) pollen compared with the zone below. Pollen frequency of herbaceous and aquatic plants, such as *Cucumis,* Gramineae (small) and *Typha*, also shows decreases. Some shrub and aquatic pollen are found sporadically, while the fern spores frequency remains nearly constant.

Ecosystem: A dense forest vegetation dominated by mangrove trees together with a few herb and aquatic species, many ferns and some grass indicating a typical mangal ecosystem.

vii. LPAZ-VII: (*Excoecaria-Heritiera-Cucumis*-Gramineae)

Depth: 625-585 cm
Lithology: Organic silty-clay

The zone is characterized by an increase of herbaceous pollen frequency (~56%) and a decrease of mangrove trees (~42%). Among the mangrove species, *Excoecaria* (~17%), *Heritiera* (~7.5%), *Sonneratia* (~5.5%) and *Aegiceras* (~1.5%) pollen have been found throughout the zone. *Avicennia* (~3.5%), *Bruguiera* (~2.7%), *Ceriops* (~2%) and *Rhizophora* (~4%) pollen are only found in the lower half of the zone; the upper half shows some *Barringtonia* (~1.5%) pollen. *Amoora, Nypa, Phoenix, Potamogeton,* *Plantago,* Cheno-amaranthaceae and *Aster*-type pollen, and *Acrostichum aureum* and *Ceratopteris* ferns spores, are sporadically, and Cyperaceae (~2%) and Gramineae (small) (~3.5%) pollen, and trilete ferns spores, are more or less evenly distributed throughout the zone. The zone is mostly characterized by an increased frequency of *Cucumis* (up to 13.9%) and Gramineae (large, up to 45.5%) pollen and monolete, verrucate ferns spores (up to 13.9%).

Ecosystem: Decrease of mangroves vegetation due to increasing marine influence.

viii. LPAZ-VIII: (*Excoecaria-Cucumis*-Gramineae-Fern)

Depth: 585-525 cm
Lithology: Peat

The zone is distinguished by a quite different pattern of pollen frequency when compared with the zones below. Mangroves tree pollen provide only about 14% of the total land pollen. *Excoecaria* (~10%) and *Heritiera* (~3%) are the only two mangrove trees of which the pollen have been recorded throughout the zone. *Excoecaria* pollen frequency first decreases at the base (2.4%) and then gradually increases (up to 16.9%) upwards. Some *Rhizophora* and *Sonneratia* pollen have been found in the uppermost part of the zone. With few exceptions, shrub and aquatic pollen are virtually absent. The zone is mostly characterized by the strong representation of herbaceous pollen (~85%) which reaches 97.6% in the lower part, where *Cucumis* pollen and monolete, verrucate ferns spores also have their highest frequency (up to 33.9% and 26.9%, respectively). *Cucumis* pollen first declines in the middle of the zone and then again increases upwards. Gramineae (large) pollen, and monolete, psilate spores have their highest frequency in the middle of the zone (up to 67.4% and ~25%, respectively).

Ecosystem: A more or less dense open grassland, but with some mangrove trees indicating mangal to freshwater terrestrial ecosystem.

ix. LPAZ-IX: (*Excoecaria-Heritiera-Avicennia*)

Depth: 525-495 cm
Lithology: Organic clay

The zone is characterized by a reappearance of mangroves tree pollen, particularly up the profile. In the lower part of the zone, except for *Excoecaria* (~30%), other trees and shrub pollen are absent. This part of the zone is mostly characterized by a large amount (up to 66.6%) of Gramineae (large) pollen and ferns spores, mostly monolete, psilate (up to 25%) but with some monolete, verrucate forms (up to 8.3%). The upper part is distinguished by a rapid increase in *Excoecaria* (up to 80.7%) pollen frequency. In addition, *Avicennia, Bruguiera, Ceriops, Rhizophora, Sonneratia* pollen occur sporadically, while the *Acrostichum aureum* and trilete, psilate ferns spores are frequently present. Unlike the zone below (LPAZ-VIII), *Cucumis* pollen disappears from this LPAZ, except in the middle part where it has a frequency of 19.6%. The occurrence of an exceedingly large number of *Typha* (50%) pollen at the lower level is a significant characteristic of the zone.

Ecosystem: First a rapid marine influence and then becoming a mangal environment.

x. **LPAZ-X: (*Rhizophora-Typha*-Gramineae-Fern)**

Depth: 495-465 cm
Lithology: Organic clay (lower part), and peat (upper part)

The zone is noticeably marked by a sudden decline of *Excoecaria* (only ~4%) pollen, the occurrence of large numbers of ferns spores and the low representation of shrub pollen. Following the lithological boundary between the peat and underlying inorganic layer, the lower part of the zone is characterized by *Rhizophora* (~5%), Cyperaceae (~6.5%) and the sporadic occurrence of pollen of mangrove trees. *Cucumis* pollen and monolete, verrucate fern spores have the highest occurrence at the lower end of this part (30.9% and 39.7%, respectively). The upper part shows an increasing number (up to 52.6%) of Gramineae (both large and small) and *Typha* (up to 23.8%) pollen and trilete, verrucate fern spores (up to 9.3%). *Plantago, Acacia,* Cheno-amaranthaceae and *Sonneratia* pollens are sporadically present in this part. The middle part of the zone is particularly characterized by increased frequencies of pollen of mangrove trees, such as *Ceriops* and *Heritiera* and those of ferns spores of *Acrostichum aureum*.

Ecosystem: A mangroves forest together with a large number of herbaceous plants, including grassland indicating a mangal ecosystem with some influence of freshwater conditions.

xi. **LPAZ-XI: (*Excoecaria-Heritiera-Sonneratia*)**

Depth: 465-435 cm
Lithology: Peat

The zone is characterized by a steep rise in pollen frequencies (up to 91.6%) of mangrove trees, mostly *Excoecaria* (~58%) and by a drop in herbaceous, particularly in the upper part. *Heritiera* pollen frequency shows an upward increasing value (up to 27.8%); *Sonneratia* pollen (~5%) and monolete, psilate fern spores (~3%) are found to be evenly distributed. *Amoora, Avicennia, Ceriops, Rhizophora, Nypa* and *Phoenix* pollen are sporadically found. *Anacardium* pollen and monolete, verrucate fern spores decrease in value upwards. Gramineae pollen, except at the lower part, are rare and at the upper part virtually absent. *Typha* pollen are infrequent in the middle part of the zone whereas in the lower and upper parts many (~13.5% & ~7.9% , respectively) have been found.

Ecosystem: A dense mangroves forest dominated by *Excoecaria* and *Heritiera* trees indicating a mangal ecosystem with some freshwater influence.

xii. LPAZ-XII: (*Excoecaria-Cucumis*-Monolete Ferns)

Depth: 435-405 cm
Lithology: Peat

The zone is distinguished by a general fall in tree (up to 17.8%) and a rise in herbaceous (up to 82.2%) pollen frequencies. *Excoecaria* pollen, although showing a decreased value compared with the zone below, constitute the major proportion (~27%) of total land pollen. The lower part of the zone is characterized by some Cyperaceae and Gramineae pollen. *Cucumis* pollen and monolete, verrucate fern spores have declining value (40-22.4% & 51.9-26.6%, respectively) towards the top of the zone. *Avicennia, Heritiera, Rhizophora, Nypa* and *Anacardium* pollen and trilete spores are sporadically found, particularly in the upper part. The middle part of the zone is remarkable for its exceedingly high frequency of *Typha* pollen (42.9%) and also for the occurrence of

Barringtonia, Umbelliferae and *Acacia* pollen.

Ecosystem: Mangroves forest dominated by *Excoecaria* trees, and together with a large number of ferns and herbaceous plants; occasional high freshwater discharge, as evident by high *Typha* values, possibly due to occasional flooding (see section 8.5.ii).

xiii. LPAZ-XIII: (*Excoecaria-Heritiera-Avicennia-Cucumis*)

Depth: 405-385 cm
Lithology: Organic peaty-clay

This zone shows another rise in mangroves tree pollen frequencies (up to 64%) of which *Excoecaria* (~40%), *Heritiera* (~9%), *Avicennia* (~3.5%), *Ceriops* (~3.5%), *Rhizophora* (~3.5%) and *Barringtonia* (~2%) are the most common types. Herbaceous pollen occupies about 35% of the total land pollen and shrub pollen are sporadically found. Gramineae pollen and monolete, verrucate fern spores have increasing value (up to 19.6% & 22.2%, respectively) towards the top of the zone contrary to the pollen frequency of *Cucumis*. Aquatic pollen and trilete fern spores are rare in the zone.

Ecosystem: Mangroves with a possible increasing marine influence

xiv. LPAZ-XIV: (*Cucumis*-Gramineae-Fern)

Depth: 385-340 cm
Lithology: Peat and peaty-clay

Except for a few *Excoecaria* and *Heritiera*, mangroves tree pollen have mostly disappeared from this zone; shrub pollen are sporadically present. The zone is mostly characterized by a high frequency of herbaceous pollen (~89%) of which *Cucumis*

($\sim$11%), Gramineae (large) ($\sim$57%), Gramineae (small) ($\sim$15%) are the major types. Gramineae (small) pollen are more strongly represented in this zone than in the underlying zones. This zone is characterized also by a large number of monolete, verrucate fern spores, particularly in the middle part (up to 49.8%). The upper part shows some aquatics, mostly *Typha* ($\sim$4.5%), and also low frequencies of Cheno-amaranthaceae and Compositae pollen. The zone indicates an open grassland.

Ecosystem: Open grassland together with a large number of ferns indicating a freshwater terrestrial ecosystem.

5.12. POLLEN CONCENTRATIONS

Pollen concentration is the number of grains per unit volume or mass of wet or dry sediment and the units are grains cm^{-3} or grains gm^{-1} (Birks and Birks, 1980). A knowledge of pollen concentrations at each level of sampling is very useful in environmental reconstructions. Changes in relative pollen frequencies presented in a pollen diagram can be more apparent than real. Such a problem can be overcome by knowing the pollen concentrations of each species because they are all independent of one another (Cundill and Whittington, 1983).

In this study, tablets containing exotic spores of *Lycopodium* (Stockmarr, 1971) were added to a known volume (0.5 cm^{-3}) of sample in order to estimate the land pollen concentration at each level. Differential pollen concentrations have been reported in different pollen zones (Fig. 5.10). The pollen concentration value varies from only less than $2x10^3$ grains per 0.5 cm^{-3} in minerogenic layers (LPAZ-II) to more than $55x10^3$

grains in peat layers (LPAZ-XI). Differential pollen concentration in various zones may either suggest differential pollen input or sedimentation rates (Cundill and Whittington, 1983), or, indeed, both. At this stage of current knowledge, it is difficult to isolate these factors, although it can be speculated that a low concentration of pollen grains, in each minerogenic layer, is due to a low pollen input, deposited in an estuarine condition. On the other hand, high concentration, which coincide with the *in situ* organic layers (Fig. 5.10), suggests a high pollen input onto the site from mangrove plants and also, possibly, low rate of peat accumulation, or both.

5.13. BIOSTRATIGRAPHIC RECORDS: DIATOMS

Attempts were made to use diatom as evidence of sea-level movements, depositional and environmental changes at Panigati. 25 samples from different levels in core P-208W and P-500W were considered for preliminary diatom identification. Most of these samples did not preserve any diatom frustules. Only a few marine and brackish species, such as *Coscinodiscus apiculatus, C. marginatus, C. radiatus, C. stellaris, C. spp. Opephora pacifica, Paralia sulcata, Cyclotella striata, Nitzschia filiformis* and *Synedra tabulata* have been recorded from depths between 8 and 10 m in core P-500W.

Application of diatoms in palaeoenvironmental reconstruction inevitably depends on the state of preservation of the frustules. The frustules are more frequently dissolved under very alkaline and also in very acid conditions (Birks and Birks, 1980). Dissolution is not considered to be a major problem in freshwater sediments (Mannion, 1982) but in marine conditions up to 75% of the frustules may be affected (Round, 1973). At present the coastal soils of Bangladesh are slightly alkaline to neutral with a pH of 6.5. to 8 (Islam, 1990; Karim, 1994). Little is known about the soil pH of the geological past, but given the evidence concerning the environment deduced from the pollen record, would suggest that the pH was possibly be the same as today. However, due to an absence of diatom frustules at Panigati, it was not possible to apply the technique at the site for this study.

5.14. CHRONOSTRATIGRAPHIC RECORDS: ^{14}C RESULTS

From Khulna and surrounding regions[1], 34 published radiocarbon dates[2] obtained by various workers, are available; these are presented in Table 5.1. Peat and mangroves wood were the most common materials used for the dating.

Careful selection of sediment samples for radiocarbon dating is a pre-requisite for any palaeoenvironmental study. The samples for dating must come from an *in situ* deposit, otherwise any dates obtained would provide a false framework for the reconstruction of a past environmental history. In this study, 5 samples from Panigati have been used for ^{14}C dating, of which 3 samples were taken from the P-208W (5P, 4P, and 3P), and 2 from core P-500W (2P and 1P). Table 5.2. shows the list of samples, their radiocarbon dates and the calibrated equivalent.

Samples 4P and 5P have been taken from the lower end of stratum-VII (peat-3) and from the upper end of stratum-XIII (peat-5), respectively and their respective ^{14}C age is 5210 $\pm$60BP and 1210 $\pm$80BP. These two samples have been taken from the sediment core collected using the Dacknowski sampler and, therefore, are unlikely to have been

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[1] Dates from Calcutta (India) and its neighbouring areas are also considered

[2] Most of these dating points are not properly levelled to any reference datum

contaminated by other sediment, either younger or older. A block of peat, about 6 cm in length, was required from each core to get sufficient carbon for conventional dating; sample 4P, therefore, may contain some younger material and sample 5P the opposite.

Sample 3P has been taken from the upper end of stratum-V (peat-2) and this gave a radiocarbon age of 3370 ±60BP. This date is not acceptable with respect to other published dates, and seems to be too young. It has, therefore, been rejected. Wood (sample 2P) was taken from the lower end of stratum-III (peat-1) of core P-500W for AMS dating; the resulting radiocarbon age was 5980 ±60BP. The field record suggests that the wood came from an *in situ* mangrove plant, and, therefore, the date it provided reflects the age of the sediments which would not be so if the wood had been detrital. The remaining sample (1P), an organic silty-clay sediment, was taken from the lower end of core P-500W and provides a radiocarbon date of 8210 ±60BP, the oldest recorded at the site.

Table 5.1.: Radiocarbon Dates Available from Khulna and Surrounding Regions

No	Site Name	Depth (cm)	Altitude (m)	Lithology	Material	C^{14} Age(BP)	Lab. Code	Source
1	Daulatpur, Khulna	500	-3.00	Peaty clay	Peat	3230 ±110	GaK 12952	Umitsu (1987)
2	*do.*	1600	-14.00	Peaty silt	Wood	6490 ±100	NUTA 342	*do.*
3	*do.*	1300	-11.00	Peaty silt	Wood	6880 ±130	GaK 12953	*do.*
4	*do*	2700	-25.00	Clay	Wood	7640 ±100	NUTA 343	*do.*
5	*do.*	3400	-32.00	Sandy clay	Plant fragment	8890 ±150	NUTA 344	*do.*
6	*do.*	3000	-28.00	Clay	Wood	10190±210	GaK 12954	*do.*
7	*do.*	4300	-41.00	Silty clay	n.a.	12010±210	NUTA 361	*do.*
8	*do.*	4800	-46.00	Fine sand	Plant Fragmt.	12320±240	NUTA 345	*do.*
9	*do.*	2000	-18.00	Clay	Shell	7060 ±120	NUTA 1342	Umitsu (1993)
10	*do.*	3500	-33.00	Sandy clay	Shell	8910 ±150	NUTA 1345	*do.*
11	Sankrail-I, Calcutta	137	+2.25	Peat	Peat	2615 ±100	TF 850	Vishnu-Mittre& Gupta(1972)
12	*do.*	182	+1.80	Peat	Peat	4075 ±100	TF 851	*do.*
13	Sankrail-II, Calcutta	304	+1.96	Peat	Peat	4720 ±135	TF 855	*do.*
14	*do.*	625	-1.25	Clay	n.a.	5810 ±100	TF 856	*do.*
15	Kolara, Calcutta	250	+2.50	Sandy clay	n.a.	1710 ±110	PRL 238	Gupta (1981)
16	*do.*	350	+1.50	Peat	Peat	4990 ±110	GrN 7138	*do.*
17	*do.*	575	+0.75	Silty-sandy-clay	Wood	5715 ±40	GrN 7136	*do.*
18	*do.*	650	-1.50	Silty clay	n.a.	6840 ±260	PRN 236	*do.*
19	Namkhana, Calcutta	175	+2.25	Sandy clay	n.a.	3170 ±70	GrN 7137	*do.*
20	Elgin Road, Calcutta	600	+0.60	Peat	Peat	2640 ±150	n.a.	Barui *et al* (1986)
21	*do.*	880	-2.20	Peat	Peat	6170 ±140	n.a.	*do.*
22	*do.*	1000	-3.40	Peat	Peat	6360 ±120	n.a.	*do.*
23	*do.*	1120	-4.60	Peat	Peat	6390 ±130	n.a.	*do.*
24	*do.*	1260	-6.00	Peat	Peat	7030 ±150	n.a.	*do.*
25	Bhowanipur, Calcutta	575	+0.25	Peat	Peat	3470 ±110	BS 544	Banerjee & Sen (1986)
26	*do.*	800	-2.00	Grey clay	Wood (*in situ*)	6210 ±130	BS 545	*do.*
27	*do.*	1210	-6.10	Peat	Peat	6650 ±120	BS 521	*do.*
28	Janai Road, Calcutta	450	+1.50	Peat	Peat	4080 ±110	BS 524	Banerjee & Sen (1987)
29	Kolaghat, Calcutta	525	-0.25	Peat	Wood	6480 ±110	BS 520	*do.*
30	*do.*	800	-3.00	Grey clay	Wood	6370 ±120	BS 533	Banerjee & Sen (1988)
31	Barakpur, Calcutta	610	-0.10	Peat	Peat	3030 ±100	BS 531	*do.*
32	Salt Lake, Calcutta	850	-2.50	Peat	Wood	4930 ±120	T 729	Chanda & Mukherjee (1969)
33	Bagirhat, Calcutta	550	-1.50	Silty clay	Wood	5080 ±110	T 730	*do.*
34	Dum Dum, Calcutta	650	-1.50	Grey clay	Wood	6175 ±125	TF 443	Agrawal & Kusumgar (1967)

Table 5.2. Radiocarbon Dates from Panigati

Sample Number	Depth (cm)	Altitude (m)	Stratum No	Sample	Lab Code	Type of Dating Technique	Conventional ^{14}C Age[1]	Calibrated Calender Years Range[2]	Intercept of ^{14}C age with Calibrated Curve[3]
P-208W									
5P	351-357	-(1.65-1.71)	XIII	Peat	Beta 79288	Conventional	1210 ±80BP	cal 665 to 1000 AD	cal 855 AD (1095 BP)
4P	575-582	-(3.89-3.96)	VIII	Peat	Beta 79287	Conventional	5210 ±60BP	cal 4215 to 4185 BC 4160 to 3940 BC and 3845 to 3830 BC	cal 3990 BC (5940 BP)
3P	650-651	-(4.64-4.65)	V	Peat	Beta 79479	AMS	3370 ±60BP	cal 1765 to 1510 BC	cal 1660 BC (3610 BP)
P-500W									
2P	840-842	-(6.50-6.52)	III	Wood	Beta 79478	AMS	5980 ±60BP	cal 4985 to 4750 BC	cal 4855 BC (6850 BP)
1P	999-1000	-(8.09-8.10)	I	Organic Sediment	Beta 79477	AMS	8210 ±60BP	cal 7415 to 7030 BC	cal 7245 BC (9195 BP)

[1] Quoted errors represent 1σ statistics (68% probability) and are based on combined measurements of the sample, background, and modern reference standard

[2] Calibrated Calendar Years represent 2σ statistics (95% probability)

[3] Calibrated results were prepared by Beta Analytic Inc. based on the works of Vogel *et al.* (1993), and Talma and Vogel (1993)

Chapter 6: PRESENTATION OF DATA: MATUAIL

6.1. INTRODUCTION

The aim of this chapter is to present data from the site at Matuail, Dhaka.

6.2. LITHOSTRATIGRAPHY

At Matuail an excavation programme enabled the author to get a clear view in all directions of the sub-surface lithology over a wide area from the exposed faces. Before detailed sampling, it was, therefore, necessary to select a suitable place, within the excavation, that would properly represent the lithological successions of the site (Photograph e. in Appendix 22). Lithology of the exposed faces was recorded following the Troels-Smith's (1955) scheme. Boreholes were put down at 5 m intervals (Fig. 6.1) along two transects (east-west and north-south). Due to significant changes in sediment characteristics, even over a short distance, a higher resolution borehole interval (5 m) than implemented at Panigati (100 m) had to be selected. The site was a depression or a burried valley filled by Holocene deposits.

The excavation work was so fast that sometimes it was difficult to have enough time to clean the excavation wall properly and to record the lithology, keeping in pace with the progress of the work[1]. The average depth of the excavation was about 2.5 m and at this depth, sometimes ground water penetrated and inundated the site. Along the east-west

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[1]The author is grateful to the labourers and their supervisor who kindly stopped their digging work for few days near to the investigated location, despite their schedule. They also enjoyed the field work and encouraged the author.

transect, boreholes were sunk to the floor of the excavation which was greatly interrupted due to such water flow. It should, however, be noted that the entire field work at the site had to follow the progress of the digging programme and in some cases, according to the advice of the supervisor of the excavation.

6.3. BOREHOLE RECORDS

24 boreholes were put down at the site of which the deepest was 707 cm (M-5E) and the shallowest was only 155 cm (M-35E). Core M-10.5E is one of those which includes the major sedimentary sequences. Figure 6.2 shows the stratigraphy and lithological description of this core; part of it, below the excavated floor (190 to 584 cm), was collected for subsequent analyses in the laboratory. Sedimentary layers above the excavation floor were collected from the free-faces in monoliths, the stratigraphy and sediment description of which are shown in Figure 6.3.

In each core about 16 sediment layers have been recorded; the highest number (29) of layers is in borehole M-25S. Descriptions of all these boreholes are presented in Appendix 8. Careful examination of all of these records (Fig. 6.4) shows at least 8 major sedimentary phases which have occurred within the area since the Pleistocene and these are discussed below.

i. Phase-I (Pleistocene Clay)

This is the lowermost sediment layer recorded at the site and has been identified as Pleistocene in age (Morgan and McIntire, 1959). It is light-blue-grey to light-grey in colour and consists of clay particles with some sand grains. In cores M-5W, M-10W and M-25W, the clay particles are replaced by sand and the base of core M-5W does not show any clay at all. Because of oxidation, the layer becomes brown to dark brown in colour, when exposed to the air for some time. In some boreholes clasts, mottled with iron, was found. A new nomenclature 'Madhupur clay' for this Pleistocene deposit was proposed by Khan in 1953 and published in 1962 (see Khan, 1991).

ii. Phase-II (Transition)

Some thin alternating layers of minerogenic components, such as sand, silt and clay with more distinctive heterogeneous sediment textures than in the underlying sediments (the Pleistocene clay) and in the sediments above (the organic silty-clay) can be characterised as a transition between the late Pleistocene and the early Holocene (Photograph d. in Appendix 22). The separating line between these early Holocene sediments and the underlying Pleistocene clay is very sharp and was seen clearly in all the boreholes, and also, in some places of the exposed face (Photograph h. in Appendix 22). This sharp contact indicates a large scale, late Pleistocene or early Holocene, erosional activity at the site. In cores M-10S, M-25S, M-5E and M-10.5E evidence of such reworking and redeposition is well recorded. A greater proportion of reworked sand particles is found in the deeper parts of the site (M-10S, M-5E); these might have as their source from the nearby higher Pleistocene landmass. The occurrence of some clasts mottled with iron, (M-15E, M-25S, M-10.5E) gives more convincing evidence about their origin and reworking. Some brown to dark-brown wood fragments also accumulated in the reworked deposits. The final stage of this transition phase can be characterized by an incremental supply of sandy particles and the development of a light brown to brown, thin layer of sandy-clay sediment (M-5N, M-15S, M-30S, M-5E and M-10.5E). In cores M-10S, M-

35S, M-40S and M-45S, a significant proportion of *limus* has been deposited with the clay particles. This indicates the possibility of the formation of a basal peat at the site. However, the record of such a basal peat, laid down within a disturbed and reworked transition phase, indicates that at least for some time the environment was relatively quiet and suitable for peat formation.

iii. Phase-III (Organic Silty-clay)

A thick layer, with some thin sub-layers, of light brown grey to brown grey, organic silty-clay sediment overlies the reworked deposits. Some sandy particles and herbaceous and woody detritus, along with rare dicot. leaves are also present. In addition, rootlets of the herbaceous plants were also found (M-20S, M-15E, M-20E); the sediment varies from very coarsely laminated to plastic and sticky. Alternating thin sub-strata, of slightly different colour and composition (mainly organic), and with a clear trace of boundary between them (M-10.5E, M-15S, M-20S, M-25S) were recorded. One of these sub-layers occurs over a wider area and has been recorded in cores M-10S to M-45S, M-15E, and M-20E. Along the north-south transect this organic-silty-clay sediment phase was well developed, with a thickness of about 2 m; the thickness increases in the deeper parts of the depression (M-10S, M-25S). In the east-west transect, it was well developed, mostly in the eastern half, which indicates that a more suitable environment existed in the deeper part of the depression for the accumulation of these sediments. Some thin layers of reworked sand with sharp upper and lower contacts were deposited within this phase (e.g. strata 6 and 8 of M-15N, stratum 9 of M-5N, strata 7, 9, and 13 of M-5S, stratum 11 of M-25S, stratum 13 of M-15E, and stratum 13 of M-10.5E). They indicate the possibility of the occurrence of extreme events, such as cyclones, tidal surges or floods in the past (see section 8.5.ii). The upper boundary of this phase is very faint which indicates a slow transformation to the next phase, except in core M-0. In this core, a 22 cm thick layer of buff grey, coarse sand with rare iron mottled clasts was present at the top of phase-III; both the upper and lower contacts were sharp. This shows convincing evidence of sediment reworking within this phase in the past.

iv. Phase-IV (Silty-clay)

This silty-clay sediment phase is battleship-grey in colour which is quite distinctive from that of the underlying sediments. It also includes fewer decomposed organic components. The phase is well developed, about 1.5 m in thick and indicates that a favourable condition existed for its deposition over a wide area; this was also the case throughout the excavated zone. The upper half of the deposits had a higher clay component and a much less sand that existed in the lower half. Thus, fining upward sequence occurred, although the identification of any separating boundary was difficult to determine. The upper half includes some clasts and diffuse iron staining (M-15N, M-10N, M-10W, M-5W, M-10.5E). In addition, some rootlets of herbaceous plants (M-10N, M-25S) and some silty clasts (M-10.5E) were also recorded from this upper half. At core M-15S (stratum 16), a light grey, thin layer (12 cm thick) of sediment, having a large proportion of sandy particles, points out sharply both upper and lower boundaries. It is, possibly, another example of a reworked sediment, deposited by some extreme events; its crumbly structure also enables such a possibility. A thin layer (about 8 cm thick) of slightly different colour (darker), which includes more organic components and shows a traceable upper and lower boundary, was recorded in the lower part of cores M-20S to M-35S. The structure of the sediment of this phase varies from plastic and sticky to very coarsely laminated, and is overlain by the next sedimentary phase (Phase-V), separated by a very distinctive boundary.

v. Phases V to VIII

Along the entire east-west and part of the north-south transect (Fig. 6.1), details of the strata of the upper half of phase-IV and those lying above it were recorded from the exposed faces. The description of Phases V to VIII will be discussed in section 6.5.

6.4. EXPOSED-FACE PROFILES

An exposed face has more advantages for studying sediment characteristics and lateral changes in detail than provided by borehole records. Changes in the physical properties of sediment layers, alignment of bedding and rare but important occurrences, such as those of artifacts, shards and macrofossils can be seen and examined in their sedimentary context. In the present study, three profiles have been studied. The details of the field techniques used to record these profiles had been discussed in section 4.2.iii. The location and alignment of these exposed faces are shown in Figure 6.1 and a short introduction to them is given below.

i. Exposed Face AB (South Facing)

This exposure is 35 m in length and about 2.5 m in height (Fig. 6.5, top). As a result of the digging, the top ~50 cm of the wall had been disturbed and so no record could be made. In the western part, some of the underlying Pleistocene clay bed with its distinctive reddish brown colour and a clear Pleistocene-Holocene boundary (Photograph h. in Appendix 22) were exposed. Part of this exposure (AB) is shown in Photograph-e. in

Appendix 22.

ii. Exposed Face BC (West Facing)

This face is 12 m long and about 2.5 m height (Fig. 6.5, bottom left); point 'B', is the same point 'B' as on profile AB, and the point 'C' is located south of the line AB (Fig. 6.1). Face BC is at right angles to AB. Two boreholes (M-5S and M-10S) were put down at the base of the face. The top ~50 cm were disturbed not only by the excavation but also a shallow pond, now dried up.

iii. Exposed Face CD (North Facing)

This face is at right angles to the eastern (BC) and is parallel to the northern (AB) face (Fig. 6.5, bottom right). Point 'C' is shared with 'C' on the BC profile and point 'D' is located on the west of it. The length of the profile is 11.5 m and the height is about 2.5 m. Like profiles AB and BC, its top ~50 cm were also disturbed. Monolith samples were collected from this face, 7.75 m west from the point 'C' (Fig. 6.5, bottom right.), for laboratory analyses. The lithology and sediment description of these monoliths are presented in Figure 6.3.

iv. Profiles from a Residual Cone (*Shakhi*) in the Excavation

In Bangladesh, traditionally, to calculate the volume of soil that has been dug, some cones (*Shakhi*) are left untouched at regular intervals (Photographs e. and f. in Appendix 22) within the excavated site. At Matuail, one such *Shakhi*, located about 7 m from 'C' and 9 m from 'B', existed (Photograph f. in Appendix 22). The eastern and northern faces of this *Shakhi* were vertically cut and cleaned so as to obtain a three dimensional view of its lithology (Fig. 6.6, left). Sediment profiles were drawn and the lithological details recorded (Fig. 6.6, right).

6.5. SEDIMENT RECORDS FROM EXCAVATED PROFILES

In section 6.3, borehole records have been used to describe four sediment phases (Phases I-IV) at the site. The remaining four phases (Phases V-VIII) are discussed below, based on the records from both the boreholes (north-south transect), and from the exposures.

i. Phase-V (Organic Silty-clay)

This organic silty-clay sediment is grey-brown to dark-brown in colour and includes frequent deposits of vivianite, some boat shaped capsules of seeds, discrete herbaceous and woody detritus, some black to blue shaded organic fragments, and some silty clasts. Inclusions of undetermined black materials were also found within the sediments (Photograph g. in Appendix 22). On the north face (AB) and part of the east face (BC), the lower boundary of the layer closely follows the present MSL. On the south face (CD) near the location from which the monoliths were taken, the boundary is about 30 cm and at the *Shakhi*, about 80 cm, below the MSL. This shows a depression with a north-south alignment which passes successively through the sites from where core M-25S, the monoliths, and cores M-5S and M-10S were taken. It forms an arc shaped sub-surface valley within the site. Similar types of undulating burried valleys have also been observed elsewhere in the excavation. Possibly these valleys are interconnected and their floors having been filled with Holocene deposits. Sequences of Holocene sediments, therefore, are well preserved at the site. However, this sediment phase is about 1 m thick on the western side of the site but only about 20 cm in the central part. Its lower boundary is remarkably irregular, forms a wave like pattern and has inclusions from the layer below (photograph g. in Appendix 22), indicating large scale erosional processes. On the western part of the profile AB, such features were not found. The layer is hard, partly consolidated, sticky and difficult to dig or to penetrate by gouge sampler. Its upper boundary is diffuse, indicating a gradual transition towards the next sedimentary phase.

ii. Phase-VI (Minerogenic Sediments)

This minerogenic sediment phase can be subdivided into a). silty-clay, b). sandy-clayey-silt, and c). clayey-silt layers.

a). The battleship grey silty-clay layer overlies the organic silty-clay (Phase-5) throughout the western half of the profile AB. The layer is coarsely laminated and includes frequent sand particles and some decomposed organic components.

b). The sandy-clayey-silt layer, overlying the Phase-5, was recorded in the eastern half of the profile AB, throughout the profiles BC and CD, and also at the *Shakhi*, suggesting that it is well developed throughout the eastern part of the depression; in the central part it becomes thinner. The layer is battleship grey to light brown grey in colour, includes fine sand particles, rare organic components and some herbaceous detritus along the lamination. It shows an upward increase in the proportion of sand and can be roughly divided into two equal halves, the upper and lower. A detailed examination of the layer from the *Shakhi* has made it possible to identify at least 6 thin sub-layers of slightly different in colour and composition (Fig. 6.6).

c). The light grey clayey-silt layer, overlying sub-layers a). and b)., includes frequent sand, rare woody and herbaceous detritus, traces of organic materials, and is coarsely laminated.

However, whether these three different sub-layers represent the same sedimentary phases or three separate sedimentary sequences, it is difficult to say. The presence of traceable boundaries (see Fig. 6.6) between sub-layers indicate the possibilities of minor changes of sedimentary sequences within the same phase.

iii. Phase-VII (Peat)

This is a dark-brown peat which overlies Phase-VI and has transitional upper and lower boundaries. The peat is formed of *limus* components with some decomposed organic materials, and some woody and herbaceous detritus. It is well developed along the east-west transects (AB and CD), particularly in the central part of the site where the thickness is up to 50 cm. Here, an underlying sub-stratum, of slightly lighter (brown-grey) colour, consisting of a significant proportion of clay particles and few *in situ* rootlets of herbaceous plants, was found. Along the north-south transect (BC) the peat layer became thinner, about 10 cm in thickness and included some clay particles, particularly at the southern part. The peat is stratified and stems of herbaceous plants were found embedded along the lamination.

iv. Phase-VIII (Silty-clay)

This battleship grey, plastic and sticky silty-clay is the youngest and uppermost sedimentary phase at the site. The phase is about 85 cm thick, although up to 137 cm in the central part (M-5E). Some sand particles, woody and herbaceous detritus, decomposed organic material, rare dicot. leaves, and frequent diffuse iron staining were recorded. The distinctive colour and particle size composition of the sediments points that it was deposited under a fluvial system and formed the floodplain of the flanking rivers, the Buriganga and the Lakha.

6.6. PARTICLE SIZE ANALYSIS AND LOSS-ON-IGNITION

7 samples from M-Monolith and 13 samples from the core M-10.5E were taken for Particle Size Analysis. It was mentioned earlier (section 5.7) that there are differences between the laboratory results and field observations, as in this case at Matuail (Appendix 11). Cumulative percentages of particle sizes at different depths are shown in Figure 6.7. They clearly reveal vertical changes in the relative proportion of sizes, and suggest different sequences of sedimentation at the site. That confirms the field observations. Sediment from the same samples has also been used to determine Loss-on-Ignition values, the results of which are shown in Figure 6.8. Most of the samples contain ~5% decomposed organic matter.

6.7. RECORDS OF SUBMERGED FOREST

Throughout the entire excavation, a large number of buried trees were recorded most of which were *in situ* and deeply rooted. They lie in the sediments mostly along a NE-SW alignment with their tops to the north-east. This reveals the possibility of their uprooting by severe south-westerly monsoon cyclones in the past. The girth of most of these trees is about 1 m.

Most of these trees have been found along the boundary between sedimentary Phase-IV and Phase-V (see profiles AB and CD in Fig. 6.5). From their physical characteristics (size, diameter, colour, bark, etc.) it is supposed that they are mangrove trees, commonly *Excoecaria agallocha* and *Heritiera fomes*. Photograph (f). in Appendix 22 shows a close up view (by arrow) of a buried *Heritiera* tree.

The presence of these submerged trees unequivocally indicates the existence of a dense mangroves forest at the site in the past. Evidence of submerged mangrove trunks have also been reported by Brammer (1971). This together with the evidence of the submerged forest at Matuail indicates that others may exist in the Basin, and this requires systematic investigation.

6.8. RECORD OF A VERTEBRATE BONE

The exposures were used not only to record the detailed lithology of the site, but were also scrutinised for other types of evidence from the past. One such piece of evidence is a vertebrate spine bone. It was found in the south face (CD) at a distance of 7.45 m west from point 'C' and 5 cm below MSL. It was embedded within the sedimentary deposits at the upper boundary of sediment Phase-V. Apart from this bone, the rest of the skeleton was destroyed by the excavation. The bone has three wings (two are broken) and each wing is about 6" long (Photograph j. in Appendix 22). Only based on this single bone[1] it is, therefore, difficult to identify the species from which it has been derived. Its estimated age is about 4000 years.

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[1] This bone was shown to some local zoologists but identification was not possible. It is now left at the author's family care in Bangladesh

6.9. RECORDS OF ARTIFACTS

Some broken pot was also found from the south face (Photograph i. in Appendix 22) at the lower part of the sediment Phase-VII, at a location of 7.70 m west from point 'C' and about 60 cm above MSL. In the same sediment phase, similar types of broken pot were found in other parts of the excavation but little is known about their typology or the history of the people who used them. Radiocarbon date of sample at this level displays that they may date from about 2300 BP (375 BC).

6.10. BIOSTRATIGRAPHIC RECORDS: POLLEN

Samples from a total of 50 levels were taken for pollen analysis of which 16 are from the monolith (105-240 cm) and 34 from core M-10.5E (200-530 cm). From the lithological records, it has already been mentioned that the boundary between the sediment Phase IV and V is very distinctive, and can be used to correlate the boreholes. In addition, the pollen record of the monolith at 240 cm depth shows more or less a similar assemblage to that of core M-10.5E at 210 cm depth; these two levels could be considered to have been deposited simultaneously under similar depositional environments and could be correlated. Under this argument the monolith and the core M-10.5E could be considered as a single profile to represent the environmental history at the site.

Only at 15 levels (13 from monolith and 2 from M-10.5E) meaningful pollen counts were obtained. Pollen percentage frequency analysis and its graphical presentation is as for Panigati (Chapter 5). Unknown[1] type pollen are classified as a separate group and have been calculated as a percentage of total land pollen plus total count of unknown type

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[1] The description of four unknown type pollen is given in Appendix 19.

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pollen.

6.11. LOCAL POLLEN ASSEMBLAGE ZONES

In core M-10.5E, except for about the upper 20 cm (depth 210 and 200 cm), pollen grains do not occur in sufficient numbers to allow any meaningful statement to be made. At each level, less than 50 land pollen were encountered. A full list of pollen counts at this core is presented in Appendix 14

Because of this insufficient count, these data could only be used for a descriptive interpretation. Among the mangrove trees, *Excoecaria* and *Heritiera* pollen are present in almost every level. Some pollen from other mangrove trees are sporadically present without showing any particular pattern. Shrub pollen are virtually absent, particularly at lower levels; herbaceous pollen are infrequent. A few unknown type pollen are also present. The number of fern spores, mainly the monolete, verrucate type, is slightly greater than for pollen grains. It is, however, difficult to use these data as evidence of vegetational changes. They could, however, add to an understanding of past environmental history, particularly the sea-level changes (see section 7.4.ii).

Samples from the monolith provided sufficient pollen (except between 160 cm and 140 cm) counts. Pollen present at each level is presented in Appendix 15. The graphical representation (Fig. 6.9) of these data shows five Local Pollen Assemblage Zones (LPAZ). They are described below.

i. LPAZ-I: (*Excoecaria-Heritiera-Rhizophora-Sonneratia*)

Depth: 240-225 cm
Lithology: Silty-clay

The zone is mainly characterized by a high frequency of mangroves tree pollen (~88%) of which *Excoecaria* (~17%), *Heritiera* (~14%), *Rhizophora* (~13%), and *Sonneratia* (~17%) are the common types. In addition, a large number of *Bruguiera* (~8.5%), *Avicennia* (~8%), Gramineae (~7%), *Ceriops* (~5%), *Amoora* (~5%) and *Potamogeton* (~5%), and a few (<2%) *Aegiceras*, *Xylocarpus*, *Suaeda* and *Typha* pollen have been recorded. Shrub pollen are sporadically present; few unknown type pollen were met. Fern spores are evenly distributed (~4%) throughout the zone. It represents a more or less dense mangroves forest together with ferns and some herbaceous plants.

ii. LPAZ-II: (*Heritiera-Excoecaria-Amoora*-Gramineae)

Depth: 225-182 cm
Lithology: Organic silty-clay

The zone is distinguished by a slight fall in mangroves tree pollen frequencies compared with the zone below. Mangroves tree pollen provides about 66% of the total land pollen count of which *Heritiera* (~20%), *Excoecaria* (~15.5%), *Amoora* (~6.5%) and *Avicennia* (~3.5%) are the common species. *Amoora, Excoecaria* and *Heritiera* have a higher representation at the lower end of the zone. Shrub pollen frequency is slightly higher (up to 4.8%) but still sporadically distributed in this zone; unknown type pollen are very infrequent. In the central part of the zone, *Typha* and *Potamogeton* pollen frequencies have suddenly increased (13.6% and 8.6%, respectively) and have formed a peak of aquatic pollen. At this level, another peak has been formed due to an increase in mangroves, particularly *Heritiera* (up to 25.5%) and *Rhizophora* (up to 9%), pollen frequencies. The upper part of the zone is mostly characterized by an increasing frequency of Gramineae (up to 22.9%) pollen; *Excoecaria* pollen also shows a similar pattern (up to 24.4%). Fern spores are more or less evenly distributed, except in the middle part where trilete, psilate fern spores have an increased frequency (up to 16.5%).

iii. LPAZ-III: (*Excoecaria-Heritiera-Avicennia*)

Depth: 182-165 cm
Lithology: Organic silty-clayey-sand

This zone shows a general increase in mangroves pollen frequency (up to 78.7%), particularly for *Excoecaria* (up to 33.9%) and *Avicennia* (up to 8.5%). Pollen frequencies of *Heritiera, Amoora, Sonneratia, Rhizophora, Xylocarpous* and Gramineae remain the same as those of the zone below. In the upper part of the zone, shrub pollen are virtually absent. A noticeable characteristic of this level is the occurrence of many (up to 24.2%) unknown pollen types. Aquatic pollen, particularly *Typha*, also show an increased value (up to 11.3%). The overall pollen frequency has decreasing values up the core, and only 94 land pollen were counted at the uppermost part (depth 170 cm) of this zone.

iv. LPAZ-IV: (Infrequent Pollen)

Depth: 165-132 cm
Lithology: Organic silty-clayey-sand (lower part) and
Clayey-silt (upper part)

This zone is characterized by an infrequent pollen frequency. Fewer than 30 land pollen have been counted at each level, and these are not shown in the pollen diagram. *Excoecaria, Heritiera, Barringtonia, Avicennia* and *Amoora* are those commonly met. Unknown type pollen occurs in slightly higher numbers than any other types. A few fern spores are also present.

v. LPAZ-V: (Gramineae-Cyperaceae-Fern)

Depth: 132-104 cm
Lithology: Clayey-peat (lower part) & Peat (upper part)

This zone is characterized by a high frequency of Gramineae (up to 64.4%) pollen. A large number of Cyperaceae (~15%) and *Typha* (~10%), and some *Phoenix* (~4%), *Aster*-type (~3%) and *Suaeda* (~1.5%) pollen are also present. Fern spores (~8%) are evenly distributed throughout the zone. The most noticeable characteristic of the zone is the presence of a large frequency (up to 41.6%) of unknown type pollen. Except *Barringtonia*, tree pollen are very infrequent. The pollen record suggests that the zone represents an open grassland in which there were ferns and unknown components.

6.12. BIOSTRATIGRAPHIC RECORDS: DIATOMS

A total of 47 samples has been used for diatom analysis of which 17 are from the monolith (105-240 cm) and 30 from core M-10.5E (200-550 cm). Most of the samples from the monolith and samples 200-240 cm from the core M-10.5E have a good frequency of diatom valves, and at least 200 have been counted at each level. Between 250 cm and 360 cm (M-10.5E), the total diatom count varies from 101 to 150 valves. From 370 to 420 cm, only 49 to 83 diatoms were counted at each level. These have not been used for statistical analysis or graphical presentation; at least 100 valves have been considered as necessary for such analyses. Levels below 420 cm contain virtually no diatoms. A full list of total diatom counts at each level are given in Appendix 16 (M-10.5E) and Appendix 17 (M-Monolith).

6.13. LOCAL DIATOM ASSEMBLAGE ZONES

Considering the monoliths and the M-10.5E core as a single unit, ten Local Diatom Assemblage Zones[1] (LDAZs) have been proposed at the site, as follows.

i. LDAZ-I: (Diatom Poor Zone)

Depth: 555-425 cm
Lithology: Inorganic sediments containing various proportion of sand, silt and clay.

A maximum of up to only 8 diatom was available at each level; at 430 cm not a single was found. This zone (Fig. 6.10) might be classed as a 'diatom poor zone'.

ii. LDAZ-II: (Infrequent Diatom Zone)

Depth: 425-375 cm
Lithology: Clayey-silt

This zone (Fig. 6.10) contains some diatoms but they are not very frequent; only about 70 valves were found at each level and that was not enough to interpret the depositional environment other than a low level. Polyhalobous diatoms are virtually absent, except at 400 cm where some *Coscinodiscus apiculatus* and *C. centralis* were found. Mesohalobous diatoms constitute the major proportion of total counts (up to 74.7%) of which *Cyclotella striata* is the main species (up to 42.1%). In the lower part of the zone, particularly at 410 cm, Oligohalobous-indifferent diatoms constitute a large proportion (up to 49%) of the total count with the numbers decreasing upwards. Some Halophobous (~12%) diatoms were recorded and Oligohalobous-halophilous diatoms were rare. The

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[1] Zone-I to VI are recorded from the core M-10.5E and Zones VI to X are recorded from the monolith.

diatom assemblage in this zone suggests a fresh-brackishwater depositional environment.

iii. LDAZ-III: (Marine-Brackish Zone)

Depth: 375-355 cm
Lithology: Silty-clay

The zone (Fig. 6.10) is characterized by a high frequency of Mesohalobous (~56%), and also a significant proportion of Polyhalobous (~20.5%) diatoms. Both Oligohalobous-indifferent (~15%) and Halophobous (~7%) diatoms have a lower frequency compared with the zone below. *Cyclotella striata* (~34%) and *Diploneis didyma* (~12%) are the most frequent species at this level. In addition, *Synedra tabulata* (~6.5%), *Coscinodiscus marginatus* (~6%), *S. ulna* (~5.5%), *Melosira granulata* (~5%), *Navicula pygmea* (~4%), *C. centralis* (~3%), and *Opephora pacifica* (~3%) are also common. *Paralia sulcata, Coscinodiscus apiculatus, Eunotia pectinalis,* and *Pinnularia acrosphaeria* occur infrequently. The diatom assemblage indicates that the zone experienced a marine-brackishwater environment.

iv. LDAZ-IV: (Brackish Zone)

Depth: 355-315 cm
Lithology: Sandy-clayey-silt

The zone (Fig. 6.10) is characterized by an extremely high frequency of Mesohalobous diatoms (up to 81.7%); *Cyclotella striata* shows an increasing frequency (up to 54%), particularly in the central part of the zone. *Diploneis didyma, Synedra tabulata, Navicula pygmea,* and *Eunotia pectinalis* diatom frequencies do not show any significant change in their vertical distribution. The zone is the most remarkable for the nearly complete disappearance of Polyhalobous diatoms. Hence the sediments of this zone were probably deposited in a brackishwater environment, with an open connection to the sea.

v. LDAZ-V: (Marine Brackish Zone)

Depth: 315-265 cm
Lithology: Sandy-clayey-silt (lower part) and
Silty-clay (upper part)

Cyclotella striata shows a slight fall at the lower part of the zone, and then an upward increase (up to 52%) in frequency (Fig. 6.10). A similar pattern is also found for *Synedra tabulata*; *Diploneis didyma* decreases upwards. At a depth of 300 cm, freshwater species, such as *Pinnularia acrosphaeria, Eunotia pectinalis* and *E. spp.* increase steeply, forming a peak which indicates an influx of freshwater deposits. The most noticeable characteristics of this zone are the increasing frequencies of Polyhalobous (up to 23.3%) and decreasing frequencies of Halophobous (up to 4%) species towards the upper boundary. In the upper part of the zone, the sporadic occurrence of Oligohalobous-indifferent and Halophobous, and the frequent occurrence of *Coscinodiscus spp.* and *Opephora pacifica* diatoms suggest an increasing marine influence; the sediments of this zone were probably deposited in a marine-brackishwater environment.

vi. LPAZ-VI: (Brackish Marine Zone)

Depth: 265-190 cm (M-10.5E) and 240-225 cm (M-monolith)
Lithology: Silty-clay

Diatom evidence for this zone (Fig. 6.10 and 6.11) has been recorded from both the monoliths (240-225 cm) and core M-10.5E (265-190 cm)[1]. The zone is characterized by a large number of marine species. Polyhalobous diatom frequency increases up to 54%;

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[1] Please see next page for this footnote.

species such as, *Coscinodiscus apiculatus, C. marginatus, Opephora pacifica,* and *Paralia sulcata* are commonly present in this zone. Some *Diploneis smithii* (lower part) and *Actinocyclus divisus* (upper part) have also been found. Oligohalobous (both types) and Halophobous species are sporadically distributed, except in the central part of the zone where the freshwater species (*Synedra ulna* and *Eunotia spp.*) have formed a little peak (up to 14.7%) in the summary graph indicating some freshwater influx. At this level, *Cyclotella striata* shows a decreasing frequency followed by a slight upward rise and then finally a decrease. Diatom records from this zone reveal that sedimentation possibly took place in a brackish-marine environment.

vii. LDAZ-VII: (Brackish Fresh Zone)

Depth: 225-195 cm
Lithology: Organic silty clay

This zone (Fig. 6.11) is characterized by an increase of Oligohalobous-indifferent (up to 65.6%) and Halophobous (up to 24.7%) diatom frequencies. Polyhalobous species are sporadically present (~7%). The Mesohalobous diatom frequency has significantly decreased in this zone (up to 9.3%), particularly those of *Cyclotella striata* (up to 4.7%). Species such as, *Melosira granulata, Pinnularia microstauron,* and *Eunotia parallela* have

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[1] From the pollen record it has already been argued that levels 210 cm (in core M-10.5E) and 240 cm (in the monolith) could be correlated (see section 6.10). Diatom species, however, show slightly different patterns. For example, species such as, *Actinocyclus divisus, Coscinodiscus africanas, C. centralis* and *Diploneis weissflogii* are only found at core M-10.5E (at 210 cm); the opposite is the case in the monoliths (at 240 cm) for species *Cymbella spp.* and *Surirella ovata*. In addition, *S. tabulata* shows a higher frequency in the monoliths. Despite these differences, both levels can be characterized by a more or less similar pattern of Polyhalobous and Mesohalobous diatom frequencies. It could, therefore be argued that a simultaneous sedimentation took place at both levels under similar environmental conditions and hence, the correlation can be sustained.

higher frequencies than in the zone below. The central part of the zone is characterized by a steep rise of *Eunotia pectinalis, Gomphonema parvulum* and other freshwater species. The diatom assemblage direct that the zone experienced a brackish-fresh water environment.

viii. LPAZ-VIII: (Marine Brackish Zone)

Depth: 195-165 cm
Lithology: Organic silty-clay (lower part) and
Organic silty-clayey-sand (upper part)

The zone (Fig. 6.11) is distinguished by the re-establishment of Polyhalobous and Mesohalobous diatoms, each occupying about 26% of the total counts. *Coscinodiscus spp., Opephora pacifica, Paralia sulcata,* and *Thalassionema nitzschiodes* are the common marine species. Among the Mesohalobous species, *Cyclotella striata* increases significantly (up to 13.8%) in this zone; other species are commonly found. Among the Oligohalobous-indifferent diatoms, *Melosira granulata* is the most frequent; other species are sporadically present. Halophobous diatoms are rare, except at depth 185 cm. At this level, Halophobous species, particularly *Eunotia spp.*, and Mesohalobous species, especially *Cyclotella striata* and *Synedra tabulata*, have an increased frequency whereas Oligohalobous-indifferent diatoms, mostly *Melosira granulata*, decrease. The diatom records indicate that the sedimentation, in this zone, possibly took place in a marine-brackishwater environment.

ix. **LDAZ-IX: (Brackish Marine Zone)**

Depth: 165-132 cm
Lithology: Organic silty-clayey-sand (lower part) and
Clayey-silt (upper part)

The zone (Fig. 6.11) is characterized by a higher frequency (up to 47.7%) of Polyhalobous diatoms than in the zone below. The Mesohalobous diatom frequency has slightly increased, especially at 150 cm where *Cyclotella striata* shows a frequency of up to 30.9% of the total count. In this level Halophobous species are totally absent. The Oligohalobous-indifferent diatom frequency shows a more or less similar vertical pattern throughout the zone, except at the upper end (at 135 cm). There, Polyhalobous and Mesohalobous diatom frequencies have declined rapidly (up to 29.9% and 19.4%, respectively). *Coscinodiscus spp., Cyclotella striata* and *Melosira granulata* are the common diatoms recorded from this zone. The lower part of the zone possibly suggests a brackish-marine depositional environment; the upper part indicates increased freshwater influences.

x. **LPAZ-X: (Brackish Fresh Zone)**

Depth: 132-104 cm
Lithology: Clayey-peat (lower part) and Peat (upper part)

This zone (Fig. 6.11) is characterised by infrequent Polyhalobous (~5.5%) and Mesohalobous (~12%), and frequent Oligohalobous-indifferent (~58%) and Halophobous (~23.5%) diatoms. At 120 cm, the diatom frequency is slightly different; some Polyhalobous diatoms, e.g. *Coscinodiscus spp., Diploneis weissflogii* and *Paralia sulcata,* as well as some Mesohalobous species, e.g. *Cyclotella striata* and *Synedra tabulata,* have been recorded, thus, suggesting a saline water influx. Despite a high frequency of *Melosira granulata* (up to 34.3%), other Oligohalobous-indifferent diatoms are practically absent at this level. However, the upper part of this zone is characterized by frequent freshwater species. The diatom records, therefore, give evidence that the sediments of this zone were deposited in a freshwater environment with occasional brackish water influences.

6.14. CHRONOSTRATIGRAPHIC RECORDS: ^{14}C RESULTS

From Dhaka and the surrounding areas, a total of 12 radiocarbon dates are available; these are presented in Table 6.1. Most of these dates were obtained from reworked wood samples and predate the sediment in which they were found (Monsur, 1990). In this research, five samples from Matuail (Table 6.2) have been used for radiocarbon dating of which three samples were taken from the monoliths (3M, 4M and 5M) and 2 from core M-10.5E (1M and 2M). The Monolith samples were subjected to conventional dating, and the age of samples 3M (lower end of Stratum-II), 4M (upper end of stratum-II) and 5M (lower end of Stratum-V) are 4080 ±60BP, 3980 ±70BP and 2280 ±80BP, respectively. Sufficient material was not available for conventional dating of samples 1M (mid of Stratum-IX) and 2M (lower end of Stratum-XIV); therefore, these have been dated by the AMS method and their radiocarbon ages are 6170 ±50BP and 6060 ±60BP, respectively. Except for one sample (1M) the others were taken either from *in situ* organic deposits (e.g. 2M, 3M and 4M), or from peaty-clay (e.g. 5M). A piece of wood was used as sample 1M; this may not have been *in situ* and has perhaps given too old a date. The age difference from sample 2M (only ~150 radiocarbon years for 110 cm sedimentation), however, supports that the date may well be correct.

Table 6.1.: Radiocarbon Dates Available from Dhaka and Surrounding Regions

No	Site Name	Depth (cm)	Altitude (m)	Lithology	Material	C^{14} Age	Lab. Code	Source
1	Kachpur, Dhaka	170	n.a.	Peat	Peat	3670 ±60BP	n.a.	Hassan (1986)
2	*do.*	265	n.a.	Peat	Peat	6060 ±75BP	n.a.	*do.*
3	*do.*	285	n.a.	Peat	Peat	6460 ±80BP	n.a.	*do.*
4	Chandina	115	+3.85	Peat	Peat	5580 ±75BP	n.a.	*do.*
5	*do.*	205	+2.95	Peat	Peat	5620 ±75BP	n.a.	*do.*
6	Gulshan Lake, Dhaka	n.a.	-2.20	n.a.	Wood	4040 ±70BP	n.a.	Monsur (1990)
7	*do.*	n.a.	-2.80	n.a.	Wood	4910 ±75BP	n.a.	*do.*
8	*do.*	n.a.	-4.40	n.a.	Wood	5730 ±60BP	n.a	*do.*
9	*do.*	n.a.	-6.30	n.a.	Wood	8940 ±105BP	n.a.	*do.*
10	Kalibari, Dhaka	890	-4.90	n.a.	Wood	12780±140BP	n.a.	*do.*
11	Dakhin gaon, Dhaka	250	0.00	n.a.	Wood	4830 ±75BP	n.a.	*do.*
12	Fatulla, Dhaka	370	n.a.	Organic Sediment	Wood	6540 ±160BP[1]	n.a.	Brammer (1967)

n.a. = not available

[1] This date together with 4 other dates (3080 ±45BP, 1790 ±85BP, 1035 ±40BP and 910 ±60BP from different parts of Barisal district) were supplied by Dr. H. Brammer to the author which is highly acknowledged.

Table 6.2. Radiocarbon Dates from Matuail

Sample Number	Depth (cm)	Altitude (m)	Stratum No	Sample	Lab Code	Type of Dating	^{14}C Age	Calibrated Calender Years Range[2]	Intercept of ^{14}C with Calibrated Curve[3]
M-Monolith									
5M	128-130	+(0.60-0.58)	V	Peaty clay	Beta 79286	Conventional	2280 ±80BP	cal 505 to 150 BC	cal 375 BC (2325 BP)
4M	183-185	+(0.05-0.03)	II	Organic Sediment	Beta 79285	Conventional	3980 ±70BP	cal 2845 to 2830 BC and 2620 to 2290 BC	cal 2475 BC (4425 BP)
3M	219-221.5	-(0.31-0.34)	II	Organic Sediment	Beta 79284	Conventional	4080 ±60BP	cal 2875 to 2790 BC and 2780 to 2465 BC	cal 2590 BC (4540 BP)
M-10.5E									
2M	420-421	-(2.32-2.33)	XIV	Organic Sediments	Beta 79476	AMS	6060 ±60BP	cal 5075 to 4815 BC	cal 4940 BC (6890 BP)
1M	530-531	-(3.42-3.43)	IX	Wood	Beta 79475	AMS	6170 ±50BP	cal 5240 to 4950 BC	cal 5070 BC (7020 BP)

[1] Quoted errors represent 1σ statistics (68% probability) and are based on combined measurements of the sample, background, and modern reference standard
[2] Calibrated Calender Years represent 2σ statistics (95% probability)
[3] Calibrated results were prepared by the Beta Analytic Inc. based on the works of Vogel *et al* (1993), and Talma and Vogel (1993).

Chapter 7: RECONSTRUCTION OF HOLOCENE SEA-LEVEL CHANGES

7.1. INTRODUCTION

The aim of this chapter is to reconstruct the Holocene sea-level history of Bangladesh. The data presented in Chapters 5 and 6 are used as evidence of such changes. Possible sources of errors associated with the reconstruction are also discussed. Panigati and Matuail are considered separately.

7.2. EVIDENCE FOR HOLOCENE SEA-LEVEL CHANGES

The primary evidence for sea-level changes is to be found within the coastal stratigraphy. Although there might have been variations between sites, coastal sedimentary layers are the natural archives of coastal, sea-level, water-level and water quality changes (Tooley, 1992). The coastal stratigraphy of Bangladesh is characterized by alternating strata of organic and minerogenic origin. Intercalated peat layers have been recorded from the western part of the Bengal Basin (India) by a number of authors (e.g. Mukherjee, 1972; Vishnu-Mittre and Gupta, 1972; Gupta, 1981; Banerjee and Sen, 1988, Sen and Banerjee, 1990; and Barui and Chanda, 1992). From the eastern part of the Basin (Bangladesh) these are found at Sylhet Basin (Alam *et al.,* 1990), Kachpur and Chandina (Hassan, 1986), Kola Mauza (Zaher, 1962), Keraniganj (Khan *et al.*, 1991), Barguna (Khan, 1993), Jhenidah (Ali *et al.*, 1992), Jessore (Hasan *et al.*, 1984) (see those works for place name). Two possible hypotheses can be put forward to explain the development of such alternating sediment layers.

In the first place, Heyworth and Kidson (1982) argued that intercalated peats underlain by minerogenic sediments could be the result of local events, such as differential sedimentation rates and subsidence. These features have been recorded for the Bengal basin by Mukherjee (1972), and Dastidar and Ghosh (1964), respectively. Barui and Chanda (1992) argued that continued river shifting and occasional earth movement have induced the differential sedimentation within the Basin. Along the Bangladesh coast, the exact sedimentation rate during the Holocene is not yet known. However, although an explanation, such as differential sedimentation rate and subsidence, could be invoked to explain the sedimentary sequences, a logical explanation can also be presented in terms of changing sea-levels.

It is noticeable that the stratigraphy of the world's coastal lowlands is similar, being characterized by alternating strata of marine and terrestrial sediments (Tooley, 1992). These have been interpreted as each minerogenic sediment layer indicating a marine episode, and the biogenic layer indicating a freshwater, telmatic or terrestrial one (Shufu, 1991; Allen, 1995). Ideally, an autogenic peat layer would contain evidence of a transgressive episode at its upper contact and a regressive episode at its lower contact. Such transgressive and regressive contacts are documented in order to provide information concerning the chronology of sea-level movement. However, there is always the possibility of a time lag between the period of sea advance and the development of a transgressive overlap, and *vice-versa*.

Peat will be formed where waterlogged conditions occur. These can develop either in freshwater swamps or in brackishwater pools colonised by mangroves. The development of the five intercalated peat layers at Panigati could only have been possible if marshy swamps (mangal or freshwater) had existed because they were necessary to allow peat accumulation.

The rate of peat formation is related to water table at the site which, in turn, is the result of relative sea-level movement. The process which controls the movement of the saltwater/freshwater interface and the deposition of intercalated peat layers can be illustrated by a simple model (Fig. 7.1). Any change of altitude of relative sea-level would change the position of the saltwater/freshwater interface which is fundamentally controlled by the differential water density. Pure water has a density of 0.9982 kg l^{-1} and salt water has a density of 1.022-1.028 kg l^{-1} at 20° C (Chow, 1964). To understand fully the coastal ecosystem it is, therefore, necessary to examine the relationship between the freshwater/saltwater interface.

The freshwater flowing seaward at the surface is replaced by denser saline water flowing landward at depth. These two layers of water show varying degrees of mixing according to local topography, tidal velocity, relative volume of freshwater and saltwater, and friction of their interface (Boaden and Seed, 1993). In a transgressive episode, the zone of diffusion between the freshwater and saltwater (Fig. 7.1) would be pushed landward due to the lateral hydraulic gradient (Ravenscroft, 1992) and sediment of different porosity and permeability will support different ground water regimes (Long, 1991), but both will be related to relative sea-level movement. These factors combine to determine the altitude at which peat will form. Jelgersma (1961) argued that the peat layers in the Netherlands were formed by rising ground water controlled by rising sea-level. Such observations are equally applicable to Bangladesh where peat will develop regardless of whether the local vegetation is of terrestrial, aquatic or mangrove in nature.

i. Peat Formation

If the coastal stratigraphy is accepted as the result of relative sea-level changes, three working hypotheses could be considered for peat formation.

A peat layer could develop in a freshwater swampy environment. The plants whose remains form this peat would be mostly grasses, sedges and rushes (such as *Typha* and *Phragmites*). These plants grow in freshwater marshy lands in *bil elakas*. During the fieldwork, such a contemporary peat formation was observed just south of Panigati. The Geological map of Bangladesh (Alam *et al.*, 1990) indicates the regional variation of surface lithology and the distribution of peat lands. Vishnu-Mittre and Gupta (1972) argued that the peats of the Bengal Basin are amorphous in nature and the occurrence of pollen of freshwater plants, such as *Lemna, Typha* and *Myriophyllum* evidences its deposition in a fresh water swampy condition. Similarly, Gupta (1981) pointed out that peat formation in the Bengal Basin took place in a lacustrine milieu. However, such environmental conditions favouring freshwater peat formation can occur during a regressive episode, and the existence of such a peat bed can thus also indicates a regression of sea-level.

Secondly, a peat layer can be deposited in a mangal environment. During the fieldwork the author was told by the Sundarbans' forest officers about the current peat formation in the backswamps (Karim, 1994) and under waterlogged conditions in the deepest part of the forest. Mukherjee (1972) recorded large numbers of pollen of mangrove species, such *Heritiera, Sonneratia, Excoecaria* and *Rhizophora* from each peat layer giving support to their accumulation in a brackish water mangal environment. Similar conclusions were also made by Barui and Chanda (1992). Sen and Banerjee (1990) came to different conclusions. Their lowermost peat layer shows an abundant occurrence of spores of *Acrostichum aureum* together with pollen of *Heritiera, Avicennia* and *Bruguiera* indicating a mangal environment during the period 7000-6650 yrs BP. Their uppermost peat of 5000-2000 yrs BP, however, displays a high value for *Potamogeton* pollen and the disappearance of the pollen of mangrove plants, except *Heritiera,* reflecting a freshwater peat formation. Evidence of mangal peats is also found in south Florida (Scholl, 1964; Scholl and Stuiver, 1967), Strait of Malacca (Streif, 1979b), Grand Cayman Island (Woodroffe, 1981), northern Australia (Woodroffe *et al.*, 1985), and Tonga (Ellison, 1989).

Although the environments described above can be used to illustrate possible situations in which peats may form, other environmental circumstances need to be considered when two peat layers are separated by a minerogenic layer. One such model which involves relative sea-level movement is illustrated in Figure 7.1.

In a marine regressive episode, the emergence of a new land area and the seaward movement of the coastline would allow the colonization of mangrove species. The plant succession in a new muddy areas at low level would be initiated by wild rice and mangroves, such as *Sonneratia acida, S. apetala,* and *Avicennia officinalis* (Vishnu-Mittre and Gupta, 1972). With relative rise in the ground surface, these plants would be replaced by *Ceriops, Excoecaria, Heritiera*, and finally would form a mangroves forest. Some salt tolerant grasses, such as *Cynodon dactylon* and *Oryza coarctata* would also start to colonize (Huq and Ali, 1990). An abundant supply of organic matter such as leaves, stems and roots from these mangrove plants would initiate the development of mangal peat, and the accumulation of such biogenic deposits overlying the littoral and neritic facies would form a regressive overlap (Zong and Tooley, 1996a). A sea-level index point from such a regressive overlap can be used as an indicative meaning of negative sea-level movement (Shennan, 1986b).

In a regressive overlap, whether the continued growth of peat would remain as mangal peat or be replaced by a freshwater type will be determined by the relative fall of sea-level, and the possible subsidence of land-level, and the rate of peat formation. If the sea-level continues to fall faster than the subsidence, the mangal ecosystem would be replaced by freshwater loving plants and the peat would be characterized as a freshwater peat. On the other hand, despite the occurrence of a regressive episode, the mangal peat would continue to form when concurrent land level remains the same because the land is subsiding at approximately the same rate at which the sea level is falling. It could, therefore, be argued that regardless of whether continued formation of the peat demonstrated mangal or freshwater conditions, a regressive phase was still continuing. Thus, the interpretation of mangal peats purely as evidence of marine transgression (Scholl, 1964; Scholl and Stuiver, 1967; Woodroffe, 1981; Woodroffe *et al*, 1985;

Banerjee and Sen, 1987; and Sen and Banerjee, 1990) is not supportable.

During a transgressive episode, due to relative rise of sea-level, the freshwater/saltwater interface is pushed further landward and the ground water table begins to rise. The coastal freshwater vegetation would, therefore, be replaced by brackish water mangrove species. The regeneration of any ecosystem does not necessarily mean its reappearance in entirety with all the earlier components. Recolonization by mangrove communities would largely be dependent on the existence of a nearby source of mangrove plants. These colonisers would then, generate the major components of the peat layer and the upper part of which could, therefore, be regarded as mangal peat, leading to a probable marine transgression.

Another situation could, however, pertain. A relative rise of sea level would affect an existing mangroves environment which had continued to grow during a regressive phase, in a slightly different way. Whether the mangroves would survive in such a transgressive phase would depend on the rate of relative sea-level rise (Woodroffe, 1995) and the rate of mangal peat formation. Ellison and Stoddart (1991) suggested that in lowlying coastal regions a mangal ecosystem could keep pace with a rising sea-level of 8-9 cm 100 yrs^{-1}, but would be under stress at a rate between 9 and 12 cm 100 yrs^{-1} and could not survive when the rate increased above that level. As the relative sea-level continues to rise, the successive replacement of terrestrial deposits by littoral and neritic facies would develop as a transgressive overlap (Zong and Tooley, 1996a). The indicative meaning of a sea-level index point from such a transgressive overlap could be used to infer a positive sea-level movement (Shennan, 1986b).

7.3. EVIDENCE OF SEA-LEVEL CHANGES AT PANIGATI

i. Lithological Evidence

It has already been argued that the intercalated peat layers were formed during the regressive phase of sea-level movement, and the minerogenic sediments in between two peat layers were deposited as littoral and neritic facies. At present, there are conflicting interpretations of these sediments (Hewlett and Birnie, 1996). Establishing an argument that the minerogenic sediments were an estuarine deposit could be challenged. Very little is known about the depositional environment of these estuarine deposits. Currently most authors (e.g. Hasan *et al.,* 1984; Khan *et al.,* 1991) have described these sediments as fluvial deposits (see also MPO, 1986). Dastidar and Ghosh (1964) interpreted the grey silty-clay with tree stumps, that lies below the present MSL at Calcutta, as the sediment deposited under a swampy environment with a substantial tidal fluctuation. This is possibly the earliest explanation which indicates evidence of a Holocene marine transgression in the Bengal basin. The sediment records provided by Umitsu (1987, 1993) for Daulatpur also suggest that the organic silty-clay layers were deposited in a marine-brackish environment. Pizzuto and Rogers (1992) recorded a higher organic content in estuarine deposits than riverine. Hence, results of Particle Size Analysis and Loss-on-Ignition of the present study points out that these minerogenic sediments in between two peat layers were deposited in an estuarine to intertidal zone.

The sediments on top of the uppermost peat layer show clear evidence of their deposition in a fluvial environment because their detailed geological mapping shows different morpho-stratigraphic units, such as channel deposits, natural levées, point bars, sand bars, floodplains and backswamp deposits (see Hasan *et al.,* 1984; Ali *et al.,* 1992).

ii. Biostratigraphic Evidence

In order to assess the direction of sea-level movement, it is necessary to establish the basic processes involved in the vegetational response and sedimentary changes in the coastal environment. For a temperate, mid-latitude coast, Godwin and Godwin (1933) elucidated the vegetational history at St. German's in East Anglia, U.K. from pollen analysis of Holocene sediments and recorded the succession from saltmarsh plant communities to a freshwater fen and then to a fen woodland. The vegetational succession in the coastal regions of Bangladesh is not yet fully understood. The model to explain it by Karim (1994) has been applied in this study as an analogue to interpret the pollen records. His model is based on the present day relationship of mangrove species to high water mark (see Fig. 2.8). It is, however, possible for these species to occur at levels both higher and lower than that mark. Thus, the use of this model as an analogue in palynological work can be dubious.

The pollen record established for Panigati site (see section 5.11, and Fig. 5.8 and 5.9) is discussed here in order to elucidate the rate and direction of sea-level movement since *ca*. 9000 cal. yrs BP.

On the basis of the pollen evidence, the lowermost inorganic layer can be divided into two phases, LPAZ-I and LPAZ-II (see Fig. 5.9). LPAZ-I (between 1010 and 985 cm in P-500W) includes a significant number of mangrove species. The occurrence of *Excoecaria, Heritiera, Sonneratia, Avicennia, Ceriops* and *Bruguiera* pollen at depth of 1000 cm (^{14}C age 8210 $\pm$60BP) indicates a mixed brackish and freshwater environments (Sen and Banerjee, 1990). Although the exact sea-level position at this depth is not clear from the pollen record, it may be considered that a rapid rise of sea-level was beginning at this stage. Umitsu (1987) collected a mollusc shell (*Neritiolae neritina* sp), dated to 8910 $\pm$150BP (Umitsu, 1993) at a depth of 35 m, which reveals the existence of a mean to high tide zone, some 33 m below the present MSL. From this evidence, it could, however, be argued that sea-level has continued to rise since that time (*ca.* 9000 cal. yrs BP).

LPAZ-II suffers from poor pollen concentration and content. This could be due the following reasons.

a). A low pollen production or under representation of pollen grains from tropical plants. In India (also Bangladesh), work has not been carried out on the pollen production rate of plants (Chanda, 1972). The recovery of mangroves pollen at different depths, recorded by a number of authors (including this study), tends to refute this reason.

b). Rapid sediment influx could be another possible cause. Radiocarbon dates show a sedimentation rate of less than 0.80 mm yr^{-1} (see Table 8.1) which rather undermines this reason.

c). Poor pollen preservation. In such case most pollen would be corroded and fainted which was not observed for the pollen counted.

d). Poor pollen frequency could possibly be because the sedimentation at this time took place in a deep estuarine environment (see Fig. 5.10).

Umitsu (1987) recorded diatoms, such as *Cyclotella stylorum, Coscinodiscus rothii, C. radiatus* and *C. lineatus* which are polyhalobous planktonic species (de Wolf, 1982) indicating a strong marine influence and a deep estuarine environment. In the present study at Panigati, diatoms were virtually absent; only a few marine and brackish species, such as *Coscinodiscus apiculatus, C. marginatus, C. radiatus, C. stellaris, C. spp. Opephora pacifica, Paralia sulcata, Cyclotella striata, Nitzschia filiformis* and *Synedra tabulata* have been recorded from depths between 8 and 10 m. Thus, it is possible that the few mangroves pollen which were found in this zone were being carried from mangroves forest located on the landward side of the site at that time. Sen and Banerjee (1990) established the existence of mangroves forest near Calcutta at about 7000 yrs BP (7800 cal. yrs BP).

The lower part of LPAZ-III (Fig. 5.8 and 5.9) shows a rapid increase in mangroves pollen frequency, of such taxa as *Sonneratia, Rhizophora, Ceriops, Bruguiera, Excoecaria* and *Heritiera*. This indicates a lowering of relative sea-level and the emergence of a shallow intertidal brackish zone suitable for mangroves colonization. The upward increase of herbaceous species, such as *Cucumis* and Gramineae reflects more freshwater influence, as does the presence of *Typha*. The presence of mangrove species throughout this LPAZ-III supports either a high rate of subsidence or, most possibly, a low rate of sea-level fall.

A second marine transgression at the site is indicated from LPAZ-IV (Fig. 5.8) where a low pollen frequency is considered to be due to the same cause as LPAZ-II. A sudden change of pollen frequency (at depth 690 cm) possibly indicates a rapid relative rise of sea-level for a short period.

A second regressive episode is evinced in LPAZ-V. The recurrence of mangroves vegetation in the lower level of this zone is interpreted as reflecting the beginning of a second marine retreat from the site, and the emergence of new land for mangroves recolonization. Thus, a repetition of an earlier regressive phase.

Interpretation of the pollen records from LPAZ-VI and LPAZ-VII as evidence of relative sea-level movement presents a difficulty. The sediment record shows a near-shore littoral environment, whereas the pollen points to a dense mangroves forest. *Avicennia, Bruguiera, Ceriops, Excoecaria* and *Heritiera* could only have survived in a transgressive episode if there had been an equilibrium between relative sea-level rise and the rate of sedimentation. During this time sea-level was possibly rising either very slowly or shows a high sedimentation, if the sea level was rising rapidly; altitudinal record and ^{14}C results suggest a rapid sea-level rise. In such a case, the relative land-level could keep pace with sea-level rise and as a result, a mangal environment continued to exist. In the later part of this phase, the sea-level begun to rise at a faster rate so that the equilibrium between sediment influx and sea-level movement was destroyed, leaving mangrove communities threatened. The fall of mangroves pollen frequencies, primarily the freshwater-loving species such as *Heritiera* and *Amoora,* in LPAZ-VII, evidences the possibility of such an accelerated sea-level rise.

A major marine regression at the site is evident in LPAZ-VIII. Except for *Excoecaria* and *Heritiera,* the absence of other mangroves pollen allied to the presence of high frequencies of *Cucumis*, Gramineae, Cyperaceae and fern spores indicates that the peat layer was deposited in a freshwater swampy environment (Islam, 1995). This regressive episode continued at the site for at least 1000 years. The occurrence of some pollen of saltwater tolerant species, such as *Rhizophora* and *Sonneratia* at the upper end of this LPAZ-VIII indicates the beginning of another marine transgressive episode.

LPAZ-IX introduces the fourth marine event at the site. The lower half of the zone shows very few mangroves pollen records directing to a rapid sea-level rise for at least about 400 years. Since then, the site had been experiencing first a slow rise and then a relative fall of sea-level. The lower half of this zone, therefore, indicates an estuarine and the upper half a brackish water intertidal environment.

LPAZs-X, XI and XII represent the fourth and longest regressive phase at the site and it continued for at least 1300 years. The occurrence of high frequencies of *Excoecaria, Heritiera, Sonneratia,* and *Avicennia* throughout this episode, however, reflects a dense mangroves forest, and that the associated peat was deposited in a mangal environment. Mangrove peat in a regressive episode could develop if the third hypothesis of peat formation is accepted (see section 7.2.i), and this peat layer would seem to be a good example with which to substantiate the hypothesis.

The fifth and final evidence for a transgressive episode at the site is recorded in the LPAZ-XIII. The reappearance of *Avicennia, Ceriops, Rhizophora*, and an increase of *Excoecaria* and *Heritiera* pollen tip the possible advance of the sea, and the existence of a shallow estuarine to intertidal fresh-brackish environment. The lithostratigraphic description of this phase includes some *limus* materials. Possibly, during this period the sedimentation rate at the site was slightly higher than the rate of rise of sea-level. Due to a rise in the water table during a transgressive phase, there would have been an environment suitable for the development of *limus*. This final marine phase continued at the site possibly over a 300-400 years period and since then the area has experienced a freshwater environment.

The uppermost peat layer was deposited during a regressive phase as a freshwater peat and is overlain by fluvially deposited sand, silt and clay particles.

7.4. EVIDENCE OF SEA-LEVEL CHANGES AT MATUAIL

i. Lithological Evidence

Lithological data presented in Chapter 6 can be used to understand the Holocene depositional environment at Matuail. The transitional zones overlying the Pleistocene clay include large quantities of reworked sandy deposits. Monsur and Paepe (1993) identified these sediments as 'Gulshan Sand' within the 'Bashaboo Formation' which they argued was deposited in a fluvial environment. During the maximum of the glaciation, a dry climatic condition prevailed in the Indian subcontinent (van Campo, 1986). During this time valley cutting by the river system in the Madhupur area was more prominent than lateral shifting (Monsur and Paepe, 1994). Kutzback and Street-Perrott (1985) considered that maximum monsoon precipitation occurred in the Northern Hemisphere during the early Holocene. During this period, due to such rainfall plus the melt water from the glaciers of the Himalayan region, the regional river system was enormously overloaded and inundated the Madhupur Tracts. The intensity of the hydraulic condition caused the

Madhupur surface to become highly dissected while the valley floors were overlain by eroded sediment. Conclusions similar to these were postulated by Alam and Aurangzeb (1975), Alam (1988) and Monsur (1990).

Sedimentation in a fluvial environment continued at the site up to about 7000 cal. yrs BP. The presence of *limus* in some cores, overlying the Pleistocene clay, also indicate a freshwater environment. It can be argued from the records of a number of thin reworked alternating heterogeneous sediment deposits (see Photograph d. in Appendix 22) that the environment at the site during the early Holocene was very unstable, although the time at which the sediments were deposited is not known. At some period during the early Holocene the environment was relatively stable as shown by the existence of *limus* indicating persistent open freshwater conditions.

However, the interpretation of the depositional environment for the period after *ca.* 7000 cal. yrs BP is rather debatable. Alam and Aurangzeb (1975), Alam (1988) and Monsur and Paepe (1993, 1994) argued that the area experienced fluvial deposition throughout the Holocene. On the other hand, Ravenscroft (1992) argued that the infilling of the incised channels of the Madhupur area was related to the rise of sea level and that the deposition took place under fluviatile to estuarine conditions. The present research shows clear evidence of submerged mangroves forest (see section 6.7), a high frequency of mangroves pollen (see section 6.11), and marine and brackish diatom species (see section 6.13); these collectively suggest the presence of the sea at the site at about 2300 cal. yrs BP. The presence of a freshwater fluvial environment at the site throughout the Holocene, therefore, is questionable and the original idea of Fergusson (1863) about the presence of the sea near to the Rajmahal Hill only about 5000 years ago should, therefore, be revived.

ii. Biostratigraphic Evidence

Pollen and diatom records collected from the site (see section 6.11 and 6.13, and Fig. 6.9, 6.10 and 6.11) have been employed to elucidate the rate and direction of sea-level movement.

Both pollen and diatom frequencies are so poor that they are of little use for the understanding of the relative sea-level movement prior to *ca.* 7000 cal. yrs BP. Calibrated radiocarbon dates indicate 110 cm of sedimentation in only 130 years, at the rate of 8.46 mm yr^{-1}. Low pollen and diatom frequency is possibly due to such rapid sediment influx rate during that time. It is, however, only possible to make little speculation about the sea-level changes for this period from such record.

Sporadic occurrence of mangroves pollen, such as *Avicennia, Ceriops, Heritiera* and *Excoecaria* (see Appendix 14), below 420 cm in core M-10.5E, indicates a brackish-fresh supratidal environment. A high rate of sedimentation and the presence of some exotic pollen, such as *Pinus, Betula,* and *Corylus* are thought to indicate an influx of material from distant and cooler environment associated with the upper catchments of the rivers, combined with the high sedimentation rate may suggest that large volumes of water were being delivered to the site. If this river water was discharged into an estuary, it was probably of a more dynamic nature than that at Panigati. A late Pleistocene-Holocene estuarine environment has also been documented by Ravenscroft (1992) close to the eastern hilly regions of Comilla and Brahmanbaria districts. He argued that the estuary had two embayments, one extending through Nabinagar and one in Brahmanbaria (for place name see Ravenscroft, 1992).

Evidence of sea-level movements at the site is available since about 7000 cal. yrs BP. The infrequent diatom recovery in LDAZ-II (Fig. 6.10) does not permit any definite conclusion to be made, although the presence of a few mesohalobous species, such as *Cyclotella striata, Diploneis didyma, Navicula pygmea* and *Synedra tabulata* (see Appendix 16, below 370 cm) indicates the increasing marine influence at the site. That can also be supported by the sporadic occurrence of mangroves pollen (see Appendix 14). LDAZ-III, on the other hand, which correlates with sediment Stratum-15, contains many marine species, such as *Coscinodiscus apiculatus, C. centralis, C. marginatus, Opephora pacifica* and *Paralia sulcata,* together with mesohalobous species which confirms an accelerated rise of relative sea level. Sedimentation at that time took place in a marine-brackish, possibly estuarine environment. This is possibly the first marine episode at the site and it continued up to about 6250 cal. yrs BP.

For the next about 400 years, relative sea-level had started to fall or ceased to rise, and as a result in LDAZ-IV marine diatoms disappear and freshwater species, such as *Eunotia parallela, Eunotia pectinalis, Eunotia spp. Pinnularia microstauron, Pinnularia acrosphaeria* and *Synedra ulna* increase their frequencies. During this negative phase of relative sea-level movement, the site was nevertheless still under a marine influence, with possibly a brackish water environment. Perhaps because the coast was open, the effect of strong waves and tidal current, prevented mangroves colonization throughout this short period of regression.

The major episode of marine transgression began at about 5850 cal. yrs BP and it continued for at least the next 1300 years. During the first 400 years or so of this episode, the sea-level was rising slowly; the presence of freshwater diatoms in LPAZ-V places the possibility of an occasional influx of freshwater. Sedimentation during this period took place in a marine-brackish environment, possibly in a nearshore estuarine condition. LDAZ-VI reveals a rising frequency of marine diatoms. The presence of *Paralia sulcata, Opephora pacifica, Actinocyclus divisus* and *Coscinodiscus spp*. directs a strong marine influence and rapid sea-level rise at the site. Sedimentation then took place possibly in a deep estuarine condition. The sea then pushed further landward, and possibly at about 5000 cal. yrs BP the northern limit of the sea was north of Dhaka. All the lowlying areas surrounding the Madhupur Tract were under marine influence. Brammer (1971; in Brammer and Brinkman, 1977) dated some wood samples, possibly mangrove tree trunks, about 3.7 m below the surface near Dhaka; the date was 6540 ±160BP, which according to Brammer and Brinkman (1977), may indicate estuarine condition at that time.

The Madhupur Tract has a distinctive dendritic drainage pattern and is dissected by a number of incised channels (*baids*) (Miah and Bazlee, 1967) with deep entrances which came into existence in response to sea-level fluctuation (Ravenscroft, 1992). Ravenscroft (1992) argued that the infilling of those incised channels would be associated with a rise of sea level; whether the aggradation would be fluvial or estuarine would depend upon the rate of sea-level rise and sediment input. The Geological map of Dhaka City (in

Rashid, 1993) shows a number of abandoned channels and depressions at and around the city which, including the Rampura valley and Gulshan Lake, were possibly the arms of the invading sea in the region. It can, however, be suggested that these incised valleys (Ravenscroft, 1992) are actually palaeotidal creeks which have been infilled during each transgressive and regressive phases, and this can be proved by evidence from the diatoms present in the sediments.

Diatom evidence from the upper part of LDAZ-VI (Fig. 6.10 and 6.11) shows a decreasing marine influence which it also borne out by the pollen evidence in LPAZ-I (Fig. 6.9). The appearance of a high frequency of mangroves pollen, such as *Avicennia, Bruguiera, Rhizophora, Sonneratia, Excoecaria* and *Heritiera* indicates a retreat of the sea and an emergence of new land for mangroves colonization. The increasing frequency of *Heritiera, Excoecaria,* Cyperaceae and Gramineae pollen and fern spores in LPAZ-II takes to a greater freshwater influence and this agrees perfectly with the diatom evidence in LDAZ-VII. This LDAZ-VII includes a high frequency of freshwater diatoms, such as *Eunotia parallela, Eunotia pectinalis, Eunotia. spp., Melosira granulata, Pinnularia microstauron, Nitzschia denticula, Cymbella tumida, Cymbella turgida* and *Gomphonema angustatum*. High frequencies of freshwater species and low frequencies of marine and brackish species suggest an intertidal to supratidal brackish-freshwater environment which was suitable for the expansion of dense mangroves forest. During this phase, the site was occasionally inundated by freshwater flooding, and as a result, the sedimentary conditions were not suitable for peat growth. The regression of the sea from the site and the development of a dense mangroves forest during this phase is also unequivocally demonstrated the existence of submerged mangroves forest macrofossils (see section 6.7).

Calibrated radiocarbon dates suggest that this regressive phase continued at the site for only about two centuries. Reappearance of a high frequency of marine and brackish water diatoms, such as *Coscinodiscus apiculatus, C. excentricus, C. marginatus, C. spp., Opephora pacifica, Paralia sulcata, Cyclotella striata, Nitzschia obtusa, N. linkei, Navicula cruciculoides* and *Synedra tabulata* indicates another invasion of the sea at the site at about 4350 cal. yrs BP which continued for about the next 2000 years. The pollen frequency at LPAZ-IV is very low, suggesting sedimentation under a strong marine influence. This is further supported by a higher frequency of marine diatoms in LDAZ-IX. It could, therefore, be argued that since about 4350 cal. yrs BP the sea-level started to rise first at a rapid rate and then more slowly. Existing mangrove communities could not keep pace with the rapid rise of sea level and finally disappeared. During this episode, the site changed from being an intertidal marine brackish water zone to a brackish-marine estuarine environment.

The sea started to retreat from the site at about 2350 cal. yrs BP, possibly very rapidly, and since then a fluvially controlled freshwater environment has existed there. The sporadic occurrence of some marine and brackish water diatoms at LDAZ-X indicates some occasional tidal flooding, possibly during extreme events. This suggests that the coastline was not too far south from the site during that time. During this regressive episode, the site was possibly a freshwater swampy area with waterlogging of long duration which was favourable for the development of freshwater peat. The transition from an intertidal to a freshwater swampy environment was so fast, due to a rapid fall of sea level and water table, that no mangrove plants could regenerate. The sporadic occurrence of the limited mangroves pollen in LPAZ-V is probably due to it being carried from a mangroves forest existing to the south, possibly not far from the coring site. The occurrence of a high frequency of unknown type pollen in this LPAZ-V presents a problem. As most of the mangroves pollen are familiar to the author, these unknown type pollen are probably non-mangrove taxa. The diatom record indirectly evidences that these pollen came from freshwater-loving terrestrial or aquatic plants.

7.5. SEA-LEVEL INDEX POINTS

Reconstruction of the sea-level curve/band of any place largely depends upon the proper recognition of sea-level index points. Long and Tooley (1995) mentioned five principal attributes of a sea-level index point: a location, an age, an altitude, an indicative meaning and a reference tide-level. Random use of radiocarbon dates without knowing their indicative meaning to a reference tide-level has no meaning in sea-level research. It is possible to make an estimate of the indicative meaning of dated material by reference to tide level (Shennan, 1982a).

Mangrove sediment is a very useful indicator of sea-level movement in tropical environments (Belperio, 1979; Crowley and Gagan, 1995). Kidson (1982) argued that the only reliable indicators are organic remains in their growth position where the relationship to a sea level or a water table can be determined within an acceptable limit. Scholl (1964) suggested that the mangrove peat forming within the upper half of the tidal range can be used as a sea-level indicator. Ellison (1989) argued that mangal peat offers only a directional indication of sea levels, whereas that mangroves pollen evidence could be used to provide a definite position of a past sea level. Tooley (1974) argued that an index point could be taken from biogenic sediments, the relationship of which to the former position of a sea-level had been established by using pollen and diatom evidence. Mangrove pollen as a sea-level indicator has been used by several researchers (Woodroffe *et al.*, 1985; Banerjee and Sen, 1987; Ellison, 1989), although the interpretation of these indicators, whether of a positive or a negative sea-level movement, is still open to debate.

Although some published radiocarbon dates[1] are available from different parts of the Bengal Basin, their indicative meaning is mostly unknown. In this section attempts are made to discuss the indicative meaning of some of those dates including 9 new dates, in reference to a tide-level, the MHWST. It is assumed that a pollen assemblage of *Excoecaria-Heritiera* indicates a position of the MHWST to within ± 10 cm (see section 2.6.iv).

i. Index Points at Panigati and the Surrounding Regions

Thirty nine ^{14}C dates, including five undertaken for this study, are now available from Panigati and the surrounding regions (see Table 5.1 and 5.2). Before using these dates to reconstruct Holocene sea-level movement, it is, therefore, necessary to determine the indicative meaning of each index point to the MHWST. Each index point could indicate any of the following meanings:-

Firstly, if the index point comes from a regressive overlap, and based on fossil evidence its relation to MHWST is known, this date would then indicate a negative sea-level movement, i.e. relative sea-level fall, but only if other index points in the area together show the same tendency.

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[1]Published ^{14}C results and pollen data from Calcutta region are in Appendix 20.

Secondly, if the index point comes from a transgressive overlap and similarly its relation to the MHWST is known, then it would mean a positive sea-level movement, i.e. sea-level rise, again only if other index points in the area together show the same tendency.

Thirdly, if the index point comes from any other levels within either a peat or an inorganic layer, it has little indicative meaning. It can only be used, with reservation, if it is possible to establish its altitudinal relation to MHWST at either regressive or transgressive overlap.

Fourthly, if an index point does not satisfy any of the above three criteria, it has no indicative meaning to any reference tide level and should not be used for sea-level reconstruction.

Out of 39 radiocarbon dates from Panigati and surrounding region, only eight dates (Table 7.1) can be used with confidence of which two are from transgressive overlaps (6390 $\pm$130BP and 6170 $\pm$140BP), indicating a relative sea-level rise, and six are from regressive overlaps (7030 $\pm$150BP, 6360 $\pm$120BP, 5210 $\pm$60BP, 4990 $\pm$110BP, 4075 $\pm$100BP and 5980 $\pm$60BP), indicating a relative fall of sea-level. Eight dates can be used with care, of which five indicate positive sea-level (8910 $\pm$150BP, 8210 $\pm$60BP, 6650 $\pm$120BP, 7060 $\pm$120BP and 4930 $\pm$120BP) and three indicate negative sea-level movement (6490 $\pm$100BP, 3470 $\pm$110BP and 3230 $\pm$110BP). One date (1210 $\pm$80BP) has no precise indicative meaning to sea-level movement but from a freshwater environment. The remaining 22 dates have no indicative meaning. It should, however, be noted that dates obtained from wood samples and dates coming from a wider area

Table 7.1:

Sea-level Index Points and Their Indicative Meaning

C^{14} Age[1]	Pollen Assemblage (%)	Diatom Assemblage (%)	Indicative Meaning
Panigati[2]			
1210 ±80BP	Grl(51), Grs(17), Cu(14), Mv(17), Ex(3), Ph(3), Ch(4),	Nil	No meaning (Freshwater !)
5210 ±60BP	Ex(10), He(5), Cu(42), Grl(34), Mv(27), Cy(3),	Nil	Regressive Overlap (*)
5980 ±60BP	Ex(38), He(24), So(3), Br(2), Ce(2), Grs(14), Ty(6), Mv(19), Ms(12), Cu(2)	Nil	Regressive Overlap (*)
8210 ±60BP	Ex(18), He(15), So(10), Av(8), Ce(4), Br(4), cu(5)	Nil	Transgressive Overlap (!)
Daulatpur[3]			
3230 ±110BP	Not Done	Not Done	Regression (!)
6490 ±100BP	Not Done	Not Done	Regression (!)
7060 ±120BP	Not Done	Not Done but records of Shell *Gelonia sp*	Transgression (!)
8910 ±150BP	Not Done	Not done but record of Shell *Neritina sp*	Transgression (!)
Calcutta[3 4]			
3470 ±110BP	A-Po,Pot.Fe; C-He; R-Ch, Ty	Not done	Regressive Overlap (!)
4075 ±100BP	A-Cy,Gr; C-Ty,Pot,Rh; R-He,Ce	Not done	Regressive Overlap (*)
4930 ±120BP	A-So, grs,Grl; C-Ty, He;	Not done	Transgressive Overlap (!)
4990 ±110BP	A-he, Gr,Fe; C-So; R-Br,Ce,Rh	Not done	Regressive Overlap (*)
6170 ±140BP	A-Grs,Grl; C-Ph; R-He	Not done	Transgressive Overlap (*)
6360 ±120BP	A-Grs,Grl,Su; C-He; R-Ex,Ph,Ba,Pol	Not done	Regressive Overlap (*)
6390 ±130BP	A-Grs,Grl; C-Ph,ly; R-Her,Ex	Not done	Transgressive Overlap (*)
6650 ±120BP	A-Au,Fe; C-Gr; R-Ex, He	Not done	Transgressive Overlap (!)
7030 ±150BP	A-Grs,Grl,Ly; C-Ph,Su; R-Ty,Fr	Not done	Regressive Overlap (*)
Matuail[2]			
2280 ±80BP	Gr(42), Cy(9), Ty(9), Mv(11), Am(8), Ex(8), He(7)	Pol(3), Mes(6), Ol-h(3), Ol-i(42), Hal(37)	Regressive Overlap (*)
3980 ±70BP	Ex(24), He(21), Am(6), Av(4), Gr(21), Ty(4), Mv(8), Ce(3),	Pol(17), Mes(40), Ol-h(1), Ol-i(24), Hal(17)	Transgressive Overlap (*)
4080 ±60BP	He(26), Ex(15), So 12), Am(9), Ae(4), Av(4), Xy(4), Gr(7),	Pol(10), Mes(13), Ol-h(1), Ol-i(52), Hal(24)	Regressive Overlap (*)
6060 ±60BP	Infrequent Pollen	Pol(0), Mes(57), Ol-h(0), Ol-i(27), Hal(16) (Infrequent)	Transgression (!)
6170 ±50BP	Infrequent Pollen	No diatoms	Unknown
Chandina & Kachpur[3]			
3670 ±60BP	Not done	Not done	Regressive overlap (!)
5580 ±75BP	Not done	Not done	Transgressive overlap (!)
5620 ±75BP	Not done	Not done	Regressive overlap (!)
6060 ±75BP	Not done	Not done	Transgressive overlap (!)
6460 ±80BP	Not done	Not done	Regressive overlap (!)

A=abundant, C=common R=rare; Gr=Gramineae, Pol=Polyhalobous, Mes=Mesohalobous, Ol-h=Oligohalobous-halophobous, Ol-I=Oligohalobous-indifferent, Hal-Halophobous, l=large, s=small, He=*Heritiera*, Ex=*Excoecaria*, Su=*Suaeda*, Rh=*Rhizophora*, So=*Sonneratia*, Cu=*Cucumis*, Mv=Monolete,verrucate, Ph-*Phoenix*, Ch=Cheno-amaranthaceae, Br=*Bruguiera*, Ce=*Ceriops*, Cy=Cyperaceae, Ty=*Typha*, Av=*Avicennia*, Pot=*Potamogeton*, Ba=*Barringtonia*, Am=*Amoora*, Xy=*Xylocarpous*, Ae=*Aegiceras*

[1]=For laboratory code and sources see tables 5.1, 5.2, 6.1 and 6.2.

[2]=This study [3]=Other sources *=with confidence !=with reservation

should not be used.

ii. Index Points at Matuail and the Surrounding Regions

Seventeen radiocarbon dates, including five new undertaken for this study, are available for Matuail and the surrounding regions (see Table 6.1 and 6.2). ^{14}C results used by Brammer (1967, 1971) and Monsur (1990) can not be applied for sea-level reconstruction because their indicative meaning to the MHWST is unknown. Although no microfossil evidence is available for the sediment layers which were used by Hassan (1986) for ^{14}C analysis, based on their lithostratigraphic records it can be suggested that possibly two dates (6060 $\pm$75BP and 5580 $\pm$75BP) have positive indicative and three (6460 $\pm$80BP, 5620 $\pm$75BP and 3670 $\pm$60BP) have negative indicative meaning of relative sea-level movement.

Out of the five new dates at Matuail available in this research, three can be used with confidence as sea-level index points of which two (4080 $\pm$60BP and 2280 $\pm$80BP) are from regressive overlaps and one date (3980 $\pm$70BP) is from a transgressive overlap. One ^{14}C result (6060 $\pm$60BP) can be used, with care, as an indication of relative sea-level rise (supported by diatom evidence). The remaining date (6170 $\pm$50BP) has no indicative meaning of sea-level movement, but is possibly from a freshwater environment.

7.6. HOLOCENE SEA-LEVEL CURVES/BANDS

Only two attempts have so far been made in the past to reconstruct the Holocene sea-level history of the Bengal Basin. Umitsu (1987) proposed a curve of continuous relative sea-level rise for the Bengal Lowlands. This curve has some convincing evidence of radiocarbon dates relating to relative sea-level movement although their precise indicative meanings are obscure. Furthermore, the development of intercalated peat sequences has not been considered as a separate depositional sequence related to relative sea-level movement. However, the curve supports the so-called continuous sea-level school of thought (see Jelgersma, 1966, and Jelgersma and Tooley, 1995).

The second relative sea-level curve has been drawn by Banerjee and Sen (1987). Despite the use of mangrove pollen records, the curve has little convincing evidence for relative sea-level movement. The use of ^{14}C dates without knowledge of their indicative meaning is not acceptable. Besides, the peat sequences are not properly interpreted. However, this relative sea-level curve again supports the so-called stable sea-level school of thought. Both Umitsu's (1987) and, Banerjee and Sen's (1987) curves do not contain index points that have been properly related to a levelled datum in Bangladesh or India.

i. Construction of Sea-level Curve and Sea-level Band

The goal of this present research is to draw a sea-level curve/band for the Bengal Basin. Evidence of Holocene relative sea-level movement at two different sites (Panigati and Matuail) has already been discussed. All those evidence are now used to draw two relative sea-level curves, one for Panigati and one for Matuail.

a). Sea-level Curve at Panigati

Eight index points available from Panigati and Daulatpur have some indicative meaning for relative sea-level movement. The index points available from Daulatpur, not far from Panigati, have not been levelled to any datum. However, the sea-level curve (Fig. 7.2) at Panigati is based on four new index points, supported by other dates and each index point is shown in an error box (Shennan, 1986b; Devoy, 1982) the horizontal axis of the box indicates the uncertainty in ^{14}C age using 2 standard deviation errors (2σ) and the vertical axis indicates all possible sources of errors (e.g. compaction, subsidence and sampling error) relating to the altitude of the sample. Although the errors in age can be calculated, their vertical uncertainties still remain.

The curve is drawn following the indicative meaning of each index point; a uniform sedimentation rate and evenly distribution of time period between index points have been assumed. The rate and direction of movement of the curve has been interpreted from pollen and diatom analyses. Finally, an error band (envelope) is drawn, joining the upper and lower end of each error box, indicating that sea-level lay within this band.

The sea-level curve from Panigati, since about 9000 cal. yrs BP shows, five transgressive episodes.

b). Sea-level Curve at Matuail

Nine index points available from Matuail, Kachpur and Chandina have some indicative meaning for relative sea-level movement. Five new index points available for Matuail, supported by other dates, are plotted as a time-altitude graph (Fig. 7.3). Construction of the sea-level curve for Matuail has followed the same procedures as those for Panigati. Furthermore, diatom results at this site have been used as additional evidence to determine the rate and direction of sea-level, a feature poorly defined at Panigati.

The sea-level curve from Matuail, since about 7000 cal. yrs BP, shows three transgressive episodes.

ii. Possible sources of Error

The two proposed relative sea-level curves have been drawn using all possible sources of evidence and maximum care has been taken to reduce the possible potential errors. Some error sources are, however, obvious and can not be eliminated. These can be classified into three categories.

First, the number of sea-level index points used for each curve is very limited. Tooley (1978a) constructed the sea-level curve for North-west England using 26 index points. Shennan (1986b) used 35 dates for the Fenland sea-level curve and Zong (1992) used 28 index points for the Han River Delta. Long and Tooley (1995) have used 57 and recently, Zong and Tooley (1996a) have used 28, index points for constructing their curves for South-east England and Morecambe Bay, respectively. When more sea-level index points available, the resolution of two proposed sea-level curves from Panigati and Matuail will, therefore, be improved.

The second possible source of error could be associated with each radiocarbon assay itself. Each radiocarbon date may be affected in a number of physical and chemical ways (see section 4.3.iv), a common problem faced by every sea-level investigator.

Finally, and most important is the possibility of a vertical displacement of the index point from its original altitude of deposition. Unless further systematic empirical evidence of sediment compaction and subsidence rates for the Bengal Basin becomes available, it is quite impossible to isolate the altitudinal parameters.

Despite such potential limitations, these curves are the product of the application of a systematic methodology and as such they are considered to provide reliable sea-level curves for the Bengal Basin.

7.7. RATES OF RELATIVE SEA-LEVEL MOVEMENTS

The period between 18000 yrs BP and 6000 yrs BP can be characterized by two phases of extremely rapid rise of sea-levels (Fairbanks, 1989) when most of the restoration of sea-level was controlled by the melting of mid and high latitude ice-sheets (Jelgersma and Tooley, 1995). Tooley (1974, 1978a) calculated an extraordinarily rapid rise of sea-level, at a rate of 34-44 mm yr^{-1} at about 7800 yrs BP for North-west England, a feature that apparently driven by the catastrophic melting of the Laurentide ice sheet (Tooley, 1992). Such a rapid rise of the early Holocene sea-levels has also been demonstrated by a number of researchers, such as Fairbanks (1989) for Barbados (rates 24-28 mm yr^{-1}), Jian *et al.* (1991) for the southern Yellow sea (rate up to 51 mm yr^{-1}), Loveson (1993) for southern Tamilnadu coast (9.26 mm yr^{-1}), Hashimi *et al.* (1995) for the western Indian continental margin (rate 10 mm yr^{-1}), and Zong and Tooley (1996a) for Morecambe Bay (rates up to 36.7 mm yr^{-1}). For the Bengal Basin, the sea-level curve presented by Umitsu (1987), also shows a high rise in sea level, $\sim$7.27 mm yr^{-1}, during the early Holocene.

Data presented in this study do not cover the late Pleistocene and early Holocene period and therefore, do not register the sea-level components operating globally; while it may still be involved, it is realistically only the regional and local processes that can be considered. Although some agreement has been reached on the early Holocene sea-level movement (Jelgersma, 1961), the changes during the last 6000 years are much disputed, because the evidence of sea-level movement is dominated by regional and local tectonic activities, long term subsidence, release of water and sediment from the catchment, and anthropogenic activities (Jelgersma and Tooley, 1995).

Rates of relative sea-level movement at Panigati and Matuail have been calculated using a sidereal time-scale for every 100 years interval, and are shown in Figures 7.4 and 7.5, respectively. Summary results for each transgressive phase at Panigati and Matuail are given in Table 7.2.

i. Rates at Panigati

The transgressions II and III at Panigati had higher rates of relative sea-level rise than the other three transgressions. At about 6200 yrs BP, the rate was 3.65 mm yr^{-1}, the highest recorded at the site. Four other peaks of high relative sea-level rises (Fig. 7.4) are at calibrated yrs 8300 BP (2.25 mm yr^{-1}), 6500 BP (2.68 mm yr^{-1}), 4250 BP (1.00 mm yr^{-1}) and 2000 BP (1.52 mm yr^{-1}); the average relative rate of sea-level rise at Panigati since 8950 cal. yrs BP is 1.27 mm yr^{-1}.

ii. Rates at Matuail

The transgression II at Matuail shows a higher rate of relative sea-level rise than the other two. The maximum rate at this site was 2.5 mm yr^{-1} at about 5300 yrs BP. Two other peaks of high relative sea-level rises are at 6250 yrs BP (1.54 mm yr^{-1}) and 4300

Table 7.2:

Rates of Holocene Relative Sea-level Movement in the Bengal Basin

Transgression	Time Period (calibrated)	Maximum rate of s.l. change	Average rate of s.l. change
Panigati			
Transgression V	2165-1765 BP	1.52 mm yr^{-1}	0.80 mm yr^{-1}
Transgression IV	4665-3715 BP	1.00 mm yr^{-1}	0.75 mm yr^{-1}
Transgression III	6315-5915 BP	3.65 mm yr^{-1}	2.17 mm yr^{-1}
Transgression II	6615-6415 BP	2.68 mm yr^{-1}	1.29 mm yr^{-1}
Transgression I	9195-6770 BP	2.25 mm yr^{-1}	1.33 mm yr^{-1}

*Average rate for Panigati during the Holocene is 1.27 mm yr^{-1}

Matuail			
Transgression III	4400-2325 BP	0.81 mm yr^{-1}	0.56 mm yr^{-1}
Transgression II	5850-4540 BP	2.50 mm yr^{-1}	0.98 mm yr^{-1}
Transgression I	6890-6225 BP	1.50 mm yr^{-1}	1.07 mm yr^{-1}

*Average rate for Matuail during the Holocene is 0.87 mm yr^{-1}

**Average rate for the Bengal Basin during the Holocene is 1.07 mm yr^{-1}

yrs BP (0.81 mm yr^{-1}); the secondary peak at 6850 yrs BP (1.5 mm yr^{-1}) is the same Transgression-I. The average relative sea-level at Matuail since about 7000 cal. yrs BP is 0.87 mm yr^{-1}. Rates of relative sea-level movement at Matuail shows fewer fluctuations than that of Panigati; the former also shows a lower average rate than that of the later. The estimated average rate of relative sea-level rise for the Bengal Basin during the last *ca.* 9000 cal. yrs BP is 1.07 mm yr^{-1}.

Due to the paucity of sea-level records during the geological past in the Bengal Basin, these calculated values cannot be compared locally or regionally. The rate of this relative sea-level rise is, however, below the estimated rate of the so called eustatic sea-level rise during the last 100 years and well below the rates estimated for Bangladesh (see section 1.2), all calculated from tidal gauge records. These calculated rates of sea-levels for the geological past can be used to aid an understanding of the present changes and to project tentatively the future coastal conditions of Bangladesh.

7.8. TENDENCIES OF SEA-LEVEL MOVEMENTS AND REGIONAL CORRELATION

The next and final scale of analysis involves the synthesis of data, collected in this study and that available from literature, to establish the regional correlations of sea-level movements based on the sea-level tendency concept (see section 3.6). The correlation is attempted by visual comparison of the indicative meaning of all available index points from the Calcutta, Khulna and Dhaka regions; index points are in Table 7.1.

The tendency approach requires a large data set for correlation. Shennan *et al.* (1983) used 47 ^{14}C dates from the Fenland, 74 from north-west England and 29 from the Tay

Estuary to correlate between those three regions. The present correlation scheme includes nine dates from the Calcutta region, eight from Khulna region, and nine from the Dhaka region; these are shown by histograms in Figure 7.6.

It has already been shown that the ^{14}C time scale is flexible, due to the non-parallelism of the ^{14}C and sidereal calender. The calibration of a ^{14}C date to a sidereal is the calculation of the probability of any date occurring within a given sidereal time period (Olsson, 1986; Mook and van de Plassche, 1986; Stuiver and Pearson, 1993). Calibrated dates are essential for sea-level tendency analysis and for the establishment of rates of sea-level change.

All ^{14}C dates used in this correlation scheme have, therefore, been calibrated to a sidereal time scale using the **CALIB** program designed by Stuiver and Reimer (1986) and presented as histogram in Figure 7.7. ^{14}C chronology and sidereal chronology of tendencies of sea-level movement in Calcutta, Khulna and Dhaka regions are presented in Figure 7.8 and Figure 7.9, respectively. It should, however, be noted that there is always a possibility of a time lag between each phase of positive and negative sea-level moment, although Shennan *et al.* (1983) argued that the scheme could be accurate to about ± 100 ^{14}C yr.

The correlation scheme illustrates five positive tendencies of the Holocene sea-level movement in the Bengal Basin, each followed by a negative tendency. After the name of the site Panigati, where the author put down his first borehole in Bangladesh, the following positive tendencies and their abbreviated name are proposed for the Bengal

Basin:

Panigati Positive Tendency 5	**PG V**
Panigati Positive Tendency 4	**PG IV**
Panigati Positive Tendency 3	**PG III**
Panigati Positive Tendency 2	**PG II**
Panigati Positive Tendency 1	**PG I**

i. Panigati Positive Tendency 1 (PG-I) (Clt[1]?-8000 BP; Khl ?-6800 BP; Dhk not recorded)

The date of the beginning of the earliest positive sea-level tendency in the Bengal Basin is not available. Umitsu (1987) suggested a continuous rise of relative sea-level in the Bengal Basin since *ca.* 10000 yrs BP. Near Calcutta this positive sea-level continued until *ca.* 8000 cal. yrs BP. The Khulna region, about 150 km east of Calcutta, was at that time under the sea. At about 8000 yrs. BP the sea retreated from the Calcutta region although in the Khulna region this tendency continued for a further *ca.* 1200 years. In the Dhaka region this marine phase is not recorded which is possibly due to early Holocene uplift of the Madhupur areas, as recorded from the altitudinal differences of the dating points.

ii. Panigati Positive Tendency 2 (PG-II) (Clt 7350-7250 BP; Khl 6750-6500 BP; Dhk 7000-6300 BP)

This positive sea-level tendency continued in the Calcutta region only for *ca.* 100 years, in the Khulna region *ca.* 250 years and in the Dhaka region *ca.* 700 years. Possibly the

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[1] Clt=Calcutta region; Khl=Khulna region; and Dhk=Dhaka region ?=not known

Madhupur uplifting ceased or was reduced during this phase and the sea, therefore, invaded further inland and started to infill the incised valleys of the region with intertidal and estuarine deposits.

iii. Panigati Positive Tendency 3 (PG-III) Clt 7050-5850 BP; Khl 6400-6000 BP; Dhk 5950-4650 BP)

Both the Calcutta and the Khulna regions are at nearly the same latitude. The record shows a positive sea-level movement at Calcutta about 650 years earlier than at Khulna; this was sustained for a longer period, the explanation of which is not clear. A close similarity, however, can be found between the Calcutta and Dhaka regions. In the Dhaka region this positive phase continued for *ca.* 1300 years and possibly during this phase the sea here reached its northernmost limit.

iv. Panigati Positive Tendency 4 (PG-IV) (Clt 5700-4650 BP; Khl 4700-3750 BP; Dhk 4550-2400 BP)

This positive sea-level tendency continued in both the Calcutta and Khulna regions for about 1050 and 950 years, respectively; in the Dhaka region it was for a much longer time (2150 years). Possibly during this phase, progradation was faster in the western part of the Basin than in the eastern which suggests differential delta building activities in different parts of the Basin. The sea finally retreated from the Calcutta and Dhaka regions at about 4650 yrs BP and 2400 yrs BP, respectively, although Dhaka is further inland than Calcutta.

v. Panigati Positive Tendency 5 (PG-V)
(Clt not recorded; Khl 2200 BP-1800 BP; Dhk not recorded)

The last positive sea-level tendency was recorded only from the Khulna area; it started at about 2200 yrs BP and continued for the next *ca.* 400 years. During this phase the sea did not invade further inland and possibly remained limited to the south of the Jessore area. Umitsu (1993) was correct in recording a marine influence north of the Khulna city during the middle Holocene; the final retreat of the sea from Khulna region was only about 1800 years ago.

In this correlation scheme a close similarity of sea-level tendency movement is noted among the three regions. Some minor regional variations have also been observed which could be due to differential crustal moment and local sedimentary processes in each region. The application of the tendency model to correlate regional sea-level movement suggests that the processes responsible for relative sea-level movement in the Bengal basin during the Holocene, operated regionally. Records of spatio-temporal gravity anomaly changes in the Bengal Basin during the Holocene are not available. Nothing can be suggested about the gravitational equilibrium of the crust, mantle and asthenosphere due to regional tectono-hydro- and -sedimento- isostasy. However, some local factors, such as variable sediment supply, sediment compaction, hydro-isostasy and differential subsidence may also be responsible for regional variations.

Chapter 8:
IMPLICATIONS OF THE HOLOCENE SEA-LEVEL CHANGES: A DISCUSSION

8.1. INTRODUCTION

Using all the available data (see Chapter 5 and Chapter 6), the history of Holocene relative sea-level movements in Bangladesh has already been reconstructed (see Chapter 7). Any change of relative sea-level would have significant environmental consequences throughout Bangladesh. The aim of this chapter is, therefore, to discuss the implications of the Holocene relative sea-level changes on the palaeogeography of the Bengal Basin. It should, however, be borne in mind that the discussion is based on limited data; thus reassessments are likely.

8.2. HOLOCENE SEDIMENTATION

i. Sedimentary History and Geomorphic Evolution

The Quaternary geomorphic evolution of the Bengal basin was first described by Morgan and McIntire in 1959. Their work was mostly based on geomorphological evidence without any consideration of the lithostratigraphic records. The sedimentary history and geomorphic evolution of the Basin could be interpreted as resulting from the post-glacial sea-level movements. If Chowdhury's (1959) hypothesis of the origin of the 'Swatch of No Ground' as an estuary of the last glacial maximum is accepted, then possibly most northern parts of the Bay of Bengal, during that time, were dry land. Umitsu (1993) argued that during the lowest stand of sea-level of the last glacial maximum, a gravel bed about 10 m thick was deposited in the Bengal lowlands. Oya (1977) argued that this gravel bed was deposited during the Würm Ice Age. The top of this gravel bed is at a depth of 44 m at Bahadurabad, 51 m at Gabargoan, 72 m at Sirajganj and 81 m at

Nagarbari showing an average gradient of about 3/10,000 (Umitsu, 1993).

Regional glaciation/deglaciation in the Himalayas is likely to have had a marked effect on the sedimentation and sea-level movements in the Bengal Basin. van Campo (1986) argued that a very humid period prevailed in the Indian Subcontinent between 11,000 and 10,000 yrs BP when valley cutting by the rivers of the Bengal Basin was predominant. The gravel bed is, thus, overlain by a coarse sandy sediment which was deposited in a markedly fluvial environment during the late-Pleistocene.

The sediments overlying this sand bed become finer and a marked change in particle size can be seen (see Fig. 5.7). During the late-Pleistocene and the early-Holocene, due to a rapid rise of relative sea-level, the freshwater/saltwater interface was pushed further north from the mouth of the 'Swatch of No Ground' and the northern parts of the Bay of Bengal were inundated by the rising sea. The river gradient decreased considerably as base level rose and as a result the sandy layer was overlain by finer particles. Available borehole records from the Bengal Basin (see Umitsu 1987, 1993) points to a strong early-Holocene marine influence throughout the southern parts of the Basin, although the northern parts were under fluvial influences.

Possibly, prior to at about 9000 yrs BP, the Basin was again under increased fluvial influence, at least for a short time; this is evidenced by deposits of about 5 m of silty sand (see zone 11 in Fig. 5.7) which overlies the fine, silt-clayey estuarine sediments. Whether these coarser sediments were deposited due to increased regional monsoon precipitation during that time (Kutzbach and Street-Perrott, 1985) or due to relative sea-level fall or both, is difficult to say. The discovery of *Neritiolae neritina* sp. in these sediments by Umitsu (1987, 1993) indicates a change in the depositional environment from an estuarine to an intertidal zone. This takes to a possible relative fall of sea-levels during that time.

Aspects of the sedimentary history of the Bengal Basin since *ca.* 9000 yrs BP can be interpreted from the data provided in this study. The depositional sequences of each intercalated peat layer and silty-clayey estuarine deposits have already been described fully in chapter 7.

Traditionally, it is believed that the Holocene sediments within the Bengal Basin are alluvial and deltaic deposits of the Ganges-Brahmaputra-Meghna river system. The evidence from the present research introduces a different explanation. It is undoubtedly true that the Ganges-Brahmaputra-Meghna system has been carrying sediments from upstream and depositing them in the Basin, but their depositional environment needs to be considered. Litho-and bio-stratigraphic evidence presented in this research suggest that the sedimentary environment within the Bengal Basin, from the early Holocene until about 2400 yrs BP at Dhaka and 1800 yrs BP at Khulna was dominated by relative regional sea-level movements. The interface of the fluvial/estuarine depositional sequence can be related to the rates and direction of this movement. The present day analogue of such a depositional environment is provided by the south-western coastal districts of Bangladesh.

Sediments deposited on top of the uppermost peat are fluvially controlled. These are the sediments deposited by the Ganges-Brahmaputra-Meghna river system. Depending on their particle size, these sediments can be characterized as deposits of floodplains, backswamps, levées, channel bars and sand bars.

ii. Sedimentation Rates

Despite the enormous scope, little attempt has been made to study the Holocene sedimentation rates of the Bengal Basin. Although it is estimated that about 1.8 to 2.4 billion tons of sediment are currently being carried by the Ganges-Brahmaputra-Meghna river system each year, much uncertainty remains (Jabbar, 1979).

Sediment accumulation in coastal lowlands occurs as a result of a complex interaction of a number of factors, primarily in relation to relative sea-level movements (Chen, 1996). The rate of sediment accumulation is a function of climate, sediment type, time, geographical location, human disturbance, compaction and secular variation in the radiocarbon time scale (Webb and Webb, 1988), and is, therefore, very difficult to calculate. The common practice is to calculate the sedimentation rate by a linear interpolation from an age-depth model (Ogden, 1967). Bennett (1994) applied three basic types of age-depth model: linear interpolation, spline interpolation and polynomial line fitting, and concluded that line-fitting of polynomials by least squares would produce narrower confidence intervals than an interpolation model.

In this research, because there is a limited number of ^{14}C dates, the sedimentation rates at Panigati and Matuail have been calculated from straight line age-depth models (Fig. 8.1 and Fig. 8.2). Due to past variations in atmospheric ^{14}C content (Suess, 1970), radiocarbon ages are not equivalent to calendar ages, and a calibration of ^{14}C results (Stuiver and Reimer, 1993) is, therefore, necessary. The sedimentation rates at different time periods are shown in Table 8.1.

Variations in sedimentation rate have been reported from the Bengal Basin. Barui and Chanda (1992) calculated a high accumulation rate of peat layers (2.34 to 9.09 mm yr^{-1}) at Calcutta. Gupta (1981) estimated differential sedimentation rates, from 0.66 to 3.33 mm yr^{-1}, in different sediment layers; the peat accumulation rate was 0.3 mm yr^{-1}. The above estimations were calculated based on uncalibrated ^{14}C dates.

In the present study the average estimated Holocene sedimentation rates vary from 0.80 mm yr^{-1} (Panigati) to 0.82 mm yr^{-1} (Matuail). During the early Holocene, the Matuail region experienced a higher sediment influx (8.47 mm yr^{-1}), probably due to excessive valley cutting by the region's incised channels. During the last millennium the rate has also been very high at both sites. However, a lower sedimentation rate at Matuail, particularly during the late Holocene, indicates a possible upheaval of the Madhupur region.

The calculation of age estimates and deposition times by means of an age-depth model does not include the possible sources of errors due to differential spatio-temporal processes of sedimentation within the basin. The approach should be applicable where sediment compaction is known, sediment stratigraphy is approximately uniform and a large number of ^{14}C dates is available. The error given with each radiocarbon date is another uncertainty in any estimation. The results presented here are based on a limited

Table 8.1:

Estimated Sedimentation Rates at Panigati and Matuail during the Holocene

Panigati		**Matuail**	
Calibrated Time Period (*ca.*)	**Sedimentation Rates(mm yr^{-1})**	**Calibrated Time period (*ca.*)**	**Sediment-ation Rates(mm yr^{-1})**
		Since 2400 BP	0.54
Since 1100 BP	3.12	4500-2400 BP	0.26
6000-1100 BP	0.46	4600-4500 BP	3.17
7000-6000 BP	1.42	7000-4600 BP	0.98
9000-7000 BP	0.67	Before 7000 BP	8.47
Average	0.80	Average	0.82

number of ^{14}C results, and, therefore, only a tentative conclusion can be made.

iii. Estimation of Compaction and Subsidence

Estimation of sediment compaction is a rather complicated matter. Most coastal regions show uneven sediment compaction which is controlled by differential sedimentation rates, sediment composition, void ratios, water content, depth of overburden sediment layers and tectonic activities (Greensmith and Tucker, 1986). In Holocene sediments, it may vary from 0 to 90% (Jelgersma, 1961). It is generally stated that peat, due to compaction, can be subject to a 80 to 90% change in thickness, clayey muds 75 to 90% and sands 25 to 35%. Streif (1979b) considered a 80% compaction of peat at Malacca and recently, Zong and Tooley (1996a) suggested that a 50% compaction of peat at Morecambe Bay had occurred. Bloom (1964) argued that the calculation of compaction was not possible by dating the top and bottom of a buried peat, although Greensmith and Tucker (1986) stated that, in a uniform sediment succession, a broad quantification of compaction could be possible. In the Bangladesh context, where the lithology is variable and can be characterized by a number of intercalated peat layers, the estimation of sediment compaction, at this stage of insufficient records, is virtually impossible.

Subsidence due to gravitational compaction and consolidation is a major potential source of error in sea-level research, particularly in deltaic conditions. Alam (1972) mentioned that the subsidence of the Bengal Basin is directly related to the uplift of the Himalayan-Burmese Mountain ranges. Brammer (1990b) also noted differential subsidence due to tectonic movement of the Basin.

However, some attempts in the past have been undertaken to estimate the subsidence rates of the Bengal Basin, although most of these estimations did not result from a systematic research methodology. The most exaggerated rate of 1 cm yr^{-1} was suggested by Milliman *et al.* (1989), with little evidence presented to support this result. If this rate is accepted, the sample with a ^{14}C age of 8210 $\pm$60BP at Panigati would be expected to have come from a depth of more than 80 m; whereas the dated sample actually comes from a depth of only 10 m.

The ^{14}C result, from fossil wood, of 28,320 $\pm$ $^{1750}/_{1440}$ at a depth of 112 m is the oldest date from the Bengal Basin (Umitsu, 1987). Ravenscroft (1992) argued that this dated wood was laid down at approximately the same depth relative to the prevailing sea-level as the present land surface above the present sea-level and thus showed a total subsidence of 60 m since that time; accordingly a rate of 2.11 mm yr^{-1} has been determined by him.

Using available published ^{14}C dates, Hasan and Alam (1991) estimated an average rate of 1 mm yr^{-1}, although their calculation procedures are perhaps questionable. It is not a good practice to divide a ^{14}C date by the measured depth to estimate the subsidence rate, without knowing the original altitude at which the dated sample was deposited and a calibrated age. Umitsu (1987), on the other hand, correlated his ^{14}C results with Vishnu-Mittre and Gupta's (1972) results and estimated a subsidence rate of 0.6 to 0.9 mm yr^{-1} (approx. 1 mm yr^{-1}) for the Bengal Basin.

The accurate determination of subsidence of the Basin is not possible due to the absence of geodetic data. It might, however, be possible to estimate the subsidence rate of any basin, provided a reference tide-level (MSL or MHWST) is known. Bloom and Stuiver

(1963) estimated subsidence rates of 0.91 to 1.82 mm yr^{-1} for the Connecticut coast from the relative sea-level curve. Coleman and Smith (1964) likewise estimated a subsidence rate of 0.73 mm yr^{-1} for the Louisiana coast of the Mississippi delta. Wunderlich and Andres (1991) applied the so-called eustatic sea-level curves of Fairbridge (1961), Curray (1965) and Kelletat (1975) to estimate the subsidence rates of the Nile delta and obtained rates of 1 mm yr^{-1}, 0 mm yr^{-1} and 0.5 mm yr^{-1}, respectively. The application of the so-called eustatic sea-level curve to estimate the subsidence rate of any site or region is questionable. Only a local or regional sea-level curve can be applied. In the present research, the relative MHWST-level curves have been applied to measure the vertical displacement of each index point due to subsidence (Fig. 8.3). Once the vertical movement of each index point is known, the measurement of the subsidence rate (Table 8.2) can easily be obtained from the calibrated ^{14}C dates. It should, however, be noted that the estimation is based on the assumption that the MHWST-level reached its present position about ^{14}C 1210 $\pm$80BP (cal. 1095 yrs BP) at Panigati.

Table 8.2 shows temporal variations in subsidence rates. Sediments deposited after *ca.* 1100 cal. yrs BP under fluvial conditions has a higher subsidence rate (1.73 mm yr^{-1}) than during the earlier part of the Holocene (0.28 to 0.36 mm yr^{-1}). In this study, an average subsidence rate of 0.68 mm yr^{-1} has been estimated for the Holocene sediments of the Bengal Basin. It should, however, be noted that the estimation of the proposed rates suffers from a number of limitations. The rates have been calculated from the index points which indicate the MHWST. Nothing is known about the palaeo-tidal range during the Holocene in the Bengal Basin and, therefore, each index point may include a potential error range.

Table 8.2: Estimated[1] Subsidence and Uplift Rates at Panigati and Matuail

Time Period (*ca.*)	^{14}C Dates	Calibrated Dates	Measured Altitude(m)	Corrected Altitude(m)	Vertical Movement(cm)	Subsidence (-)/ Uplift (+) rate
Panigati						
After 1100 BP	1210 ±80BP	1095 BP	-1.71	+0.25	196	-1.73 mm yr^{-1}
6000-1100 BP	5210 ±60BP	5940 BP	-3.96	-1.80	216	-0.36 mm yr^{-1}
7000-6000 BP	5980 ±60BP	6805 BP	-5.19	-2.85	234	-0.34 mm yr^{-1}
9000-7000 BP	8210 ±60BP	9195 BP	-8.10	-5.50	260	-0.28 mm yr^{-1}
Matuail						
Since 2350 BP	2280 ±80BP	2325 BP	+0.58	0.00	58	+0.25 mm yr^{-1}
4450-2350 BP	3980 ±70BP	4425 BP	+0.03	-0.75	78	+0.17 mm yr^{-1}
4550-4450 BP	4080 ±60BP	4540 BP	-0.34	-1.20	86	+0.19 mm yr^{-1}
7000-4550 BP	6060 ±60BP	6890 BP	-2.33	-3.45	112	+0.15 mm yr^{-1}
Before 7000 BP	6170 ±50BP	7020 BP	-3.43	-4.50	107	+0.15 mm yr^{-1}

[1] The estimation is based on the assumption that the MHWST was reached at its present position at ^{14}C 1210 ±80BP (cal. 1095 yrs BP) at Panigati and at ^{14}C 2280 ±80BP (cal. 2325 yrs BP) at Matuail.

Sediment compaction due to the load of overburden sediment layers and tectonic activities within the Basin is also unknown. If a compaction of 50% (Zong and Tooley, 1996a) for the Holocene sediment is assumed, then the average subsidence rate is very close to Umitsu's (1987) estimated result.

iv. Estimation of Uplift

Geological records, geomorphic studies, and geophysical investigations of seismic, gravity and magnetic data indicate that the late Pliocene-Pleistocene Himalayan orogenic movement has continued to be active up to the present time (see MPO, 1986). The Bengal Basin is a part of the Himalayan orogeny, and parts of the Basin have been uplifted and have subsided as a result of neotectonic activities (Morgan and McIntire, 1959; Khandoker, 1987). Generally, a high gravity anomaly in the Bouger Gravity map (see MPO, 1986) relates to uplifted while a low gravity anomaly to subsided areas.

Morgan and McIntire (1959) argued that the uplift of the Barind-Madhupur Tracts and Tippera surface are tectonically controlled. Khandoker (1987) explained that their uplift can be characterized by an isostatic compensatory subsidence of the bordering regions. However, the upheaval of the Barind and Madhupur Tracts is well known, although its quantification is yet to be established.

The interpretations of sea-level changes at Matuail in terms of subsidence or uplift (Table 8.2) clearly indicate the post-glacial uplift of the Madhupur tract. This is supported by the evidence of marine and brackish water diatoms which have been recorded close to the level of present MSL and could only mean a land upheaval at the site. The upheaval rate of the Tract determined from the reconstructed MHWST-level curve at Matuail and calculated as discussed above for Panigati are shown in Table 8.2.

The early Holocene record at the site is not available, so, nothing can be said on the rate of uplift during that period. Since the mid-Holocene the tract has been rising at a rate of 0.15 to 0.19 mm yr^{-1}. During the recent time (after *ca.* 2350 yrs BP), the rate has significantly increased (0.25 mm yr^{-1}). Such an accelerated rate of uplift could be related to isostatic adjustment due to the accelerated subsidence rate of the surrounding floodplains in recent times. It should, however, be noted that the estimation is based on the assumption that the MHWST-level reached its present position about ^{14}C 2280 $\pm$80BP (cal. 2325 yrs BP) at Matuail.

v. *In situ* Origin of the Bengal Peat

In the preceding chapters, it has been shown that the Holocene lithology of the Bengal Basin is characterized by a number of peat beds separated by minerogenic sediment layers. Possible explanations for the formation of each peat layer have also been given (see section 7.2.i). Discussion of the field and laboratory results, to support the contention of an *in situ* origin of the Bengal peats, is also required.

The environment in which the peats of the Bengal Basin were deposited is debatable. Most of the earlier authors argued that the Bengal peats were reworked and drifted deposits. Ghosh (1964) maintained that a large amount of partially decayed vegetable matter was carried into and deposited by the regional river system in the Bengal marshy floodplains. Dastidar and Ghosh (1964) concluded that the peats are detrital in character and contain material which has drifted from a long distance. Based on palynological work, Mallik and Chaudhury (1968) concluded that the Calcutta peats were different from the mangrove elements and, therefore, supported the contention of the 'drifted origin' of the Bengal peat.

New explanations occurred when more evidence from palynological works became available. Chanda and Mukherjee (1969) and Mukherjee (1972) reported the presence of large numbers of mangroves pollen in each peat layer, attributing the existence of mangroves forest in and around Calcutta about 5000 years ago, and attesting an *in situ* origin of the Bengal peats. Vishnu-Mittre and Gupta (1972), and Gupta (1981) supported the view of an *in situ* peat formation under a freshwater swampy condition. They ruled out an explanation for the occurrence of the *Rhizophora* pollen in their samples as having been associated with freshwater peat, and concluded that the occurrence was due to long distance transport.

Further evidence of an *in situ* origin for the Bengal peats is available from the palynological works of Barui and Chanda (1979, 1992), Barui *et al.* (1986), Banerjee and Sen (1987, 1988), and Sen and Banerjee (1988, 1990). Pollen diagrams presented by those authors include the pollen of common mangrove plants indicating environmental conditions under which each *in situ* peat layer was deposited. In the current research, evidence both from the field and laboratory, is also available to support the contention of an *in situ* origin for the Bengal peats.

Bengal peats are mostly composed of vegetative fragments of mangrove plants, such as

Heritiera fomes and *Excoecaria agallocha* and *in situ* rootlets of herbaceous plants. These peats are moderately to well laminated. Dicot. and monocot. leaves, stems of herbaceous plants such as *Phragmites karka* and frequent pieces of wood from mangrove plants are found well stratified in the laminations. No trace of reworking or mixture with any inorganic sediment was observed. This field evidence clearly indicates that these peats accumulated in an undisturbed waterlogged condition and lie in their growth positions. If they had been reworked and redeposited by rivers (Ghosh, 1964, Mallik and Chaudhury, 1968), laminations would have been disturbed and inorganic sediments mixture would have taken place. Finally, in drifted peat layers, which would come from the north, it is very unlikely that there would be frequent presence of pieces of mangroves wood.

The pollen diagram (see Fig. 5.8) reveals a high frequency of the pollen of mangrove plants in each peat layer and this indicates the existence of mangroves vegetation in and around the site in each sequence of peat formation. The high frequency of mangroves pollen of major species, now found in the Sundarbans, can not be dismissed as a product of long distance transport (Vishnu-Mittre and Gupta, 1972). If the peats had been brought by the river from different localities, they must have been transported from the north of the Basin and would include exotic pollen records. Neither the previous palynological work nor this present research has reported such an occurrence. The palynological evidence of the present research clearly supports the records obtained in the field and it can be unequivocally stated that the Bengal peat is *in situ* in origin. If the peat layers display signs of erosion, that is most likely the result of local factors, such as differential sedimentation or hydro-dynamics.

8.3. COASTAL VEGETATIONAL HISTORY

An account of the Holocene vegetational history from pollen records at Panigati and Matuail can be found in sections 5.11 and 6.11, respectively. Each Local Pollen Assemblage Zone (LPAZ) in Figures 5.8, 5.9 and 6.9 shows the vegetational changes during this period and will not be discussed further. However, a brief account of possible coastal mangal limits during the Holocene is given below.

i. Holocene Mangal Limits

Evidence available from the Calcutta region, Panigati and Matuail indicates the existence of mangroves vegetation along the coastal belt of the Bengal Basin. Its landward limits at different stages of the Holocene would have been determined by the relative land-level and sea-level movements. If the past landward extents of mangal limit were similar to todays' and once the land and sea-level relations are known, the reconstruction of the landward mangal limit becomes straightforward. Plotting the information from the reconstructed relative sea-level curves (Fig. 7.2 and 7.3) on a contour map (Islam *et al.* 1981), five mangal phases, covering part of the Bengal Basin, for different time periods, have been reconstructed (Fig. 8.5).

a). Mangal Phase One (*ca.* 9000 to 8000 BP)

About 9000 to 8000 yrs BP the mangroves ecosystem possibly existed in most parts of Jessore and Narail, parts of Jhenaidah and Magura, and the northern parts of the Calcutta region. This formed a mangal belt extending from the Chandannagar and Barakpur regions in India to the Padma (Ganges) course in Bangladesh.

b). Mangal Phase Two (ca. 8000 to 7000 BP)

During this phase, the sea possibly started to retreat southwards in the Basin and as a result the mangal belt also migrated seaward. Between *ca.* 8000 and 7000 yrs BP, mangroves vegetation covered most parts of Narail, southern Jessore and northern Satkhira, and parts of the Calcutta region.

c). Mangal Phase Three (*ca.* 7000 to 5000 BP)

Between *ca.* 7000 and 5000 yrs BP, the contours imply a narrow belt of mangroves vegetation existed along the southern parts of the Calcutta region. In Bangladesh the belt was much wider, covering the Gopalpur and Madaripur districts, and the northern parts of Khulna and Satkhira districts. During this time, two short periods of marine transgression and regression were evident in the Khulna region. It is, therefore, difficult to determine the southern mangal limit during this phase.

d). Mangal Phase Four (*ca.* 5000 to 3000 BP)

From *ca.* 5000 to 3000 yrs BP, the pollen record implies a dense mangroves forest belt existed along the south-western coastal belt. It formed an arc-shaped mangal belt covering the central parts of the 24-Pargans district in India and parts of Satkhira, Khulna, Pirojpur and Patuakhali districts in Bangladesh. During this period, evidence of mangroves (pollen and submerged forest) vegetation has also been reported from the Dhaka region. It is, however, not clear whether those mangroves near Dhaka were the continuation of the Khulna-Calcutta mangroves belt or existed as a single unit. If they were separate colonizations, then one may suggest that there were two discrete ecosystems on either side of the present day Padma (Ganges) river courses. Further evidence is required to support such a suggestion

e). Mangal Phase Five (since *ca.* 3000 BP)

Gupta (1981) reported the last existence of mangroves vegetation at Namkhana at about 1500 BC (3450 yrs BP). It is possible that the northern limit of the present day Sundarbans was established (with some local variation) at *ca.* 3000 yrs BP. Although the sea finally retreated from the Khulna region at about 1800 yrs BP, the northern limit of this last transgression is unknown, but it was probably not far from Panigati. It is, therefore, difficult to define the limit of the last marine transgression from this mangal phase.

The above generalization of Holocene mangal phases in the Bengal coastal belt is established on limited litho-bio and-chrono-stratigraphic records available from only three areas (Calcutta, Khulna and Dhaka). Records for the rest of the vast area of the Basin still await collection. Therefore, confirmation and refinement of the proposed reconstruction requires further evidence.

ii. Mangroves Vegetation and Relative sea-level Changes

Relative sea-level movement has an immediate and direct effect on the coastal intertidal ecosystem, particularly on vegetation. A rise of relative sea-level decreases the influence of terrestrial processes and increases the influence of marine processes. In section 2.6, different environmental factors which determine the growth, development and zonation of mangroves vegetation were discussed. Over and above those factors, the most important controlling factor for colonization, expansion and sustainability of mangroves in tropical coastal regions is the relative sea-level movement. The Sundarbans forest reserve along the south-western coastal belt of Bangladesh are considered by some to be already under the threat of a future potential relative sea-level rise (Broadus, 1993).

In the context of the Holocene sea-level movement, the sustainability of the present mangroves vegetation of Bangladesh could be predicted. Stratigraphic records of mangal deposits and their accumulation rates under different rates of sea-level movement should be considered. The evidence from this study suggests that, during each transgressive phase, mangroves vegetation could keep pace with a rising relative sea-level of 0.75 to 1.00 mm yr^{-1}. This study would therefore suggest that most mangals along the Bangladesh coast would collapse under sea-level scenarios where rate of rise up to 1.5 cm yr^{-1} have been predicted (Milliman *et al.*, 1989; Resource Analysis, 1992).

8.4. PALAEO-SHORELINES

i. Coastline Changes in the Past

Some attempts have been made in the past to establish shoreline changes of the Bengal Delta during different geological time periods. Based on photogeomorphic mapping, Niyogi (1975) recognised four geomorphic units in the plain lands of West Bengal and Orrisa. He tried to incorporate his results into the so-called Shepard's (1961) eustatic sea-level curve and suggested two shorelines of 220,000 and 80,000 yrs BP (see Niyogi, 1975, Fig. 4)). Kamal and Varadarajan (1984) applied mathematical modelling to estimate the sediment accumulation in West Bengal. They used all available seismic and borehole data in their model to date the shorelines since the Oligocene (see Kamal and Varadarajan, 1984, Fig. 3 to 6). Sen (1988) studied the biological remains, and, based on ^{14}C

results, he has shown that during the mid-Holocene the coastline extended from the SW to NE of the Bengal Basin between Kolaghat, Kolara, Sankrail, Calcutta and Dum Dum (for place name see Sen, 1988).

In this study coastline changes have been reconstructed along the Bengal Delta for the period since the early mid-Holocene (Fig. 8.6) using the reconstructed sea-level curves, contour map and reconstructed mangal limits. The coastlines at *ca.* 7000 and 4000 yrs BP are in close agreement with those presented by Sen (1988) for West Bengal (solid lines in Fig. 8.6). Due to a lack of evidence, it is difficult to extend the lines beyond the Padma-Meghna course, although records from Matuail suggest that the site was under a marine influence until about 2400 cal. yrs BP.

Umitsu (1987, 1993) suggested that at about 6000 yrs BP the coastline was slightly north of Khulna city. The present study shows that at that time the sea was further landward. The site of Khulna city was then under the sea and possibly the coastline was very close to the sites of Jessore and Narail (for place name see Fig. 1.1.)

ii. Progradation of the Bengal Delta

Studies of historical records indicate that the Bengal delta has not grown seaward significantly during the last 200 years which is surprising considering the discharge of sediments into the Bay of Bengal (see section 2.5.iii). Attempts are made here to estimate the progradation rates of the delta from the palaeoshoreline data along five sections (see Fig. 8.6 for section positions) at regular intervals since the early mid-Holocene.

Although the data base is limited, the results suggest a differential spatio-temporal delta progradation rate (Fig. 8.7). The western part of the Basin (sections 1, 2 and 3) has a lower rate, about 15 m yr^{-1}, than the central part (sections 4 and 5), about 25 m yr^{-1}; the average estimated rate for the Basin is 18.93 m yr^{-1}.

During the early and mid-Holocene, the study suggests that the rate of land emergence was nearly the same throughout the entire coastal belt. So, the shore line was moving uniformly in a south-east direction. Significant changes in land formation took place during the later part of the mid- Holocene. Delta building was faster (up to 41.17 m yr^{-1}) in Khulna, Pirojpur and the surrounding region than in the Calcutta, Satkhira, Jessore and surrounding regions. This suggested pattern of delta progradation thus support the idea that the Moribund deltaic region (Bagchi, 1944) is much older than the rest of the area. It also suggests that the Bengal coastlines have been moving in a south-eastern direction since the early mid-Holocene.

The advance or retreat of a coastline is a complex interaction of relative sea-level movement, coastal subsidence, wind-wave activities, and sediment supply and compaction. During about the last one thousand years the sedimentation rate has increased significantly, at a rate of 3.12 mm yr^{-1}, which is much higher (nearly double) than the estimated subsidence rate (1.73 mm yr^{-1}). The average progradation rate during this time, however, has reduced significantly. These facts indicate that, during this time, either sediment compaction was extremely high, or sediment was being lost into the deep ocean, or, most possibly sea-level was rising faster than the estimated average. It should, however, be noted here that the present study does not cover the sea-level records of this period and provide no supporting evidence for any of these mechanisms.

8.5. COASTAL EVENTS IN THE PAST

i. Palaeo-tidal Range

An important potential difficulty in current sea-level research is the assessment of palaeo-tidal data. Each considered sea-level index point, at the level of MHWST, might show a relationship with the former sea-level with variations in the tidal range. A small change in tidal range would alter the relationship between the freshwater/saltwater interface and would have an obvious impact on coastal ecosystem.

A basic assumption made by many sea-level investigators in constructing their sea-level curves (e.g. Jelgersma, 1961; Tooley, 1978a) was that the tidal range had remained more or less constant during the Holocene. However, Grant (1970) suggested an increasing tidal range since about 6000 yrs BP due to a change of water depth in the Bay of Fundy. Scott and Greenberg (1983) have shown that the tidal range in the Bay of Fundy has increased much more rapidly between 7000 and 4000 yrs BP than afterwards. Gehrels (1994) stated that the palaeo-tidal ranges of the Gulf of Maine were non-linear and increased more rapidly between 3000 and 2000 yrs BP. The empirical and theoretical studies on palaeo-tidal changes show that this factor is important in any evaluation of the altitude of sea-level index points (Tooley, 1985a).

The tidal range on any coast is mostly determined by the geometry of the estuary, and the configuration of the coastline. Different configurations of the Bengal coastline (discussed above) during the Holocene would have an obvious effect on the palaeo-tidal range of the estuary. At present, the mean spring tide (MST) on the Bangladesh coast varies from 1.14 m at Chandpur to 5.03 m at Sandwip (see Table 2.1). At Mongla, representing the Panigati site (about 30 km south of Panigati) the value is 2.65 m, although the range may have changed considerably over a short distance at some sites. The palaeo-tidal range on the Bangladesh coast is completely unknown, and for the reconstruction of an accurate relative sea-level curve, Bangladesh must wait until the palaeogeographic changes and palaeo-tidal regimes throughout the Bay are established. Until then an assumption is required (e.g. Jelgersma, 1961; Tooley, 1978a) and in this research an assumption of a constant of 2 m MHWST level from the national GTS datum during the Holocene has been adopted.

ii. Palaeo-storm Surges and Flooding Events

At present, tidal surges and coastal flooding are common annual natural phenomena in Bangladesh (see section 2.5.iv). Whether they are the natural disasters of the recent years or have also operated in the geological past provides another area for investigation.

At Matuail, some thin layers of reworked sands and silty-sand with sharp upper and lower contacts have been recorded (see sections 6.3.). These thin layers of coarse particles, intruded into the silty-clay estuarine sediment, indicate the possible occurrence of extreme natural events, such as catastrophic coastal flooding and storm surges at different stages of the Holocene. Kidson and Heyworth (1979) accounted that extreme storm surges could raise sea level several metres above the 'normal' levels. During a storm surge, a rapid rise in the surface of the sea, accompanied by a strong onshore wind, would lead to the deposition of a sandy layer. The intrusion of a 5 cm sandy layer, with some detrital organic particles (stratum 13 in core M-10.5E), clearly indicates an interruption of regular coastal sedimentary sequences as a result of such events. Storm surges and floods are erosional events, characterized by a net movement of coastal sediments, and are accompanied by the deposition of sand particles into fine estuarine sediment (Long *et al.*, 1989). The sandy particles intruded into the silty-clay layer could also be due to a sudden migration of tidal channels caused by extreme flooding events.

Haggart (1988) recorded a thin micaceous layer, predominantly composed of a grey, silty-sand from north-east Scotland which he argued was deposited by a short-lived event, such as a tsunami or a storm surge. This thin, regionally extended, sandy layer within the Holocene coastal depositional sequences of eastern Scotland, dated to 7000 yrs BP was recognised as being a tsunami deposit[1] by Smith and Dawson (1990). During each tsunami flood wave, a large accumulation of suspended marine sand (Dawson *et al.*, 1988) is transported landward across lowlying coastal areas (Smith and Dawson, 1990). Shi *et al.* (1995) have given an example of a modern tsunami from December 12, 1992, and its associated sediment deposit over a wide coastal lowland in Flores, Indonesia. In Bangladesh, a record of a tsunami due to the Chittagong earthquake in April, 1762 is found in FPCO report (1993).

Tsunamis normally produce more regionally extensive (Long *et al.*, 1989) and distinctive (Dawson *et al.*, 1991; Dawson *et al.*, 1995) sediments than those created by storm

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[1] The author had an opportunity to visit the site at St. Michael's Wood, Fife, Scotland, with Prof. David Smith who demonstrated the deposits to a group of students (including the author). The physical properties of these sediments, in respect of grain size and organic content, are quite different from those of the thin sandy layers recorded by the author at Matuail.

surges. The thin, sand dominated, reworked sediment layers which have been recorded at Matuail have not been reported from the Panigati site which indicates that they were not regionally extensive, rather they were deposited by some local extreme event, possibly a storm surge.

During the early and mid-Holocene, the funnel-shaped mouth of the Bay was possibly much wider than today, and Dhaka and the surrounding regions were then at the head of the Bay. During these periods, the south-western coastal belt was well sheltered, as is evident from the existence of a dense mangroves vegetation there, in contrast to the Matuail region. The areas at the head of the funnel would be more vulnerable to frequent catastrophic events. During the later part of the Holocene, however, evidence of such storm surges has not been reported from the sedimentary records. This indicates that during that time Matuail and the surrounding regions were possibly quieter and thus favourable for colonization by dense mangroves forest (see section 6.11).

More evidence of palaeo-storm surge and flooding can be found from the pollen and diatom records. For example at Matuail, a sudden increase of marine and brackish diatoms, such as *Coscinodiscus africanas, C. apiculatus, C. spp., Diploneis weissflogii, Paralia sulcata, Cyclotella striata* and *Synedra tabulata* in a freshwater diatom assemblage zone (see LDAZ-X in Fig. 6.11), suggest seawater flooding that might be associated with a tidal surge. On the other hand, at Panigati, for example, a sudden increase of *Typha* pollen frequency in a predominantly mangroves pollen assemblage zone (see LPAZ-XII in Fig. 5.8) possibly helps to infer an unusual freshwater discharge associated with catastrophic flooding. Similar incidents have also been reported for

LPAZ-IX and X. All these evidence assist to conclude that the Bengal coast land has been as vulnerable to extreme natural events during the Holocene as it is today.

It should, however, be noted that in this study samples at 10 cm interval were taken for pollen and diatom analysis. An average sedimentation rate of 0.82 mm yr^{-1} (12.24 yr cm^{-1}) has been calculated for the Bengal Basin which means evidence for more than a century is missing in between two successive pollen or diatom samples. However, high resolution pollen and diatom records (Zong and Tooley, 1996b) could be applied with confidence to record the incidence of extreme natural events in the geological past, along the coastal belt of Bangladesh.

8.6. PALAEO-RIVER SYSTEM

Very little is known about the palaeo-river channels of Bangladesh and the surrounding regions. R.D. Oldham (1894) originally suggested that in the Tertiary the drainage of the Indo-Gangetic depression had but one outlet, where the Indus now reaches the sea, and that this great river system drained the whole of the Himalayan region. Pascoe (1919) and Pilgrim (1919) separately studied the Punjab Oil-belt and the Siwalic Boulder Conglomerates, respectively and came to the same conclusion as Oldham (1894). This single river, from the combined discharge of the Brahmaputra, Ganges and Indus, was called the 'Indobrahma' by Pascoe (1919) and the 'Siwalic River' by Pilgrim (1919). However, based on faunal evidence, their hypothesis was later challenged by Prashad (1939).

Due to an intensification of the tectonic forces of the Himalayan upheaval during the last stage of the Siwalic period (end of Tertiary), the single river divided into two separate drainage systems, and the direction of the flow of the rivers was totally changed (Oldham, 1894). Based on sedimentary strata drilled from the distal Bengal fan in the central Indian Ocean, Amano and Taira (1992) also suggested that the drainage system of the Ganges and Indus river changed between 7.5 MA and 6.5 MA, in association with tectonic movement. The Ganges and its tributaries changed the original direction of flow and started to discharge into the Bay of Bengal (Pascoe, 1919; Pilgrim, 1919). The diversion of the drainage was a gradual process; at the final stage, the permanent diversion of the Jamuna, took place within historic times (Oldham, 1894).

The Quaternary history of river channels within the Bengal Basin is poorly known. The Ganges was probably the first river to develop and this, according to Khan (1991), occurred during the Pleistocene upheaval and flowed south along the present Bhagirathi and Hooghly (West Bengal) to discharge into the Bay of Bengal. He also mentioned that the Brahmaputra-Jamuna seemed to be much younger than the Ganges, and, along with the Meghna, it (Brahmaputra-Jamuna) made little contribution to the building up of the delta.

Some attempts have been made in the past to reconstruct the Holocene river courses within the Basin. Niyogi (1975) has shown that the Bhagirathi-Hooghly was the earliest course of the Ganges, to be followed by the Garai-Madhumati channel and finally the present day Padma course (see his Fig. 4) emerged. Dastidar and Ghosh (1964), however, argued that Bhagirathi-Hooghly was the main course of the Ganges barely 600 years ago, and was much younger than the 'Normal Calcutta Deposits'. Umitsu (1993) has reconstructed the palaeogeographic map of the Bengal Delta and surrounding region for the period since *ca.* 18,000 yrs BP (see his Fig. 6). Two salient features of his reconstruction are:-

a). The Brahmaputra-Jamuna has followed through the present course, since the late Pleistocene, west of the Madhupur Tract, which according to most of the authorities (e.g. Morgan and McIntire, 1959; Coleman, 1969; Islam, 1988, 1989a) is only about 200 years old.

b). The Ganges has had a confluence with the Brahmaputra near Aricha since *ca.* 7000 yrs BP which, according to the FPCO report (1993), up until the mid-eighteenth century had no confluence with either the Brahmaputra or the Meghna rivers, both of which flowed into the north-eastern part of the Bay of Bengal.

From the above discussion, it is clear that the current knowledge of the palaeo-river system of the Bengal basin is insufficient and inconsistent. It is, therefore, very difficult to suggest anything on the nature of the past river system of the Basin. Only speculation can be made on the basis of the evidence available in this study.

At Panigati, each inorganic sediment layer, in general, consists of clay and fine silty particles, and peat layers are well developed. Mangroves are well documented and the pollen assemblages do not include any exotic pollen types. On the other hand, at Matuail, in general, the sediments are coarser than those of Panigati, particularly during the early Holocene. Records of localized erosion, valley cuts and occasional extreme natural events are also evident in the sediment layers. Despite sea-level regressions, conditions were not favourable for peat development and mangroves could not colonize, and expand during most of the Holocene. It could, therefore, be argued that possibly these two sites experienced two different environmental conditions during the Holocene. This indicates the possibility of the Ganges and Brahmaputra-Meghna as two river systems operating separately in the Delta building process. A similar possibility can also be deduced from the records of more consolidated silty-clay deposits of the Chandina formation (Bakr, 1977) which underlie the Tippera surface of Morgan and McIntire (1959), and are older than the surrounding sediments. The Chandina formation is now found on the right and left banks of the Padma near its confluence with the Meghna (see Alam *et al*, 1990). These two deposits of Chandina formation were joined in the recent past (FPCO, 1993) and thus, do not show any indication of a combined flow of the Ganges-Brahmaputra (Padma) river systems.

If Khan's (1991) argument is accepted that the Ganges is much older than the Brahmaputra, then the former river has been playing a major role in delta building activities, in association with the relative sea-level movement, throughout most part of the Holocene. During the last glacial maximum, the -80 m contour line at the head of the 'Swatch of No Ground' (see Fig. 2.1) had nearly the same alignment as the mouth of the Harianghata river through which the Garai-Madhumati now discharges into the Bay. It could, therefore, be suggested that possibly the Garai-Madhumati was the original course of the Ganges which was not as active as today, and had later been reduced in size due to rapid siltation and river migration during the recent past. The Brahmaputra and Meghna could have flowed together into the north-eastern part of the Bay, near their present confluence at Bhairab. The area, therefore, was an estuary even in historic time, as is indicated by the diatom records at Matuail. However, the present day river network of Bangladesh has been established in only the last *ca.* 1000 years, during which time river instability, channel migration, bank erosion, sedimentation and other fluvial activities have been exceedingly high.

i Shifting of River Courses

The shifting of the river courses, river bank erosion, river flooding, and other river related natural and social issues are possibly the most widely studied areas by present day geographers, geologists, engineers, hydrologists, economists, and other natural and social scientists in Bangladesh (see Habibullah, 1987; Miah, 1988; Elahi *et al.,* 1991; Adnan, 1991a, 1991b) and, therefore, need no discussion here. There is one feature, however, concerning the shifting of river courses that does need consideration. There appears to be a belief (e.g. Dastidar and Ghosh, 1964) that where rivers are unstable and shifting in nature, as in deltaic regions, the occurrence of undisturbed sediment layers is unlikely. Microfossil analysis in such areas might prove otherwise.

The historical records indicate that the rivers flowing into the Bengal Basin, particularly in Bangladesh, have often changed their courses. The changes of the Ganges (Bagchi, 1944; Umitsu, 1985;), Teesta (Morgan and McIntire, 1959), Brahmaputtra (Morgan and McIntire, 1959; Coleman, 1969; Islam, 1989a, 1989c) and their distributaries are well documented. The shifting of the river courses have been caused either by tectonic (Fergusson, 1863; Morgan and McIntire, 1959; Oya, 1977) or hydraulic (LaTouche, 1919; Goswami, 1985) forces or both. This river shifting, whether tectonically or hydrologically induced did not cause the drifting (Mallik and Chaudhury, 1968) of the

Holocene peats (see below).

At Matuail, the fluvially deposited sediment layers above the peat are less than a metre thick due to their location in an uplifted area. At Panigati, which possibly represents the Basin better than Matuail, those layers are more than 3 m thick and have been deposited during the last millennium. Before that time sedimentation within the basin had mostly been associated with the relative sea-level fluctuation, and the activities of river migration and bank erosion were less insignificant than today. Such activities have only operated for less than 1000 years.

The change of one river course for another need not disturb the sediments which lay between the two courses, as illustrated by a simple model (Fig. 8.8). The change of course-A to course-B may erode the sediment layers immediately close to their banks (levée), but sediments in backswamp areas remain quite undisturbed. The shifting, for example, of the Ganges from Garai-Madhumati into Arial Khan (Bagchi, 1944; Umitsu, 1985) and finally to its present course, has left the Holocene lithological sequences between those rivers courses virtually undisturbed. In these situation the sediments can, therefore, be used for litho-bio and-chrono-stratigraphic analysis.

Chapter 9: CONCLUSIONS

9.1. INTRODUCTION

The aim of this concluding chapter is to summarise the results of this study, and to assess the extent to which the initial research objectives outlined in section 1.3 have been met. Some avenues for future research are also outlined. Potential techniques and the application of an interdisciplinary approach for palaeoenvironmental studies of Bangladesh have also been suggested.

9.2. SUMMARY RESULTS OF THE THESIS

Four important contexts dealt within this thesis are: the sea-level research methodology; the application of litho-bio-chrono-stratigraphic techniques; the reconstruction of the Holocene sea-level curves or sea-level bands (envelopes) and the implication of those curves for the understanding of various palaeoenvironmental issues in Bangladesh. It is, therefore, necessary to outline these contexts which are discussed below.

i. Sea-level Research Methodology:
Is it suitable for tropical lowlying coasts, such as Bangladesh?

The development of sea-level research methodologies has been discussed fully in Chapter 3. It has already been mentioned that the tendency methodology has been applied in this research as the final and most reliable way to interpret sea-level data. This methodology allows a statistical presentation of ^{14}C dates collected from a range of palaeoenvironments and does not depend on the use of altitude, like the time/altitude analysis. The application of this concept permits a meaningful correlation of events of sea-level movements between sites.

In this study the tendency approach was applied to correlate the events of marine transgressions and regressions in three regions; Calcutta, Khulna and Dhaka. The results suggest that the concept of sea-level tendency could equally be applied in sea-level studies for tropical deltaic areas, as has already been proved for temperate regions (Shennan *et al.*, 1983; Tooley, 1982; Haggart, 1986; Long, 1991 amongst others). It should, however, be noted that perfect correlation of marine events between sites requires a large number of ^{14}C results. In that sense, the present research is only a beginning of the application of the methodology to Bangladesh and indicates a wide scope for its application in future when more radiocarbon results, linked to systematic, detailed litho-and-bio-stratigraphic investigations at many sites, could be available.

ii. Techniques in Sea-level Research: *Could they be extended in Bangladesh studies?*

Four techniques have been applied in this research, namely sediment analysis, pollen analysis, diatom analysis and radiocarbon dating. Whether these techniques have any potential for future research on past sea level and palaeoenvironmental studies in Bangladesh can be discussed with regards to the present research.

a). Sediment Analysis and Characterization

One of the aims of this study was the application of the Troels-Smith (1955) scheme to describe the sediment layers of Bangladesh. The general strength and limitations of the scheme have been discussed elsewhere (see Aaby, 1979; Birks and Birks, 1980; Aaby and Berglund, 1986; Faegri and Iversen, 1989). This analytic-descriptive scheme developed in a Danish context has become universal because the number of elements are limited and the elements can be found in the sediment everywhere, independent of the origin of the plant composition (Aaby, 1979). The scheme has been widely applied in temperate regions (e.g. Tooley, 1974, 1978a; Devoy, 1979; Papadopoulou, 1981; Shennan, 1986a; Haggart, 1986; Odgaard, 1994; Hewlett and Birnie, 1996; Long and Tooley, 1995; and Zong and Tooley, 1996a), and also in a tropical country (e.g. Ireland, 1989).

In the present study, the Troels-Smith's scheme has been used for the first time in Bangladesh. In temperate regions, particularly in a closed lacustrine system, the successional pathways of organic sediment (peat) from limnic to terrestrial via telmatic peats, related to water table movements, are different from the stages of peat formation in an open tropical coastal system, as in Bangladesh. In closed temperate ecosystems, the vegetational succession and the deposition of autochthonous sediments (peat) are mostly climatically controlled, a phenomenon which can operate over a wider regional or even on a global scale. In an open coastal system, like Bangladesh, the successions of peat formation, from a mangrove via a freshwater to mangrove peats, are mostly the results of fluctuating local and regional environmental conditions, particularly the relative land and sea-level movements. However, due to the flexibility of the Troels-Smith scheme (Aaby and Berglund, 1986), it can be used as a powerful technique to describe the sediment characteristics of Bangladesh. The aim of this scheme to introduce a universally accepted common methodology, is worthy enough and the present study suggests that the environmental scientists (e.g. geographers, sedimentologists, archaeologists and botanists) of Bangladesh can apply this scheme to investigate and to elucidate the past environmental history of the country with great confidence.

b). Pollen Analysis

Pollen analysis has been widely used as a technique in the correlation and reconstruction of vegetational history, mainly in temperate regions (e.g. Godwin, 1940a; Birks, 1970; Huntley, 1990; Whittington *et al.,* 1990; Kelly and Huntley, 1991; Russell *et at.,* 1993; Whittington and Edwards 1993; Watts and Hansen, 1994; Odgaard, 1994; Allen *et al.*, 1996). The technique has also been used widely by a number of workers (e.g. Godwin, 1940b; Jelgersma, 1961; Kidson and Heyworth, 1973; Tooley, 1974, 1978a; Devoy, 1979; Shennan, 1986a; Robinson, 1993; and Hewlett and Birnie, 1996) as a powerful tool to reconstruct past sea-level history.

In tropical countries palynology developed late because, according to Flenley (1973), of the legendary floristic diversity of the tropics which has led to fears that determination of pollen types would be exceptionally difficult. In India, some attempts (e.g. Mukherjee, 1972; Caratini *et at.*, 1973; Gupta, 1981; Blasco, 1984; Caratini *et al.*, 1990; and Barui and Chanda, 1992) have been made, and its potential application in palaeoenvironmental reconstruction of tropical regions has already been proved, although it suffers from a number of limitations (see Chanda, 1972; Vishnu-Mittre, 1972).

In Bangladesh, palynology is still almost in its pre-natal stage. In this study, for the first time, it has been employed as a tool to reconstruct the Holocene sea-level history of the country and the results are encouraging for future applications. Each organic layer, both at Panigati and Matuail, includes generally a good frequency of mangroves pollen, which precisely indicates land-level and sea-level relationship. However, at this stage, the technique can only be used as an indication of events and in the future, some fundamental problems (see below) need to be solved.

At present, pollen production, dispersal, deposition and redeposition, and pollen representation of mangrove trees are totally unknown. Caratini *et al.* (1973) argued that all members of Rhizophoraceae produce a lot of pollen; they are wind and water pollinated, and are over-represented in the pollen assemblage. On the other hand, Noske (1993) suggested that *Bruguiera hainesii*, the largest genus of the Rhizophoraceae family, are mainly bird pollinated and hence, poorly represented. The current knowledge on these issues is, therefore, insufficient and inconsistent.

The lack of any pollen type reference collection is another difficulty. Every pollen-analyst needs this and every individual worker should, therefore, prepare or have available a workable pollen key of local and regional flora.

Despite these limitations, the present study suggests that pollen analysis is a suitable technique and could be used as a powerful tool to study the palaeoenvironmental history of Bangladesh.

c). Diatom Analysis

Diatoms are useful palaeoenvironmental indicators and have been widely used to reconstruct water qualities, such as pH (e.g. Foged, 1978; Anderson *et al.,* 1986; Sutcliffe and Carrick, 1988; Batterbee *et al.*, 1989; Round, 1990; Anderson and Renberg, 1992; Flower, *et al.*, 1988; Jones *et al.*, 1993; Davis *et al.*, 1994) and water chemistry (Fritz *et al.*, 1991; Veres *et al.,* 1995), and environmental changes (e.g. Pennington *et al.*, 1972; Papadopoulou, 1981; Haworth and Allen, 1982; Stabell, 1987; Haworth, 1989; Pienitz and Smol, 1993; Straub, 1993; Vos and de Wolf, 1993a, 1993b; Wolfe, 1994; Moser *et al.*, 1996) of temperate regions, especially in closed lacustrine systems. Diatoms are very sensitive to water salinity and have been used as a powerful tool to reconstruct the Holocene sea-level changes by a number of sea-level researchers (e.g. Tooley, 1978a; Devoy, 1979; Lie *et al.,* 1983; Shennan 1986a; Nelson and Kashima, 1993; Robinson, 1993; Vos and de Wolf, 1994; Long and Tooley, 1995; and Zong and Tooley, 1996a). In tropical countries the technique has also proved equally applicable (e.g. Ireland, 1987, 1989 and Zong, 1992).

In Bangladesh, except for Umitsu (1987), the use of diatom analysis as a tool for palaeoenviromental reconstruction has not yet been applied. Only a few attempts, however, been made to study the present day diatom assemblage (e.g. Islam and Aziz, 1975, 1977; Whitton *et al.*, 1988). The present study is the first systematic attempt to use diatom assemblages as a technique to study the country's Holocene sea-level movements. At the Panigati site, diatoms were virtually absent; only a few marine and brackish species, such as *Coscinodiscus apiculatus, C. marginatus, C. radiatus, C. stellaris, C. spp. Opephora pacifica, Paralia sulcata, Cyclotella striata, Nitzschia filiformis* and *Synedra tabulata* have been recorded from depths between 8 and 10 m. Umitsu (1987) also found some marine and brackish species, such as *Coscinodiscus rothii, C. radiatus,* *C. lineatus* and *Cyclotella stylorum* within these sediments. Whereas at Matuail site, a high frequency of diatoms has been recorded (see section 6.13) and they indicate a clear fluctuation of relative sea-level movements at the site. Such evidence at Matuail indicate the possibilities of obtaining a diatom record from sediments at other sites. However, some fundamental problems related to the application of the technique still remain and must be solved.

Before making any reconstruction from fossil diatoms, it is necessary to know the representation of modern diatoms in a known environment. Successful application of the technique requires a proper understanding of the present day analogue.

The 'autochthonous/allochthonous' problems (Beyens and Denys, 1982; Vos and de Wolf, 1988) of diatom analysis are palaeogeographical criteria and result from the palaeo-tidal current or river discharge (Vos and de Wolf, 1993a). Attempts should be made to understand these problems.

The problems of 'dissolution' (Denys, 1984), 'fragmentation' (Beyens and Denys, 1982, and 'non-diatom criteria' (Vos and de Wolf, 1988) for diatoms in Bangladesh also need to be known.

Despite these limitations, the present study suggests that diatom analysis could be used as a powerful tool to study the palaeoenvironmental history of Bangladesh, although this study also shows that poor preservation may be encountered at some sites.

iii. Holocene Sea-level Changes of Bangladesh:
Can we rely on the results?

The main objective of this study was to reconstruct the Holocene sea-level history of Bangladesh. There are numerous records of changes of climate and sea levels for this period from all over the world (see Pirazzoli, 1991). Most published sea-level curves converge at about 5000 BC (7000 yrs BP) which, according to Mörner (1971), was a real problem in sea-level research. It is now well accepted that the early Holocene rapid rise of sea level was mostly the results of glacio-eustatic components (see Tooley, 1992; Jelgersma and Tooley, 1995; and Mörner, 1995). In this study, it has not been possible to isolate such eustatic components of sea-level rises from the regional components. The sea-level movements along the coastal belts of Bangladesh were mostly dominated by regional and local components.

During the last *ca.* 9000 years, five periods of marine transgressions, each followed by a regression, have been recorded (see Chapter 7). Spatio-temporal variations of those transgressive phases, either in terms of duration or in terms of rates of relative sea-level rises, have been observed. A maximum rate of 3.65 mm yr^{-1} has been estimated between 6315 and 5915 yrs BP (Transgression III); the average rate for the Bengal Basin, during the Holocene, was 1.07 mm yr^{-1} (see Table 7.2).

The reconstruction of the Holocene sea-level history was based on all the available sources of information. However, some potential difficulties still remain and further refinements are to be achieved.

The reconstruction has been made using only a limited number (9 new) of index points

(^{14}C dates) and therefore, the possibility of having missed the records of potential sea-level index points in between those dates can not be ruled out.

Each index point is considered to represent the MHWST, although the records of palaeo-tidal range on the Bangladesh coast are quite unknown. Any variation of tidal range during the Holocene might include potential vertical errors in each dating point. Errors due to sediment compaction are also unknown and cannot be eliminated from the derived results.

Problems are also associated with the pollen and diatom records. Current knowledge of present day analogues is very limited and the representation values of those fossil pollen and diatoms in the studied samples are unknown. Although equal representation has been assumed, taxa could either be over-or be under-represented. Difficulties are also related to the interpretation of pollen and diatom records, available from an open coastal system, where many unknown potential factors, such as differential meteorological forces, forest composition, oceanic and fluvial activities and sediment budgets might be involved.

However, despite such difficulties, the study was undertaken following a well established and systematic research methodology (Tooley, 1974, 1978a, Shennan 1982a, 1986b, Shennan *et al.*, 1983), and therefore, the reconstruction is reasonably acceptable. The author accepts the possibility of some potential errors (which are at this stage unavoidable), but, at the same time regards his reconstruction of sea-level history (including the curves/bands) an important, first systematic contribution to such work in Bangladesh and the Bengal Basin as a whole.

iv. Implication of the Thesis:
How much dependence should be placed on the results?

In chapter one, the use of only short-term historical records for an understanding of the present day natural environment and as a means of projecting the near future (e.g. Brammer *et al.*, 1994) was criticized, and an alternative approach utilising long-term geological records, was advocated. The present study is an endeavour to justify the possible application of the latter approach.

Very little is known about the environmental changes and the associated environmental issues, such as sedimentation rates, subsidence and uplift, delta progradation and coastline migration, and shifting of river courses during the Holocene in Bangladesh. In this study, the reconstructed sea-level curves have been applied to understand these hydro-geomorphic processes and spatio-temporal variations have been observed (see Chapter 8).

In this study, the average estimated Holocene sedimentation rates have varied from 0.80 to 0.82 mm yr^{-1}, although, in general, a higher rate (up to 3.12 mm yr^{-1}) has been estimated in a fluvially controlled system (last millennium) than in estuarine and intertidal conditions (early and mid-Holocene). Similarly, a high subsidence rate (1.73 mm yr^{-1}) has been estimated for the former system and the estimated subsidence rates during the early and mid-Holocene have varied from 0.28 mm yr^{-1} to 0.36 mm yr^{-1}. The Holocene average rate was 0.68 mm yr^{-1}, a lower value than most previous estimations. Post-glacial tectonic uplift at Matuail in Madhupur Tract has been quantified and since the early mid-Holocene, average uplift rates of 0.15 mm yr^{-1} to 0.19 mm yr^{-1} have been estimated; during the recent period, the rate has increased significantly (0.25 mm yr^{-1}).

The study also shows that the mangroves forest have dominated much of the coastal ecosystem of Bangladesh throughout the Holocene. The migration of mangal belts and the appearance, disappearance and reappearance of mangal ecosystem were the results of relative sea-level and land-level movements. The long-term records suggest that the mangroves vegetation could keep pace with a relative sea-level rise of 0.75 mm yr^{-1} to 1.00 mm yr^{-1}. The present day Sundarbans are, therefore, already under threat, and would collapse if the extreme predicted sea-level scenario was to be realised.

Differential progradation rates over time and space have been observed during the Holocene. The western parts of the Bengal Basin have undergone lower progradation than the central parts; the estimated average rate for the Basin was 18.93 m yr^{-1}. During the last *ca.* 1000 years, despite a high rate of sedimentation, delta progradation rate has rather reduced, which indicates an accelerated relative sea-level rise for this time. The Ganges and Brahmaputra river system played a significant role in sediment supply and delta building processes. These sediments were deposited in estuarine to intertidal conditions, depending upon the relative land-level and sea-level movements. Each peat layer was *in situ* in origin and remains in its growth position. The convergence of the Ganges and Brahmaputra could, possibly, be a recent event, with these two rivers being separate during most of the Holocene. Thus, the hypothesis of the existence of two separate estuarine environments, each associated with these two rivers within the Basin, has been put forward for further investigation.

9.3. LIMITATIONS OF THIS STUDY

The present study suffered from a number of difficulties, some are as follows.

i. Lack of Previous work

Except for a few studies in West Bengal (India), the paucity of similar work in Bangladesh made it difficult to interpret the field and laboratory evidence in the light of previously published results. The results are, therefore, quite inductive in nature.

ii. Lack of Analogues

The principle of palaeoenvironmental reconstruction is primarily based on the doctrine of-*The Present is the Key to the Past*. Due to the lack of information about current analogues, it was difficult to interpret the records of the past.

iii. No Re-checking

Most palaeoenvironmental studies need subsequent verification and repeated checking in the field. It was not possible to visit the sites (Bangladesh) more than once. Since the last visit (April, 1994), the author is quite unaware of recent relevant publications from Bangladesh, as even with computer on line searching, they are difficult to discover, and access to them, even via interlibrary loan is virtually impossible.

iv. Resource Constraint

Most palaeoenvironmental studies require ^{14}C results, which are very expensive. Each AMS date costs nearly double the Conventional one. Due to resource constraint, only a few dates were possible to use in this study.

v. Time Limitation

Most of the techniques (particle size analysis, loss-on-ignition, pollen analysis, diatom analysis) used in this study are lengthy and time consuming procedures. A year long early preparatory stage (pre-fieldwork) and six months long fieldwork, considerably reduced the time period for subsequent work (sample preparation, counting, analyses and writing). Single handed dealing with all of the techniques within a limited time period has forced the author to keep the pollen (land pollen) and diatom counts, normally, to not more than 150 and 200 per level, respectively.

9.4. FURTHER RESEARCH NEEDED

It is realistic to conclude that this thesis is only a beginning. The results of this first attempt of its kind, are encouraging for future studies. Some future research directions are, therefore, suggested below.

i. Sea-level Research: Its Future in Bangladesh

In this study, evidence of the Holocene sea-level changes has come only from two sites and in this sense the initial research aims outlined in section 1.3 have been met. However, huge areas of the country remain to be explored. Not only the pollen and diatom records, which have already been proved to be applicable for Bangladesh, but also other techniques (see van de Plassche, 1986) can be explored. Coral evidence, for example, (see Hopley, 1986; Katupotha and Fujiwara, 1988) from St. Martin's Island, the only offshore coral island of Bangladesh, can be used in sea-level studies. Some sites, such as Matamuhuri delta, Karnafully delta and Maishkhal island, along the eastern coastal belt, could well preserve undisturbed sediment layers and biogenic records for investigation. Samples from inland areas, such as Sylhet basin, Barind region, Teesta plains and Kushtia regions can also be used to investigate landward extension of Holocene transgressions. More evidence of Holocene sea-level movements along the coastal regions of Bangladesh and east coast of India are necessary for regional correlation of marine events. It is, therefore, necessary to establish a regional sea-level data bank for the countries of the North Indian Ocean.

ii. Environmental Reconstructions: Further Scope

Holocene sea-level reconstruction is just one part of the wider field of palaeoenvironmental reconstruction. Techniques are now available, including pollen and diatom analysis (see Berglund, 1986), with which to discover past vegetational history, changes in lacustrine and terrestrial environment, palaeohydrology and prehistoric human settlements; these have applicability for Bangladesh.

iii. Archaeological Investigations: Charcoal Analysis

Charred particle analysis, when combined with a pollen record, can lead to an understanding of not only vegetational succession and natural fires (Earle *et al.*, 1996), but also to an investigation of the part played by humans in the origin of the fire. The findings from the quantitative analysis of charred particles (see Green, 1981; Clark, 1982; Tolonen, 1986) can be explored by the archaeologists of Bangladesh. During fieldwork, charred macrofossils were frequently recorded at Panigati (see section 5.6). As other workers have shown, the occurrence of those records indicate an untapped potential (e.g. Whittington *et al.,* 1990; Whittington *et al.*, 1993; Hall *et al.,* 1994; Odgaard, 1994) for future investigations.

9.5. CONCLUSION

In conclusion, this study has been conducted based on careful collection and rigorous analysis of data which can be used to investigate Holocene sea-level records. The environments in which changes to the Holocene sea-levels and coastal sedimentation took place were complex. To understand fully these environments, group efforts utilising multidisciplinary approaches and institutional co-operation are prime needs. This is summed up by '*most men have a blind spot unless they are a genius, but a team, drawing on the collective experiences of diversified specialization and background, reduces the effect of an individual's blind spot*' (Anon, 1993). However, it is remarkable what individuals can solve, and the inspiration their example provides.

REFERENCES

Aaby, B. (1979) Characterization of Peat and Lake Deposits. In: *Palaeohydrological Changes in the Temperate Zone in the Last 15000 years,* Project Guide, IGCP Project 158, 77-98.

Aaby, B. and Berglund, B.E. (1986) Characterization of Peat and Lake Deposits.In: Berglund, B.E. (Ed.) (1986) *Handbook of Holocene Palaeoecology and Palaeohydrology,* John Wiley and Sons Ltd., 231-246.

Adnan, S. (1991a) *Flood, People and the Environment: Institutional Aspects of Flood Protection Programmes in Bangladesh,* Resource and Advisory Services, Dhaka.

Adnan, S. (1991b) Flood, People and the Environment; A Critical Review of Flood Protection Measures in Bangladesh. *Grassroots,* 1(1), 27-48.

Agrawal, D.P. and Kusumgar, S. (1967) Radiocarbon Dates of Some Prehistoric and Pleistocene Samples. *Curr. Sci.*, 36(21), 566-568.

Akeroyd, A.V. (1972) Archaeological and Historical Evidence for Subsidence in Southern Britain. *Phil. Trans. Royal Soc. London,* A272, 151-169.

Alam, M. (1972) Tectonic Classification of Bengal Basin. *Bull. Geol. Soc. America,* 83, 519-522.

Alam, M.K. (1988) *Geology of Madhupur Tract and Its Adjoing Areas in Bangladesh.* Geol. Surv. of Bang., Dhaka.

Alam., M.K. and Aurangzeb, M.M. (1975) Geological Environment for Greater Dhaka City. *Conf. Issue, 3rd Ann. Conf. Bang. Geol. Soc.*, 34-37.

Alam, M.K. and Rahman, M. (1982) A Study of the Land Accretion in the Bay of Bengal and Succession to Accelerate the Process. *Bang. Jour. Geol.,* 1, 69-73.

Alam, M.K., Hasan, A.K.M.S., Khan, M.R. and Whitney, J.W. (1990) *Geological Map of Bangladesh.* Geol. Surv. of Bang.

Alam, M.S., Chowdhury, R., Shamsuddin, S.D. and Chowdhury, L.R. (1991) Observation on Stratigraphical and Selected Geochemical Aspects of Matamuhuri Deltaic Deposits. *The Jour. Noami,* 8(1&2), 39-46).

Ali, R.M.E., Hasan, M. and Ahmed, M. (1992) *Geology of Jhenidah Sadar Upazila, Jhenaidah District, Bangladesh.* Unpub. Report of Geol. Surv. Bang.

Allen, J.R.M., Huntley., B. and Watts, W.A. (1996) The Vegetation and Climate of Northwest Lberia Over the Last 14,000 Years. *Jour. Quat. Sci.*, 11(2), 125-147.

Allen, R.J.L. (1995) Salt-marsh Growth and Fluctuating Sea Level: Implications of a Simulation Model for Flandrian Coastal Stratigraphy and Peat-based Sea-level Curves. *Sedim. Geol.*, 100, 21-45.

Amano, K. and Taira, A. (1992) Two-phase Uplift of Himalayas Since 17 Ma. *Geology,* 20, 391-394.

Anderson, D.S., Davis, R.B. and Berge, F. (1986) Relationships Between Diatom Assemblages in Lake Surface-Sediments and Limnological Characteristics in Southern Norway. In: Smol, J.P., Battarbee, R.W., Davis, R.B. and Meriläinen, J. (Eds) *Diatom and Lake Acidity,* Dr. W Junk Publishers, 97-113.

Anderson, N.J. and Renberg, I. (1992) A Palaeolimnological Assessment of Diatom Production and Responses to Lake Acidification. *Envi. Pollution,* 78, 113-119.

Andrews, J.T., King, C.A.M. and Stuiver, M. (1973) Holocene Sea-level Changes, Cumberland Coast, Northwest England: Eustatic and Glacio-isostatic Movements. *Geol. en Mijn.,* 52(1), 1-12.

Anon (1993) *Institute of Engineers, Bangladesh,*

Anwar, J. (1989) Geology of Coastal Area of Bangladesh and Recommendations for Resource Development and Management. In: Maudud, H.J. (Ed.) *National Workshop on Coastal area Resource Development and Management, Part-II,* Coastal Area Resource Development and Management Association (CARDMA), Dhaka.

Bagchi, K. (1944) *The Ganges Delta.* Univ. of Calcutta, India.

Bakhtine, M.I. (1966) Major Tectonic Features of Pakistan, part II.-Eastern Province. *Science and Industry,* 4(2), 80-100.

Bakr, M.A. (1977) *Quaternary Geomorphic Evolution of the Brahmanbaria-Noakhali Areas.* Geol. Surv. Bang., Vol 1, Part 2.

Banerjee, M. and Sen, P.K. (1986) Late Holocene Organic Remains From Calcutta Peat. *Bull. Geol. Min. Meta. Soc. Indi.,* 54, 272-284.

Banerjee, M. and Sen, P.K. (1987) Palaeobiology in Understanding the Changes of Sea-level and Coastline in Bengal Basin During Holocene Period. *Ind. Jour. Eart. Sci.* 14(3-4), 307-320.

Banerjee, M. and Sen, P.K (1988) Palaeobiology and Environment of Deposition of Holocene Sediments of the Bengal Basin,India. *Proc. of the Second Conf. on the Palaeoenvironment of East Asia from the Mid-Tertiary, Vol-1 Geology, Sea-level*

Changes, Palaeoclimatology and Palaeobotany, Centre of Asian Studies, Hong Kong, 703-730.

Banerji, R.K. (1981) Cretaceous-Eocene Sedimentation, Tectonism and Biofacies in the Bengal Basin, India. *Palaeogeo. Palaeocli. Palaeoeco.,* 34, 57-85.

Barber, H.G. and Haworth, E.Y. (1994) *A Guide to the Morphology of the Diatom Frustule.* Freshwater Biol. Asso.

Barnett, T.P. (1983) Possible Changes in Global Sea-level and Their Causes. *Climatic Change,* 5(1), 15-38.

Barnett, T.P. (1984) The Estimation of Global Sea-level Change: A Problem of Uniqueness. *Jour. Geophy. Res.,* 89, 7980-7988.

Barnett, T.P. (1990) Recent Sea-level: A Summary. In NRC (Ed.) *Sea-Level Changes,* National Academy Press, Washington, 37-51.

Barth, M.C. and Titus, J.G. (Eds) (1984) *Greenhouse Effect and Sea level Rise.* Van Nostrand Reinhold Company Inc., New York.

Barui, N.C. and Chanda, S. (1979) Microfloristic Analysis and Vegetational History of the Late-Quaternary Peat Deposits (Belgachi, Calcutta). *Trans. Bose Res. Inst.,* 42(1-2), 39-43.

Barui, N.C. and Chanda, S. (1992) Late Quaternary Pollen Analysis in Relation to Palaeoecology, Biostratigraphy and Dating of Calcutta Peat. *Proc. Ind. Nat. Sci. Acad.,* B54(4), 191-200.

Barui, N.C., Chanda, S. and Bhattacharya, K. (1986) Late Quaternary Vegetational History of the Bengal Basin. *Bull. Geol. Min. Met. Soc. India.* 54, 197-201.

Battarbee, R.W., Stevenson, A.C., Rippey, B., Fletcher, C., Natkanski, J., Wik, M. and Flower, R.J. (1989) Causes of Lake Acidification in Galloway, South-west Scotland: A Palaeoecological Evaluation of the Relative Roles of Atmospheric Contamination and Catchment Change for Two Acidified Sites with Non-Afforested Catchments. *Jour. Ecol.,* 77, 651-672.

Baulig, H. (1935) The Changing Sea Level. *Inst. Brit. Geogra. Publ.,* 3, 1-46.

BBS (1993) *Statistical Pocket Book: Bangladesh.* Govt. of Bangladesh.

Becker, B. (1993) An 11,000-Years German Oak and Pine Dendrochronology of Radiocarbon Calibration. *Radiocarbon,* 23(1), 201-214.

Belperio, A.P. (1979) Negative Evidence for a Mid-Holocene High Sea-level Along the Coastal Plain of the Great Barrier Reef Province. *Mar. Geol.,* 32, M1-M9.

Bennett, K.D. (1994) Confidence Intervals for Age Estimates and Deposition Time in Late-Quaternary Sediment Sequences. *The Holocene,* 4(4), 337-348.

Berglund, B.E. (Ed.) (1986) *Handbook of Holocene Palaeoecology and Palaeohydrology.* John Wiley & Sons Ltd.

Beyens, L. and Denys, L. (1982) Problems in Diatom Analysis of Deposits: Allochthonous Valves and Fragmentation, *Geol. en Mijn.,* 61, 159-162.

Bird, E.C.F. (1969) *An Introduction to Systematic Geomorphology; Coasts.* MIT press, Massachusetts Institute of Technology, Messachusetts.

Birks, H.H. (1970) Studies of Vegetational History of Scotland. *Jour. of Ecology,* 58, 827-846.

Birks, H.J.B. and Birks, H.H. (1980) *Quat. Palaeoecology.* Edward Arnold Ltd, London, UK.

BIWTA (1982) *Bay of Bengal: Harinbhanga River to St. Martin's Island.* Survey Map, Bangladesh Inland Water Transport Authority.

Blasco, F. (1975) *The Mangroves in India.* Institut Francais de Pondichery, India.

Blasco, F. (1977) Outline of Ecology, Botany and Forestry of the Mangal of the Indian Subcontinent.In: Chapman, V.J. (Ed.) *Ecosystem of the World, Vol-1. Wet Coastal Ecosystem,* Elsevier Scientific Publishing Co. Oxford, 241-260.

Blasco, F. (1984) Mangrove Evolution and Palynology. In: Snedaker, S. and Snedakar, J. (Eds) *The Mangrove Research Methods,* UNESCO, UK, 36-49.

Bloom, A.L. (1964) Peat Accumulation and Compaction in a Connecticut Coastal Marsh. *Jour. Sedi. Petro.*, 34(3), 599-603.

Bloom, A.L. (1967) Pleistocene Shorelines: A New Test of Isostasy. *Geol. Soc. of Am. Bull.,* 78, 1477-1493.

Bloom, A.L. and Stuiver, M. (1963) Submergence of the Connecticut Coast. *Science,* 139, 332-334.

Boaden, P.J.S. and Seed, R. (1993) *An Introduction to Coastal Ecology,* Blackie Academic & Professional, London.

Bolin, B., Jager, J. and Doos, B.R. (1986a) The Green House Effect, Climate Change and Ecosystem: A Synthesis of Present Knowledge. In: Bolin, B., Doos, B.R., Jager, J. and Warrick, R.A. (Eds) *The Greenhouse Effect, Climate Change and Ecosystem*, John Wiley and Sons, Chichester.

Bolin, B., Doos, B.R.,Jager, J. and Warrick, R.A. (1986b) (Eds) *The Greenhouse Effect, Climate Change and Ecosystem*. John Wiley and Sons, Chichester.

Brammer, H. (1967) *Soil Survey Project of Pakistan: Samples From East Pakistan for ^{14}C Dating, 1967*. Personal communication.

Brammer, H. (1971) *Soil Survey Project, Bangladesh. Soil resources*. FAO, Rome.

Brammer, H. (1990a) Floods in Bangladesh I. Geographical Background to the 1987 and 1988 Floods. *The Geog. Jour.*, 156(1), 12-22.

Brammer, H. (1990b) Floods in Bangladesh II Flood Mitigation and Environmental Aspects. *The Geog. Jour.*, 156(2), 158-165.

Brammer, H. (1993) Geographical Complexities of Detailed Impact Assessment for the Ganges-Brahmaputra-Meghna Delta of Bangladesh. In: Warrick, R.A., Barrow, E.M. and Wigley, T.M.L. (Eds) *Climate and Sea-level Change: Observations, Projections and Implications*, Cambridge Univ. Press, 246-262.

Brammer, H. (1996) *The Geography of the Soil of Bangladesh*. Univ. Press Ltd., Dhaka.

Brammer, H. and Brinkman, R. (1977) Surface-water Gley Soils in Bangladesh: Environment, Landforms and Soil Morphology. *Geodarma*, 17, 91-109.

Brammer, H., Asaduzzaman, M. and Sultana, P. (1994) *Briefing Document No. 3: Effects of Climate and Sea-level Changes on the Natural Resources of Bangladesh*. Bangladesh Unnayan Parishad, Dhaka.

Broadus, J.M. (1993) Possible Impact of, and Adjustment to Sea Level Rise: the Cases of Bangladesh and Egypt. In: Warrick, R.A., Barrow, E.M. and Wigley, T.M.L. (Eds) *Climate and Sea-level Change; Observations, Projections and Implications*, Cambridge University Press, 263-275.

BWDB (1984) *Project Proforma of Barakpur-Digholia Scheme, Upazila Daulatpur, Khulna*. Govt. of Bangladesh.

Calhoun, R.C. and Flatcher III, C.H. (1996) Late Holocene Coastal Plain Stratigraphy and Sea-level History at Hanalei, Kauai, Hawaiian Islands. *Quat. Res.*, 45, 47-58.

Caratini, C., Blasco, F. and Thanikaimoni, G. (1973) Relation Between Pollen Spectra and the Vegetation of South Indian Mangrove. *Pollen et Spores*, 15, 281-292.

Caratini, C., Delibrias, G. and Rajgopalan, G. (1990) Palaeomangroves of Kanara Coast, Karnataka, India and Their Implications on Late Pleistocene Sea-level Changes. *Palaeobotanist*, 38, 370-378.

CEEHM (1979) *Seismic Zoning Map of Bangladesh and Outline of a Code for Earthquake Design of Structures*. Geol. Surv. Bang., Dhaka.

Chaffey, D.R. and Sandom, J.H.(1985) *Sundarbans Forest Inventory Project, Bangladesh; A Glossary of Vernacular Plant Names and a Field Key to the Trees.* ODA Project Record-98.

Chaffey, D.R., Miller, F.R. and Sandom, J.H. (1985) *A Forest Inventory of the Sundarbans, Bangladesh.* Main Report, ODA, England.

Champion, H.G. (1936) A Preliminary Survey of the Forest Types of India and Burma. *Indian Forest Record,* 1(1), 1-294

Chanda, S. (1972) Potentiality and Problems of Quaternary Pollen Analysis in India. In: Ghosh, A.K., Chanda, S., Ghosh, T.K., Baksi, S.K. and Banerjee, M. (Eds) *Proc. of the Seminar on Palaeopalynology and Indian Stratigraphy,* Calcutta University, Calcutta, 336-343.

Chanda, S. and Mukherjee, B.B. (1969) Radiocarbon Dating of Two Microfossiliferous Quaternary Deposits in and around Calcutta. *Science and Culture*, 35, 275.

Chapman, V.J. (1976) *Mangrove Vegetation.* Cramer, Lehre.

Chapman, V.J. (1977) Introduction. In: Chapman, V.J (Ed.) *Wet Coastal Ecosystem,* Elsevier, Amsterdam, 1-30.

Chappell, J. (1974) Late Quaternary Glacio- and Hydro-isostasy on a Layered Earth. *Quat. Res.,* 4, 429-440.

Chappell, J. and Polach, H. (1991) Post-glacial Sea-level Rise from a Coral Record at Huan Peninsula. *Nature*, 349, 147-149.

Chatterjee, S.P. (1961) Fluctuation of Sea-level Around the Coasts of India During the Quaternary Period, *Zeit. fur Geomor. Suppl.-III*, 47-56.

Chen, X. (1996) An Integrated Study of Sediment Discharge from Changjiang River, China and the Delta Development Since the mid-Holocene. *Jour. Coastal Res.*, 12(1), 26-36.

Chow, V.T. (1964) *Handbook of Applied Hydrology.* McGraw-Hill, New York.

Chowdhury, M.I. (1959) *Morphology of the Bengal Basin.* Unpub. M.Sc. Thesis, Univ. of Cambridge, UK.

Chowdhury, M.I., Hoque, M. and Pramanik, A.H. (1985) Morphology and Origin of the Swatch of No Ground, Bay of Bengal. *Jour. Nat. Ocean. Marin. Inst.,* 2, 19-29.

Clark, J.A. and Primus, J.A. (1987) Sea-level Changes Resulting from Future Retreat of Ice Sheets: An Effect of CO2 Warming of Climate. In: Tooley, M.J. and Shennan, I. (Eds) *Sea level Changes,* Blackwell, Oxford, 356-370.

Clark, J.A., Farrell, W.E. and Peltier, W.R. (1978) Global Change of Postglacial Sea-level: a numerical calculation. *Quat. Res.*, 9, 265-287.

Clark, R.L. (1982) Point Count Estimation of Charcoal in Pollen Preparation and Thin Section of Sediments. *Pollen et Spores*, 24, 523-535.

Coleman, J.M. (1969) Brahmaputra River: Channel Process and Sedimentation. *Sedi. Geol.*, 3 (2/3), 129-237.

Coleman, J.M. and Smith, W.G. (1964) Late Recent Rise of Sea Level. *Geol. Soc. Am. Bull.*, 75, 833-840.

Cook, A.H. (1972) The Geoid. *Earth Sci. Rev.*, 8, 13-44.

Coulson, A.L. (1940) The Geology and Underground Water Supply of Calcutta. *Mem. Geo. Surv. India,* 76, 1-150.

Crowley, G.M. and Gagan, M.K. (1995) Holocene Evolution of Coastal Wetland in Wet-Tropical Northeastern Australia. *The Holocene,* 5(4), 385-399.

Cullingford, R.A., Caseldine, C.J. and Gotts, P.J. (1980) Early Flandrian Land and Sea-level Changes in Lower Strathearn. *Nature,* 184, 159-161.

Cundill, P. and Whittington, G. (1983) Anomalous Arboreal Pollen Assemblages in Late Devensian and early Flandrian Deposits at Creich Castle, Fife. *Boreas,* 12, 297-311.

Curray, J.R. (1960) Sediments and History of Holocene Transgression, Continental Shelf, Northwest of Mexico. In: Shepard, F.P., Phleger, F.B. and van Andel, T.H. (Eds) *Recent Sediments, Northwest Gulf of Mexico, Am. Asso. Petro. Geol,* 1951-1958.

Curray, J.R. (1961) Late Quaternary Sea-level: A Discussion. *Geol. Soc. Am. Bull.*, 72, 1707-1712.

Curray, J.R. (1965) Late Quaternary History, Continental Shelves of the United States. In: Wright, H.E. and Frey, D.G. (Eds) *The Quaternary of the United States,* Princeton University, 723-735.

Daly, R.A. (1920) A Recent Worldwide Sinking of Ocean Level. *Geol. Magaz.*, 57, 246-261.

Daly, R.A. (1925) Pleistocene Changes of Level. *Am. Jour. Sci.,* 5th series, V-X(58), 281-313.

Darwin, C.R. (1842) *The Structure and Distribution of Coral Reefs.* Smith, Elder, London.

Das, S.C. (1992) Physical Oceanography of the Bay of Bengal. In: Elahi, K.M., Sharif, A.H.M.R. and Kalam, A.K.M.A. (Eds) *Bangladesh: Geography, Environment and Development,* Bang. Nat. Geog. Asso., Dhaka, 36-52.

Dastidar, A.G. and Ghosh, P.K. (1964) A Study of Subsoil Conditions of Calcutta. *Proc. of the Symp. on the Study of Soil Properties in Calcutta Region,* Sept.18-19, 1964, 37-64.

Davis, R.B., Anderson, D.S., Norton, S.A. and Whiting, M.C. (1994) Acidity of Twelve Northern New England (USA) Lakes in Recent Centuries. *Jour. Palaeolimn.,* 12, 103-154.

Dawson, A.G., Foster, I.D.L., Shi, S., Smith, D.E. and Long, D. (1991) The Identification of Tsunami Deposits in Coastal Sediment Sequences. *Sci. of Tsunami Hazards*, 9(1), 73-82.

Dawson, A.G., Hindson, R., Andrade, C., Freitas, C. and Bateman, M. (1995) Tsunami Sedimentation Associated with the Lisbon Earthquake of 1 November, AD 1755, Boca do Rio, Algarve, Portugal. *The Holocene*, 5(2), 209-215.

Dawson, A.G., Long, D. and Smith, D.E. (1988) The Storegga Slides: Evidence from Eastern Scotland for a Possible Tsunami. *Mar. Geol.,* 82, 271-276.

Denys, L. (1984) Diatom Analysis of Coastal Deposits: Methodological Aspects. *Bull. de la Société Belge de Géologie*, 93(1), 291-295.

Desikachar, S.V. (1974) A Review of the Tectonic and Geological and History of Eastern India in Terms of 'Plate Tectonics' Theory. *Jour. Geol. Soc. India,* 15(2), 137-149.

Devoy, R.J.N. (1979) Flandrian Sea Level Changes and Vegetational History of the Lower Thames Estuary. *Phil. Trans. Royal Soc. London,* B, 285, 355-407.

Devoy, R.J.N. (1982) Analysis of the geological evidence for Holocene Sea-level Movement in South-east England. *Proc. Geol. Asso.,* 93, 65-90.

Devoy, R.J.N. (1987) Introduction: First Principles and Scope of Sea-surface Studies. In: Devoy, R.J.N. (Ed.) *Sea Surface Studies; A Global View,* Croom Helm, London, 1-30.

de Wolf, H. (1982) Method of Coding of Ecological Data from Diatoms for Computer Utilization. *Meded. Rij. Geol. Dienst,* 36, 95-98.

Doodson, A.T. and Warburg, H.D. (1941) *Admiralty Manual of Tides,* London.

Earle, C.J., Brubaker, L.B. and Anderson, P.M. (1996) Charcoal in Northcentral Alaskan Lake Sediments Relationship to Fire and late-Quaternary Vegetation History. *Rev. Palaeobot. Palynol.*, 92, 83-95.

Elahi, K.M., Ahmed, K.S. and Mafizuddin, M. (Eds)(1991) *Riverbank Erosion, Flood and Population Displacement in Bangladesh,* River Erosion Impact Study, Jahangirnagar University, Bangladesh.

Ellison, J.C. (1989) Pollen Analysis of Mangrove Sediments as a Sea-level Indicator: Assessment from Tongatapu, Tonga. *Palaeogeo. Palaeocli. Palaeoeco.*, 74, 327-341.

Ellison, J.C. and Stoddart, D.R. (1991) Mangrove Ecosystem Collapse During Predicted Sea-level Rise: Holocene Analogues and Implications. *Jour. Coastal Res.*, 7(1), 151-165.

Emery, K.O. (1980) Relative Sea level from Tide-gauge Records. *Proc. Nat. Aca. Sci.*, 77, 6968-6972.

EPWDB (1967) *WAPDA Bench Marks in East Pakistan (now Bangladesh)*. Hydrology Directory, East Pakistan Water Development Board.

Erdtman, G. (1943) *An Introduction to Pollen Analysis.* Verdoorn, New Ser. Pl. Sci. Books 12. Waltham Mass.

Erdtman, G. (1952) P*ollen Morphology and Plant Taxonomy Angiosperms*. Stockholm & Wattham, Mass, USA.

Faegri, K. and Iversen, J. (1989) *Text Book of Pollen Analysis*. John Wiley and Sons, Chichester, UK.

Fairbanks, R.G. (1989) A 17,000 years Glacio-Eustatic Sea level Records: Influence of Glacial Melting Rates on the Younger Dryas Events and Deep-Ocean Circulation. *Nature*, 342, 637-642.

Fairbridge, R.W. (1961) Eustatic Changes in Sea-level. In: Ahren, L.H., Press, F., Rankama, K. and Runcorn, S.K. (Eds) *Physics and Chemistry of the Earth,* 4, Pergamon Press, London, 99-185.

FAO (1988) *Land Resources Appraisal of Bangladesh for Agricultural Development.* UNDP/FAO, Rome.

Fergusson, J. (1863) Recent Changes in the Delta of the Ganges. *Jour. Geol. Soc. London.*, 19, 321-354.

Fisk, H.N. (1951) Loess and Quaternary Geology of the Lower Mississippi Valley. *Jour. Geol.*, 59, 333-356.

Flemming, N.C. (1982) Multiple Regression Analysis of Earth Movement and Eustatic Sea-level Change in the United Kingdom in the Past 9000 years. *Proc. Geol. Asso.*, 93, 113-125.

Flenley, J.R. (1973) The Use of Modern Pollen Rain Samples in the Study of the Vegetational History of Tropical Regions. In: Birks, H.J.B and West, R.G. (Eds) *Quaternary Plant Ecology,* Blackwell Scientific Publications, London, 131-141.

Flierl, G.R. and Robinson, A.R. (1972) Deadly Surges in the Bay of Bengal, Dynamics and Storm Tide Table. *Nature,* 239, 213-215.

Flower, R.J., Battarbee, R.W., Natkanski, J., Rippey, B. and Appleby, P.G. (1988) The Recent Acidification of a Large Scottish Loch Located Partly within a National Nature Reserve and Site of Special Scientific Interest. *Jour. Applied Ecol.,* 25, 715-724.

Foged, N. (1978) Diatoms from the Middle and Late Weichselian and the Early Flandrian Period on Andoya, North Norway. *Boreas,* 7, 41-47.

Folk, R.L. and Ward, W.C. (1957) Brazos River Bar: A Study in the Significance of Grain Size Parameters. *Jour. Sedi. Petrol.,* 27, 3-26.

FPCO (1993) *FAP-4; Draft Final Report, Vol 3: Morphological Studies.* Ministry of Irrigation, Bangladesh (Unpublished).

Frei, A., MacCracken, M.C. and Hoffer, M.I. (1988) Eustatic Sea-level and CO_2, *Northeastern Jour. Envi. Sci.,* 7(1), 91-96.

Friedman, G.M. (1961) Distribution Between Dune, Beach and River Sands from Their Textural Characteristics. *Jour. Sedi. Petrol.,* 31, 524-529.

Friedman, G.M. (1967) Dynamic Processes and Statistical Parameters Compared for Size Frequency Distribution of Beach and River Sands. *Jour. Sedi. Petrol.,* 37(2), 327-354.

Fritz, S.C., Juggins, S., Batterbee, R.W. and Engstrom, D.R. (1991) Reconstruction of Past Changes in Salinity and Climate Using a Diatom-based Transfer Function. *Nature,* 352, 706-708.

Gehrels, W.R. (1994) *Holocene Sea-level Changes in the Northern Gulf of Maine: Regional Trends and Local Fluctuations Determined from Foraminiferal Analyses and Palaeotidal Modelling.* Unpub. Ph. D. Thesis, Univ. of Maine, USA.

Geyh, M.A., Kudrass, H.R. and Streif, H. (1979) Sea-level Changes During the Late Pleistocene and Holocene in the Strait of Malacca. *Nature,* 278, 441-443.

Ghosh, A.K. (1964) A Study of Calcutta Peat and Associated Sediments. *Ind. Jour. Power and River Valley Development,* 14-21.

Gill, E.D. (1961) Changes in the Level of the Sea Relative to the Land in Australia During the Quaternary Era. Z. *Geomorphol. Suppl., 3,* 73-79.

Gill, E.D. and Hopley, D. (1972) Holocene Sea-level in Eastern Australia- a Discussion. *Mar. Geol.,* 12, 223-233.

Godwin, H. (1940a) Pollen Analysis and Forest History of England and Wales. *New Phytologist,* 39, 370-400.

Godwin, H. (1940b) Studies of the Post-glacial History of British Vegetation, III. Fenland Pollen Diagram, IV. Post glacial Changes of Relative Land-and Sea-level in the English Fenland. *Phil. Trans. Royal Soc.*, B230, 239-303.

Godwin, H. and Godwin, H. (1933) Pollen Analysis of Fenland Peats at St. Germans, Near King's Lynn. *Geol. Magaz.,* 70, 168-180.

Godwin, H., Suggate, R.P. and Willis, E.H. (1958) Radiocarbon Dating of the Eustatic Rise of Ocean Level. *Nature,* 181, 1518-1519.

Gornitz, V. (1995) Sea-level Rise: A Review of Recent Past and Near Future Trends. *Eart. Sci. Proc. Land.*, 20, 7-20.

Gornitz, V., Lebedeff, L. and Hansen, J. (1982) Global Sea Level Trend in the Past Century. *Science,* 215, 1611-1614.

Goswami, D.C. (1985) Brahmaputra River, Assam, India: Physiography, Basin Denudation and Channel Aggradation. *Water Resources Res.,* 21(7), 959-978.

Gould, H.R. and McFarlan, E. (1959) Geological History of Chenier Plain, Southwest Louisiana. *Gulf Coast Assoc. Geol. Soc. Trans.* 9, 261-270.

Grant, D.R. (1970) Recent Coastal Submergence of the Maritime Provinces, Canada. *Cana. Jour. Earth Sci.,* 7, 676-689.

Green, D.G. (1981) Time Series and Post Glacial Forest Ecology, *Quat. Res.,* 15, 265-277.

Greensmith, J.T. and Tucker, E.V. (1986) Compaction and Consolidation. In: van de Plassche, O. (Ed.) *Sea-level Research: A Manual for the Collection and Evaluation of Data,* Geo Books, Norwich, 591-603.

Grindrod, J. (1985) The Palynology of Mangroves on a Prograded Shore, Prince Charlotte Bay, North Queensland, Australia. *Jour. Biogeo.,* 12, 323-348.

Grindrod, J. (1988) The Palynology of Holocene Mangrove and Saltmarsh Sediments, Particularly in Northern Australia. *Review Palaeobot. Palynol.,* 55, 229-245.

Guilcher, A. (1958) Coastal Corrosion Forms in Limestones around the Bay of Biscay. *Scot. Geog. Magaz.,* 74, 137-147.

Gupta, H.P. (1981) Palaeoenvironments During Holocene Time in Bengal Basin, India as Reflected by Palynology. *Palaeobotanist,* 27(2), 138-159.

Gutenberg, B. (1941) Changes in Sea Level, Post Glacial Uplift and Mobility of the Earth's Interior. *Geol Soc. Am. Bull.,* 52, 721-772.

Habibullah, M. (1987) *Computer Modelling of River Channel Changes in Alluvial Condition.* Bang. Univ. Eng. Tech., Dhaka.

Haggart, B.A. (1982) *Flandrian Sea-level Changes in the Moray Firth Area.* Unpub. Ph.D. Thesis, Univ. of Durham, UK.

Haggart, B.A. (1986) Relative Sea-level Change in the Beauly Firth, Scotland. *Boreas,* 15, 191-207.

Haggart, B.A. (1988) The Stratigraphy, Depositional Environment and Dating of a Possible Tidal Surge Deposits in the Beauly Firth Area, North-west Scotland. *Palaeogeo. Palaeocli. Palaeoeco.,* 66, 215-230.

Haider, R., Rahman, A.A. and Huq, S. (1991) *Cyclone'91: An Environmental and Perceptional Study.* Bangladesh Centre for Advanced Studies.

Halden, B.E. (1929) Kvartärgeologiska Diatomacéstudier Belysade den Postglaciala Transgressionen a Svenska Västkusten. *Geol. För Stoc. För.*, 51(3), 311-366.

Hall, A.M., Whittington, G., Duller, G.A.T. and Jarvis, J. (1994) Late Pleistocene Environments in Lower Strathspey, Scotland. *Trans. Roy. Soc. Edin.:Eart. Sci.,* 85, 253-273.

Hasan, A.K.M.S. and Alam, M.K. (1991) System of Sediment Dispersal and Concept of Compatible Flood Action Plan in Bangladesh. *Bang. Geol. Jour.,* 10, 19-29.

Hasan, A.K.M.S., Muminullah, M., Khan, S.R. and Chowdhury, S.Q. (1984) *Geology of Parts of Jessore and Khulna Districts.* Unpub. Report of Geol. Surv. of Bang.

Hashimi, N.H., Nigam, R., Nair, R.R. and Rajagopalan, G. (1995) Holocene Sea-level Fluctuations on Western Indian Continental Margin: An Update. *Jour. Geol. Soc. India*, 46, 157-162.

Hassan, M. (1986) *Stratigraphic and Sedimentological Studies on Quaternary Deposits of the Lalmai Hills (with Relation to the Madhupur Tract and Adjoining Flood Plains), Bangladesh.* Unpub. Ph. D. Thesis, Vrije Universiteit, Brussels.

Haworth, E.Y. (1989) Changes of Lake District Trans- the Microfossil Evidence. *Microscopy,* 36, 221-227.

Haworth, E.Y. and Allen, P.V. (1982) Temporary Changes in the Composition of a Postglacial Diatom Profile from Ullswater. *7th Diatom Symposium,* 431-441.

Hendey, N.I. (1964) An Introductory Account of the Smaller Algae of British Coastal Water. Part-V: Bacillariophyceae (Diatoms). *Fisheries Investigations Ser., v-IV.* London.

Hervay, D. (1969) *Explanation in Geography,* Edward Arnold, London.

Hewlett, R. and Birnie, J. (1996) Holocene Environmental Change in the Inner Severn Estuary, Uk: An Example of the Response of Estuarine Sedimentation to relative Sea-level Change. *The Holocene,* 6(1), 49-61.

Heyworth, A. and Kidson, C. (1982) Sea-level changes in southwest England and Wales. *Proc. Geol. Assoc.,* 93(1), 91-111.

Hirst, F.C. (1916) *Report on the Nadia Rivers, 1915.* Bengal Secretarial Book Depot. Calcutta.

Hoffman, J.S., Keyes, D. and Titus, J.G. (1983) *Projecting Future Sea-level Rise: Methodology, Estimates to the Year 2150, and Research Needs.* US Environmental Protection Agency, Washington D.C., USA.

Hopley, D. (1971) Sea-level and Environmental Changes in the Late Pleistocene and Holocene in North Queensland, Australia. *Quaternaria,* 14, 159-166.

Hopley, D. (1986) Corals and Reefs as Indicators of Palaeo-sea Levels, with special Reference to Great Barrier reef. In: van de Plassche, O. (1986)(Ed.) *Sea-level Research: A Manual for the Collection and Evaluation of Data,* Geo Books, Norwich, 195-228.

Hossain, M., Islam, A.T.M.A. and Saha, S.K. (1987) *Floods in Bangladesh; Recurrent Disaster and People Survival.* Dhaka Univ. Res. Centre, Dhaka.

Houghton, J.T., Jenkins, G.T. and Ephraums, J.J. (Eds) (1990) *Climate Change: The IPCC Scientific Assessment,* Cambridge University Press, Cambridge.

Huntley, B. (1990) European Vegetation History: Palaeovegetation Maps from Pollen Data-13000 yr BP to Present. *Jour. Quat. Sci.,* 5(2), 103-122.

Huq, S. and Ali, S.I. (1990) *International Sea-level Rise: A National Assessment of Effect and Possible Responses for Bangladesh.* Unpub. Report of Bangladesh Centre for Advances Studies, Dhaka.

Inman, D.L. (1952) Measures for Describing the Size Distribution of Sediments. *Jour. Sedi. Petro.,* 22, 125-145.

Ireland. S. (1987) The Holocene Sedimentary History of the Coastal Lagoon of Rio de Janiero State, Brazil. In: Tooley, M.J. and Shennan, I. (Eds) *Sea-level Changes,* Blackwell, Oxford, 24-66.

Ireland, S. (1989) *Holocene Coastal Changes in Rio-De-Janiero, Brazil.* Unpub. Ph.D. Thesis, Univ. of Durham, UK.

Islam, A.K.M.N. (1990) Ecological Characteristics of the Coastal Zone, Sundarbans, Coastal Islands and Saline Belt. In: Rahman, A.A., Huq, S. and Conway, G.R. (Eds) *Environmental Aspects of Surface Water Systems of Bangladesh,* University Press Limited, Dhaka, 52-62.

Islam, A.K.M.N. and Aziz, A. (1975) Studies of Marine Phytoplankton from the North-east Bay of Bengal, Bangladesh. *Bang. Jour. Botany,* 4(1-2), 1-31.

Islam, A.K.M.N. and Aziz, A. (1977) Studies on the Phytoplankton of the Karnaphuli River Estuary. *Jour. Bang. Acad. Sci.,* 1(2), 141-153.

Islam, M.A. (1978) The Ganges-Brahmaputra River Delta. *Jour. Univ. Sheffield Geol. Soc.,* 7(3), 116-122.

Islam, M.A., Miah, M.M, Islam, N., Huq, M.F. and Taher, M.A. (Eds) (1981) *Bangladesh in Maps,* University of Dhaka, Bangladesh.

Islam, M.R. (1975) Geology of Continental Shelf and its Mineral Resources. *Conf. Issue, 3rd Annual Conf. Bang. Geol. Soc.*

Islam, M.S. (1988) Bed Level Changes of the Brahmaputtra Jamuna within Bangladesh. *Jour. Bang. Nat. Geog. Asso.,* Vol 15 &16 (1-2), 139-148.

Islam, M.S. (1989a) *Channel Morphology of the Brahmaputra Jamuna River within Bangladesh; A Study of its Changes.* Unpub. M. Sc. Thesis, University of Dhaka, Bangladesh.

Islam, M.S. (1989b) *Salinity Intrusion in the South-western Coastal Region of Bangladesh; A Study of the Rupsa-Pussur River at Khulna.* Presented in Regional Conf. of Bang. Nat. Geog. Asso., Khulna.

Islam, M.S. (1989c) Bangladesher Abhantarey Brahmaputtra-Jamuna Nadeer Tatarekher Paribartaner Dharan 1830-1988. *Bhogul Patrika,* 8, 5-12. (in Bengali): {translation: River Banks Movement of the Brahmaputra-Jamuna within Bangladesh 1830-1988. *Geog. Jour.,* 8, 5-12}

Islam, M.S. (1995) Mid-Holocene Environmental and Vegetational Changes in the Coastal Region of Bangladesh. In: McLelland, S.J., Skellern, A.R. and Porter, P.R. (Eds) *Postgraduate Research in Geomorphology; Selected Papers from the 17th BGRG Postgraduate Symposium;* Brit. Geom. Res. Grou., Leeds, 14-20.

Jabber, M.A. (1979) *Land Accretion in the Coastal Areas of Bangladesh, SPARRSO Report on Offshore and Coastal Development.* Govt. of Bangladesh.

Jabber, M.A. (1992) *A Draft Report on Special Study on Pattern of Erosion and Accretion of Land in the Coastal Belt of Bangladesh Using Satellite Imagery and Aerial Photographs.* SPARRSO, Dhaka.

Jahan, C.S., Majumder, T.K. and Roy, M.K. (1990) Sedimentary Environmental Discrimination Using Grain-size Analyses. *Jour. Geol. Soc. India,* 35, 529-534.

Jardine, W.G. (1975) Chronology of Holocene Marine Transgression and Regression in South-western Scotland. *Boreas,* 4, 173-196.

Jardine, W.G. (1982) Sea-level Changes in Scotland During the Last 18,000 years. *Proc. Geol. Asso.,* 93, 25-41.

Jardine, W.G. (1986) Determination of Altitude. In: van de Plassche, O. (Ed) *Sea Level Research; A Manual for Collection and Evaluation of Data,* Geo Books, Norwich, 569-589.

Jelgersma, S. (1961) Holocene Sea-level Changes in the Netherlands. *Meded. Geol. Sticht., Serie C. VI,* 7, 1-100.

Jelgersma, S. (1966) Sea-level Changes During the Last 10,000 Years. In: Sawer, J.S. (Ed.) World Climate 8000 to 0 BC, *Royal Met. Soc. London*, 229, 54-71.

Jelgersma, S. and Tooley, M.J. (1995) Sea-level Changes During the Recent Geological Past. *Jour. Coastal Res. Special Issue No. 17: Holocene Cycles; Climate, Sea-level and Sedimentation,* 123-139.

Jian, W., Zechun, L., Shiying, S., Jian, Z. and Qiaohau, H. (1991) Quaternary Reconstruction of the Sea-level Changes in Southern Yellow Sea Since 130 ka BP and Its Correlations with Marine Transgressions of Northern China. In: Zechun, L. (Ed.) *Quaternary Sediments and Environmental Changes,* Nanjing Normal University, China, 133-142.

Jones, V.J., Flower, R.J., Appleby, P.G. Natkanski, J. Richardson, N., Rippey, B., Stevenson, A.C. and Battarbee, R.W. (1993) Palaeolimnological Evidence for the Acidification and Atmospheric Contamination of Lochs in the Caringorm and Lochnagar Areas of Scotland. *Jour. Ecol.,* 81, 3-24.

Kabir, M.H. (1993) *Secular Variation in Mean Sea Level Along the Coast of Bangladesh.* Unpub. M. Sc. Thesis. Univ. of Chittagong, Bangladesh.

Kamal, D.S. and Varadarajan, K. (1984) Application of a Mathematical Model to Determine Sedimentary Thickness in a Prograding Deltaic System; A Case History from West Bengal Delta. *Proc. Semi. on Remote Sensing in Petroleum Exploration, O.N.G.C.* Dehradune, India, 9, 1-10

Karim, A. (1988) *Environmental Factors and the Distribution of Mangroves in Sundarbans with Special Reference to Heritiera fomes,* Unpub. Ph.D. Thesis, Univ. of Calcutta, India.

Karim, A. (1994) Sundarbans: The Physical Environment, Vegetation, and Environmental Impacts. In Hussain, Z. and Acharya, G. (Eds) *Mangroves of the Sundarbans. Volume two: Bangladesh,* IUCN, Bangkok, 11-74.

Katupotha, J. (1992) New Evidence of Holocene Sea-level Changes of SriLanka. *Jour. Geol. Soc. SriLan.*, 4, 39-44.

Katupotha, J. and Fujiwara, K. (1988) Holocene Sea-level Changes on the Southwestern and South Coast of SriLanka. *Palaeogeo. Palaeocli. Palaeoeco.,* 86, 189-203.

Kelletat, D. (1975) Eine Eustatische Kurve für Das Jüngere Holozän, Konstruiert Nach Zeugnissen Früherer Meeresspiegelstände im Östlichen Mittelmeergebiet. *Neues Jb. Geol. Paläontol.,* Mh. 6, 360-374.

Kelly. M.G. and Huntley, B. (1991) An 11000-years Record of Vegetation and Environment from Lago di Martignano, Latium, Italy. *Jour. Quat. Sci.,* 6(3), 209-224.

Khalequzzaman, M. (1968) *Preliminary Report on Geological Mapping Around Narail District.* Unpub. Report of Geol. Surv. of Bang.

Khalil, G.M. (1992) Cyclone and Storm Surges in Bangladesh; Some Mitigation Measures. *Natural Hazards,* 6(1), 11-24.

Khan, F.H. (1957) *Investigation of Peat in the Faridpur District, East Pakistan.* Geological Survey of Pakistan, Quetta.

Khan, F.H. (1991) *Geology of Bangladesh.* University Press Limited, Dhaka.

Khan, M.I.H. (1986) Tides in Bangladesh. *The Sunshine,* 2(2), 18-30.

Khan, S.R. (1990) Geomorphology and Holocene Geology of the Patuakhali and Barguna Districts- a Part of the Lower Deltaic Plain in the Recent Ganges Delta. *Bang. Jour. Geol.,* 9, 9-18.

Khan, S.R. (1993) *Geology of Barguna District, Bangladesh.* Unpub. Report of Geol. Surv. of Bang.

Khan, S.R., Das, S.K. and Ali, R.M.K. (1991) *Geology for Landuse Planning in Tropical Deltas: Greater Dhaka City (Keraniganj Upazila), Bangladesh.* ESCAP Report.

Khandoker, R.A. (1987) Origin of Elevated Barind-Madhupur Areas, Bengal Basin: Result of Neotectonic Activities. *Bang. Jour. Geol.,* 6, 1-9.

Kidson, C. (1982) Sea Level Changes in the Holocene. *Quat. Sci. Rev.,* 1, 121-151.

Kidson, C. and Heyworth, A. (1973) The Flandrian Sea-level Rise in the Bristol Channel. *Proc. Ussher Soc.,* 2, 565-584.

Kidson, C. and Heyworth, A. (1979) Sea Level. In: Suguio, K., Fairchild, T.R., Martin, L. and Flexor, J.M. (Eds) *Proc. of the 1978 International Symposium on Coastal Evolution in the Quaternary,* Sao Paulo, Brazil, 1-28.

Krishnan, M.S. (1982) *Geology of India and Burma.* CBS Pub. Delhi.

Kutzbach, J.E. and Street-Perrott, F.A. (1985) Milankovitch Forcing of Fluctuations in the Level of Tropical Lakes from 18 to 0 kyr BP. *Nature,* 317, 130-134.

LaFond, E.C. (1966) Bay of Bengal. In: Fairbridge, R.H. (Ed.) *The Encyclopedia of Oceanography,* Reinhold Pub. Cor., New York, 110-118.

LaTouche, T.H.D. (1919) *Relics of the Great Ice Age on the Plains of Northern India.* The Bengal Secretariat Book Depot. Calcutta.

LeBlanc, R.J. and Bernard, H.A. (1954) Resume of Late Recent Geological History of the Gulf Coast. *Geol. en Mijn.*, 16, 185-194.

Lewin, J. (1991) Mean Sea Level. In: Goudie, A., Atkinson, B.W., Gregory, K.J., Simmons, I.G., Stoddart, D.R. and Sugden, D. (Eds) *The Encyclopedic Dictionary of Physical Geography,* Basil Blackwell Ltd., Oxford.

Libby, W.E. (1955) *Radiocarbon Dating*, University of Chicago Press.

Lie, S.E., Stabell, B. and Mangerud, J. (1983) Diatom Stratigraphy Related to Late Weichselian Sea-level Changes in Sunnmore, Western Norway. *Norg. Geol. Under.,* 380, 203-219.

Lisitzin, E. (1974) *Sea-level Changes,* Elsevier Oceanography Series 8, Elsevier, Amsterdam.

Lloyds, C. (1938) Note on Specimens of Mud Brought up from the Swatch of No Ground in the Bay of Bengal. *Proc. Asi. Soc. Bengal,* 7, 369.

Long, A.J. (1991) *Holocene Sea-level Changes in the East Kent Fens*. Unpub. Ph. D. Thesis, University of Durham, UK.

Long, A.J. and Shennan, I. (1994) Sea-level Changes in Washington and Oregon and the Earthquake Deformation Cycle. *Jour. Coastal Res.,* 10(4), 825-838.

Long, A.J. and Tooley, M.J. (1995) Holocene Sea-level and Crustal Movement in Hampshire and Southeast England, United Kingdom. *Jour. of Coastal Res. Special Issue No. 17: Holocene Cycles; Climate, Sea-level, and Sedimentation,* 229-310.

Long, D., Smith, D.E. and Dawson , A.G. (1989) A Holocene Tsunami Deposit in Eastern Scotland. *Jour. Quat. Sci.,* 4(1), 61-66.

Loveson, V.J. (1993) *Geological and Geomorphological Investigations Related to Sea Level Variation and Heavy Mineral Accumulation Along the Southern Tamilnadu Beach.* Unpub. Ph. D. Thesis, Tamil University, Thanjavur, India.

MacLaren, C. (1842) The Glacial Theory of Professor Agassiz. *Am Jour. Sci.*, 42, 346-365.

MacNae, W. (1968) A General Account of the Fauna and Flora of Mangrove Swamps and Forests in the Indo-West Pacific Region. *Advan. Marine Biol.,* 6, 73-270.

Mafizuddin, M. (1992) The Physiography of Bangladesh: An Overview. In: Elahi, K.M., Sharif, A.H.M.R. and Kalam, A.K.A.M. (Eds) *Bangladesh: Geography, Environment and Development,* Bang. Nat. Geog. Asso., Dhaka, 20-35.

Mahmood, N., Chowdhury, S.R. and Chowdhury, M.J.U. (1992) Sea Level Rise Situation in Bangladesh: Problem Identification, Policy Implication and Research Needs. *Proc. Workshop on Coastal Zone Management in Bangladesh.*

Majumder, S.C. (1941) *Rivers of the Bengal Delta,* Bengal Govt. Press. Alipur.

Mallik, N. and Chaudhury, S.K. (1968) Palynological Studies of the Sundarban Flora for Identification of Peat Pollen. *Bull. Bota. Soc. Bengal,* 22(1), 105-108.

Mannion, A.M. (1982) Diatoms: Their Use in Physical Geography. *Prog. Physi. Geog.*, 6(2), 233-259.

Marsh, J.G. and Martin, T.V. (1982) The SEASAT Altimeter Mean Surface Model. *Jour. Geophy. Res.,* 87, 3269-3280.

Matin, M.A. and Hossain, M. M. (1992) Appraisal of Seasonal Variation of Mean Water Level Along Coast of Bangladesh. *The Jour. of Noami,* 9(1&2), 27-30.

McFarlan, E. (1961) Radiocarbon Dating of Late Quaternary Deposits, South Louisiana. *Geol. Soc. Am. Bull.*, 72, 129-158.

Miah, M.M. (1972) *The Madhupur Tract: is it a Pleistocene Terrace?* Ind. Ins. Tech. Conf. Kharagpur.

Miah, M.M. (1975) Changing Morphology of the Ganges-Meghna Delta. *Proc. of Bang. National Seminar on Remote Sensing,* 91-93.

Miah, M.M. (1988) *Flood in Bangladesh; A Hydromorphological Study of the 1987 Flood.* Academic Publishers, Dhaka.

Miah, M.M. (1989) *Siltation and Coastal Zone Management; Bangladesh Country Study.* Unpub. Report BIDS, Dhaka.

Miah, M.M., and Bazlee, B.L. (1967) Some Aspects of the Geomorphology of the Madhupur Tract. *Oriental Geographer,* 12(1), 39-48.

Milliman, J.D., Broadus, J.M. and Gable, F. (1989) Environmental and Economic Implication of Rising Sea Level and Subsiding Deltas: The Nile and Bengal Examples. *Ambio,* 18(6), 340-345.

Monsur, M.H. (1990) *Stratigraphical and Palaeomagnetical Studies of Some Quaternary Deposits of the Bengal Basin, Bangladesh.* Unpub. Ph.D. Thesis, Vrije Universiteit, Brussels.

Monsur. M.H. and Paepe, R. (1993) Quaternary Stratigraphy of the Madhupur Area of the Bengal Basin. *Bang. Jour. Sci. Res.,* (press)

Monsur, M.H. and Paepe, R. (1994) Holocene Stratigraphy and Palaeoclimatological Interpretation of the Deposits of the Madhupur, Barind and Chalanbil Area of the Bengal Basin, Bangladesh; *Bang. Jour. Sci. Res.,* (press)

Mook, W.G. and van de Plassche, O. (1986) Radiocarbon Dating. In: van de Plassche, O. (Ed.) *Sea-level Research: A Manual for the Collection and Evaluation of Data,* Geo Books, Norwich, 525-560.

Moore, P.D., Webb, J.A. and Collison, M.E. (1991) *Pollen Analysis,* Oxford Blackwell Scientific Publications, London.

Morgan, J.P. and McIntire, W.G. (1959) Quaternary Geology of the Bengal Basin; East Pakistan and India. *Geol. Soc. Am. Bull.*, 70, 319-342.

Mörner, N.A. (1969) The Late Quaternary History of the Kettegatt Sea and The Swedish West Coast: Deglaciation, Shore-level Displacement, Chronology, Isostasy and Eustasy. *Sver. Geo. Under.* Ser C Nr 640, Arsbok 63 Nr 3, 1-487.

Mörner, N.A. (1971) The Holocene Eustatic Sea Level Problem. *Geol. en Mijn.,* 50(5), 699-702.

Mörner, N.A. (1973) Eustatic Changes During the Last 300 years. *Palaeogeo. Palaeocli. Palaeoeco.,* 13, 1-14.

Mörner, N.A. (1976a) Eustasy and Geoid Change. *Jour. Geol.*, 84(2), 123-151.

Mörner, N.A. (1976b) Eustatic Changes During the Last 8,000 years in View of Radiocarbon Calibration and New Information from the Kattegatt Region and Other Northwestern European Coastal Areas. *Palaeogeo. Palaeocli. Palaeoeco.*, 19, 63-85.

Mörner, N.A. (1977) Eustasy and Instability of the Geoid Configuration. *Geol. Foren. Stockh. Forh,* 99, 369-376.

Mörner, N.A. (1980) Eustasy and Geoid Changes as a Function of Core/Mantle Changes. In: Mörner, N.A. (Ed.) *Earth Rheology, Isostasy and Eustasy,* John Wiley & Sons, Chichester, 535-553.

Mörner, N.A. (1984) Geodal Topography: Origin and Time Consistency. *Mar. Geophy. Res.,*. 7, 205-208

Mörner, N.A. (1987) Models of Global Sea-level Changes. In: Tooley, M.J. and Shennan, I. (Eds) *Sea-level Changes,* Blackwell, Oxford, 332-355.

Mörner, N.A. (1988) Terrestrial Variations within Given Energy, Mass and Momentum Budgets; Palaeoclimate, Sea-level, Palaeomagnitisom, Differential Rotation and Geodynamics. In: Stephenson, F.R. and Wolfendale, A.W. (Eds) *Secular Solar and Geomagnetic Variations in the Last 10,000 years,* Kluwer Acad. Publ. 455-478.

Mörner, N.A. (1995) Sea Level and Climate- The Decadal to Century Signals. *Jour. of Coastal Res. Special Issue No. 17: Holocene Cycles; Climate, Sea-level, and Sedimentation,* 261-268

Moser, K.A., MacDonald, G.M. and Smol, J.P. (1996) Application of Freshwater Diatoms to Geographical Research. *Prog. Phy. Geog.*, 20(1), 21-52.

MPO (1986) *Geology of Bangladesh; Technical Report 4.* Ministry of Irrigation, Government of Bangladesh.

Mukherjee, B.B. (1972) Pollen Analysis of a Few Quaternary Deposits of Lower Bengal Basin. In: Ghosh, A.K., Chanda, S., Ghosh, T.K., Baksi, S.K. and Banerjee, M. (Eds) *Proc. of the Seminar on Palaeopalynology and Indian Stratigraphy,* Calcutta University, India, 357-374.

Mukherjee, B.B. (1992) On the Ecology of the Mangroves with Special Reference to Those in Sundarbans in the Territory of India and Bangladesh. *Jour. Nat. Hist. Mus. Inst. Chiba,* 2(1), 77-81.

Muller, J. (1964) A Palynological Contribution to the History of the Mangrove Vegetation in Borneo. *Ancient Pacific Flora,* Hawaii, 33-44.

Muller, J. (1969) A Palynological Study of Genus Sonneratia (Sonneratiaceae). *Pollen et Spore,* 11(2), 223-298.

Munk, W. and Revelle, R. (1952) Sea-level and the Rotation of the Earth. *Am. Jour. Sci.,* 250, 829-833.

Murty, T.S. (1984) Storm Surges-Meteorological Ocean Tides. *Cana. Jour. Fish. Aqu. Sci.,* 12, 897.

Murty, T.S., Flather, R.A. and Henry, R.F. (1986) Storm Surges in the Bay of Bengal. *Progr. Oceano.,* 16, 195-233.

Nandy, D.R. (1980) Tectonic Pattern in North-East India. *Ind. Jour. Earth Sci.,* 7(1), 103-107.

Nelson, A.R. and Kashima, K. (1993) Diatom Zonation in Southern Oregon Tidal Marshes Relative to Vascular Plants, Foraminifera, and Sea Level. *Jour. Coastal Res.,* 9(3), 673-697.

Newman, W.S. and Munsart, C.A. (1968) Holocene Geology of the Wachapreague Lagoon, Eastern Shore Peninsula, Virginia. *Mar. Geol.*, 6, 81-105.

Niyogi, D. (1975) Quaternary Geology of the Coastal Plain in West Bengal and Orissa. *Ind. Jour. Earth Sci.,* 2(1), 51-61.

Noske, R.A. (1993) Bruguiera hainesii: Another Bird-Pollinated Mangrove. *Biotropica,* 25(4), 481-483.

NRC (1990) *Sea-Level Changes.* National Academy Press, Washington, USA.

Odgaard, B.V. (1994) The Holocene Vegetation History of Northern West Jutland, Denmark. *Opera Botanica,* 123, 1-171.

Ogden, J.G. (1967) Radiocarbon Determination of Sedimentation Rates from Hard and Soft Water Lakes in the North-eastern North America. In: Cushing, E.J and Wright, H.E. (Eds) *Quaternary Palaeoecology,* Yale University Press, USA, 176-183.

Oldham, R.D. (1894) The Evolution of Indian Geography, *The Geog. Jour.,* 3(3), 169-196

Olsson, I.U. (1986) Radiocarbon Dating. In: Berglund, B.E. (Ed.) *Handbook of Holocene Palaeoecology and Palaeohydrology,* John Wiley & Sons Ltd., Chichester, 273-312.

Oya, M. (1977) Applied Geomorphological Study on the Selection of the Proposed Bridge Site Along the Jamuna River in Bangladesh. *National Geographer,* 12(2), 101-113.

Palmer, A.J.M. and Abbott, W.H (1986) Diatoms as Sea-level Indicators. In: van de Plassche, O. (Ed.) *Sea-level Research: A Manual for the Collection and Evaluation of Data,* Geo Books, Norwich, 435-456.

Panikkar, N.K. and Srinivasan, T.M. (1971) The Concept of Tides in Ancient India. *Ind. Jour. Hist. Sci.*, 6, 36-50.

Papadopoulou, F. (1981) The Diatom Succession of Snärjegöl, SE Sweden. *Striae,* 14, 122-125.

Pascoe, E.H. (1919) The Early History of the Indus, Brahmaputtra and Ganges. *Quaterly Jour. Geol. Soc.,* 75, 138-157.

Peltier, W.R. (1987) Mechanisms of Relative Sea-level Change and the Geophysical Responses to Ice-Water Loading. In: Devoy, R.J.N (Ed.) *Sea Surface Studies: A Global View,* Croom Helm, London, 57-94.

Peltier, W.R. (1990) Glacial Isostatic Adjustment and Relative Sea-level Changes. In: NRC (Eds) *Sea-Level Changes,* National Academy Press, Washington, USA, 73-87.

Pennington, W, Haworth, E.Y. Bonny, A.P. and Lishman, J.P. (1972) Lake Sediments in Northern Scotland. *Phil. Trans. Royal Soc. London,* B264, 217-293.

Pienitz, R. and Smol, J.P. (1993) Diatom Assemblages and Their Relationship to Environmental Variables in Lakes from the Boreal Forest-Tundra Ecotone Near Yellowknife, Northwest Territories, Canada. *Hydrobiologia,* 269/270, 391-404.

Pilgrim, E. (1919) Suggestions Concerning the History of the Drainage of Northern India, Arising Out of a Study of the Siwalic Boulder Conglomerate. *Jour. Proc. Asi. Soc. Bengal,* 15, 81-99.

Pirazzoli, P.A. (1991) *World Atlas of Holocene Sea-Level Changes.* Elsevier, Amsterdam.

Pizzuto, J.E. and Rogers, E.W. (1992) The Holocene History and Stratigraphy of Palustrine and Estuarine Wetland Deposits of Central Delaware. *Jour. Coastal Res.*, 8(4), 854-867.

Prain, D. (1903) Flora of the Sundarbans. *Records of the Botanical Survey of India,* V-II, 231-371.

Pramanik, M.A.H. (1980) Geomorphological Studies of Bangladesh Coast Using Landsat Data. *Proc. of First Asian Conf. on Remote Sensing, Bangkok,* 1-11.

Pramanik, M.A.H. (1983) *Remote Sensing Application to Coastal Morphological Investigations in Bangladesh.* Unpub. Ph. D. Thesis. Jahangirnagar University, Bangladesh.

Prashad, B. (1939) The Indobrahma or the Siwalic River. *Rec. Geol. Surv. India,* 74, 555-561.

Pugh, D.T. (1991) Tides. In: Goudie, A., Atkinson, B.W., Gregory, K.J., Simmons, I.G., Stoddart, D.R. and Sugden, D. (Eds) *The Encyclopedic Dictionary of Physical Geography,* Basil Blackwell Ltd., Oxford.

Rainey, J.R. (1891) The Sundarbans: its Physical Features and Ruins. *Proc. Royal Geog. Soc.*, 13, 273-287.

Rajamanickam, G.V. and Gujar, A.R. (1988) Depositional Environment of the Sediments in Konkan Bay: Inferred from Multigroup Discrimination Analysis Using Grain Size Distribution Statistics. *Indi. Jour. Earth. Sci.*, 15(3), 234-247.

Rajamanickam, G.V. and Loveson, V.J. (1990) Results of Radiocarbon from Some Beach Terraces Around Rameshwaram Island, Tamilnadu. In: Rajamanickam, G.V.(Ed.) *Sea Level Variation and Its Impact on Coastal Environment*, Tamil University Press, Tanjavur, India.

Rajamanickam, G.V. and Muthukrishnan, N. (1995) Grain size Distribution in the Gadilam River Basin, Norther Tamil Nadu. *Jour. Indi. Asso. Sedi.*, 14, 55-66.

Rashid, H. (1966) Morphology of the Jamuna Flood Plains. *Oriental Geographer*, 10(2), 57-72.

Rashid, H. (1991) *Geography of Bangladesh,* Univ. Press Ltd., Dhaka.

Rashid, M.H. (1993) *Some Aspects of Quaternary Geology of Dhaka City*. Unpub. M.Sc. Thesis, University of Dhaka, Bangladesh.

Ravenscroft, P. (1992) *Late Quaternary Buried Valleys in Northeast Bangladesh.* Mott McDonald, U.K.

Resource Analysis (1992) *Assessment of the Vulnerability of Coastal Areas to Sea Level Rise: Case Study Bangladesh.* Resource Analysis, The Netherlands.

Robinson, M. (1993) Microfossil Analyses and Radiocarbon Dates of Depositional Sequences Related to Holocene Sea-level Change in the Forth Valley, Scotland. *Trans. Royal Soc. Edinburgh: Earth Sci.,* 84, 1-60.

Rossiter, J.R. (1962) Long-term Variations in Sea-level.In: Hill, N.M. (Ed.) *The Sea 1*, Interscience Publishers, London, 590-610.

Round, F.E. (1973) *The Biology of the Algae.* Edward Arnold, London.

Round, F.E. (1990) Diatom Communities-Their Response to Changes in Acidity. *Phil. Trans. Royal Soc. London,* B327, 243-249.

Russell, E.W.B., Davis, R.B., Anderson, R.S., Rhodes, T.E. and Anderson, D.S. (1993) Recent Centuries of Vegetational Changes in the Glaciated North-eastern United States. *Jour. Ecol.,* 81, 647-664.

Sabadini, R., Doglioni, C., and Yuen, D.A. (1990) Eustatic Sea-level Fluctuations Induced by Polar Wander. *Nature,* 345, 708-710.

Sahu, B.K. (1964) Depositional Mechanisms from the Size Analysis of Clastic Sediments. *Jour. Sedi. Petrol.,* 34(1), 73-83.

Sahu, B.K. (1982) Multigroup Discrimination of River, Beach, and Dune Sands Using Roundness Statistics. *Jour. Sedi. Petrol.,* 52(3), 779-784.

Savage, J.C. (1983) A Dislocation Model of Strain Accumulation and Release at Subduction Zone. *Jour. Geophy. Res.,* 88, 4984-4996.

Savage, J.C., Lisowski, M. and Prescott, W.H. (1991) Strain Accumulation in Western Washington. *Jour. Geophy. Res.*, 96, 14493-14507.

Schofield, J.C. (1960) Sea-level Fluctuations During the Past Four Thousand Years. *Nature,* 185, 836.

Scholl, D.W. (1963) Sedimentation in a Modern Coastal Swamp, Southwest Florida. *Bull. Am. Assoc. Petro. Geol.,* 47, 1581-1603.

Scholl, D.W. (1964) Recent Sedimentary Record in Mangrove Swamps and Rise in the Sea-Level Over the Southwestern Coast of Florida, Part 1. *Mar. Geol.,* 1, 344-366.

Scholl, D.W. and Stuiver, M. (1967) Recent Submergence of Southern Florida: A Comparison with Adjacent Coasts and Other Eustatic Data. *Geol. Soc. Am. Bull.,* 78, 437-454.

Schoute, J.K.T., Griede, J.W., Mook, W.G. and Roeleveld, W. (1981) Radiocarbon Dating of Vegetation Horizons, Illustrated by and example from the Holocene Coastal Plain in the Northern Netherlands. *Geol. en Mijn.,* 60, 453-459.

Scott, D.B. and Greenberg, D.A. (1983) Relative Sea-level Rise and Tidal Development in the Fundy Tidal system. *Cana. Jour. Earth Sci.,* 20, 1554-1564.

Sen, P.K. (1988) *Palaeoenvironment of Bengal Basin During Holocene Period Through Study of Biological Remains.* Unpub. Ph.D. Thesis, University of Calcutta, India.

Sen, P.K. and Banerjee, M. (1988) Palaeoenvironment of Bengal Basin During the Holocene Period. *Geog. Rev. India,* 50(4), 21-38.

Sen, P.K. and Banerjee, M. (1990) Palyno-plankton Stratigraphy and Environmental Changes During the Holocene in the Bengal Basin, India. *Rev. Palaeob. Palynol.,* 65, 25-35.

Sengupta, S. (1966) Geological and Geophysical Studies in Western Part of the Bengal Basin. *Bull. Am. Asso. Petro. Geol.,* 50(5), 1001-1017.

Sesoren, A. (1984) Geological Interpretation of LANDSAT Imagery of Bangladesh Ganges Delta. *ITC Jour.,* 3, 229-232.

Sewell, R.B.S. (1935) Studies on Coral and Coral-Formations In Indian Waters. *Mem. Asi. Soc. Bengal,* 9,

Shennan, I. (1980) *Flandrian Sea-level Changes in the Fenland.* Unpub. Ph. D. Thesis, University of Durham, UK.

Shennan, I. (1982a) Interpretation of Flandrian Sea-level Data from the Fenland, England. *Proc. Geol. Asso.,* 83(1), 53-63.

Shennan, I. (1982b) Problems of Correlating Flandrian Sea-level Changes and Climate. In: Harding, A. (Ed.) *Climatic Change in Later Pre-history,* Edinburgh Univ. Press, Edinburgh, 52-67.

Shennan, I. (1983a) A Problem of Definition of Sea-level Research Method, *Quaternary Newsletter,* V-39, 17-19.

Shennan, I. (1983b) Flandrian and Late Devensian Sea-level Changes and Crustal Movements in England and Wales. In: Smith, D.E. and Dawson, A.G.(Eds) *Shorelines and Isostasy,* Inst Brit. Geog., London, 255-283.

Shennan, I. (1986a) Flandrian Sea-level Changes in the Fenland. I. The Geographical Setting and Evidence of Relative Sea level Changes. *Jour. Quat. Sci.,* 1, 119-154.

Shennan. I. (1986b) Flandrian Sea-level Changes in the Fenland. II. Tendencies of Sea-level Movement, Altitudinal Changes, and Local and Regional Factors. *Jour. Quat. Sci.,* 1(2), 155-179.

Shennan, I. (1987) Global Analysis and Correlation of Sea level Data. In: Devoy, R.J.N. (Ed) *Sea Surface Studies: A Global View,* Croom Helm, London, 198-232.

Shennan, I. (1989) Holocene Crustal Movement and Sea-level Changes in Great Britain. *Jour. Quat. Sci.*, 4(1), 77-89.

Shennan, I. (1993) Sea-level Changes and the Threat of Coastal Inundation, *Geog. Jour.*, 159(2), 148-156.

Shennan, I., Tooley, M.J., Davis, M.J. and Haggart, B.A. (1983) Analysis and Interpretation of Holocene Sea-level Data. *Nature,* 302, 404-406,

Shepard, F.P. (1960) Rise of Sea-level Along the Northwest Gulf of Mexico.In: Shepard, F.P., Phleger, F.B. and van Andel, T.H. (Eds) *Recent Sediments, Northwest Gulf of Mexico,* Am. Asso. Petro. Geol., 338-344.

Shepard, F.P. (1961) Thirty-five Thousand Tears of Sea-level. In: Clement, T. (Ed.) *Essays in Marine Geology in Honour of K.O. Emery,* Univ of South California Press, Los Angeles, 1-10.

Shepard, F.P. and Suess, H.E. (1956) Rate of Postglacial Rise of Sea-level. *Science,* 123, 1082-1083.

Shi, S., Dawson, A.G. and Smith, D.E. (1995) Coastal Sedimentation Associated with the December 12th, 1992 Tsunami in Flores, Indonesia. *Pageoph,* 144 (3-4), 525-536.

Shufu, Z. (1991) Holocene Peat and Sea-level Changes in Ningshao Plain. In: Zechun, L. (Ed.) *Quaternary Sediments and Environmental Changes,* Nanjing Normal University, China, 152-156.

Siddiqui, M.H. (1990) Flood Control and Drainage Development: Physical Environmental Issues. In: Rahman, A.A., Huq, S. and Conway, G.R. (Eds) *Environmental Aspects of Surface Water Systems of Bangladesh,* University Press Limited, Dhaka, 104-108.

Smith, D. E. and Dawson, A. G. (1990) Tsunami Waves in the North Sea. *New Scientist,* 4 August, 46-49.

Smith, D.E., Cullingford, R.A. and Brooks, C.L. (1983) Flandrian Relative Sea-level Changes in the Ythan Valley, Northeast Scotland. *Earth Surface Process and Landform,* 8, 423-438.

Sned, R.E. (1985) Bangladesh. In: Bird, E.C.F. (Ed.) *The World's Coastline,* Van Nostrad Reinhold, 761-764.

SPARRSO (1984) *Bangladesh: Land Zones and Land Systems,* Sheet 2. Map,

SPARRSO (1987) *Project Report on Remote Sensing Application to Coastal Zone Dynamics in Bangladesh.* Govt. of Bangladesh.

Stabell, B. (1987) Changes in Diatom Floras in the late Quaternary Western and Southeastern Norwegian Marine and Freshwater Sediments: Response to Basin Isolation from the Sea. *Nova Hedwigia,* 44(3-4), 305-326.

Stearns, H.T. (1935) Shore Beach of Island of Oahu, Hawaii. *Geol. Soc. Am. Bull.,* 46, 1467-1482.

Stockmarr, J. (1971) Tablets with Spores Used in Absolute Pollen Analysis. *Pollen et Spores,* 13, 615-621.

Stoddart, D.R. and Pethick, J.S. (1984) Environmental Hazard and Coastal Reclamation: Problems and Prospects in Bangladesh. In: Bayliss-Smith, T.P. and Wanmali, S. (Eds) *Understanding Green Revolution: Agrarian Change and Development Planning in South Asia,* Cambridge University Press, 339-361.

Straub, F. (1993) Diatoms and Their Preservation in the Sediments of Lake Neuchâtel (Switzerland) as Evidence of Past Hydrological Changes. *Hydrobiologia,* 269/270, 167-178.

Streif, H. (1972) The Result of Stratigraphical and Facial Investigations in the Coastal Holocene of the Woltzeten/Ostfriesland, Germany. *Geol. For. Stockh. Forh.,* 94(2), 281-299.

Streif, M. (1979a) Cyclic Formation of Coastal Deposits and their Indications of Vertical Sea-level Changes. *Oceanis,* 5, 303-306.

Streif, H. (1979b) Holocene Sea-level Changes in the Strait of Malacca. In: Suguio, K., Fairchild, T.R., Martin, L. and Flexor, J.M. (Eds) *Proc. of the 1978 International Symposium on Coastal Evolution in the Quaternary,* Sao Paulo, Brazil, 552-572.

Stuiver, M. and Pearson, G.W. (1993) High-precision Bidecadal Calibration of the Radiocarbon time Scale, AD 1950-500 BC and 2500-6000 BC. *Radiocarbon,* 35, 1-23.

Stuiver, M. and Reimer, P.J. (1986) A Computer Programm for Radiocarbon Age Calibration. *Radiocarbon,* 28, 1122-1030.

Stuiver, M. and Reimer, P.J. (1993) Extended ^{14}C Data Base and Revised CALIB 3.0 ^{14}C Age Calibration Program. *Radiocarbon,* 35, 215-230.

Sturges, W. (1990) Large Scale Coherence of Sea-level at Very Low Frequencies. In: NRC (Eds) *Sea-Level Changes,* National Academy Press, Washington, USA, 63-72.

Suess, H.E. (1955) Radiocarbon Concentration in Modern Wood. *Science,* 122, 415-417.

Suess, H.E. (1970) The Three Causes of Secular ^{14}C Fluctuation, their Amplitude and Time Constants. In: Olsson, I.U. (Ed.) *Radiocarbon Variations and Absolute Chronology,* Almqvist and Wiksell, 595-605.

Sundquist, E.T. (1990) Long Term Aspects of Future Atmospheric CO_2 and Sea-Level Changes. In: NRC (Eds) *Sea-Level Changes,* National Academy Press, Washington, USA, 193-207.

Sutcliffe, D.W. and Carrick, T.R. (1988) Alkalinity and pH of Tarns and Streams in the Lake District (Cumbria). *Freshwater Biology,* 19, 179-189.

Sutherland, D.S. (1987) Dating and Associated Methodological Problems in the Study of Quaternary Sea-level Changes. In: Devoy, R.J.N (Ed.) *Sea Surface Studies: A Global View,* Croom Helm, London, 165-197.

Sutherland, F.M.J. (1984) *Flandrian Sea-level Changes on the South Coast of England.* Unpub. Thesis, Univ. of Durham.

Talma, A.S. and Vogel, J.C. (1993) A Simplified Approach to Calibrating ^{14}C Dates. *Radiocarbon,* 35(2), 317-322.

Tarafder, M.R. (1975) Reclamation of Land from Sea in Bangladesh. *Proc. Semi. on Flood Control and Allied Problems in Bangladesh,* Oct, 1995, BWDB, 1-6.

Task Force (1991) *Report of the Task Force on Action Plan for Flood Control.* Govt. of Bangladesh.

Thanikaimoni, G. (1987) *Mangrove Palynology.* Institut Fransais de Pondichery, India.

Thatcher, W. (1984) The Earthquake Deformation Cycle, Recurrence and Time Predictable Model. *Jour. Geophy. Res.*, 89, 5674-5680.

Thom, B.G., Hails, J.R. and Martin, A.R.H. (1969) Radiocarbon Evidence Against Higher Postglacial Sea-level in Eastern Australia. *Mar. Geol.,* 7, 161-168.

Thompson, R.D. (1995) The Impact of Atmospheric Aerosols on Global Climate: A Review. *Prog. Phy. Geog.,* 19(3), 336-350.

Tolonen, K. (1986) Charred Particle Analysis. In: Berglund, B.E. (Ed.) *Handbook of Holocene Palaeoecology and Palaeohydrology,* John Wiley & Sons Ltd., Chichester, 485-496.

Tooley, M.J. (1974) Sea-level Changes During the last 9000 years in North-west England. *Geog. Jour.,* 140, 18-42.

Tooley, M.J. (1976) Flandrian Sea-level Changes in West Lancashire. *Geol. Jour.,* 11(2), 37-52.

Tooley, M.J. (1978a) *Sea-level Changes: Northwest England During the Flandrian Stage.* Clarendon Press, Oxford.

Tooley, M.J. (1978b) Interpretation of Holocene Sea-level Changes. *Geol. For. Stoc. Forh.,* 100, 203-212.

Tooley, M.J. (1981) Methods of Reconstruction. In: Simmons, I.G. and Tooley, M.J. (Eds) *The Environment in British Prehistory,* Duckworth, London, 1-48.

Tooley, M.J. (1982) Sea-level Changes in North England. *Proc. Geol. Asso.*, 93, 43-51.

Tooley, M.J. (1985a) Sea Levels. *Prog. Physical Geog.,* 9(1), 113-120.

Tooley, M.J. (1985b) Climate, Sea-level and Coastal Changes. In: Tooley, M.J and Sheail, G.M. (Eds) *The Climatic Scene.* George Allen & Unwin, London, 206-234.

Tooley, M.J. (1986) Sea Levels. *Prog. Physical Geog.,* 10(1), 120-129.

Tooley, M.J. (1987) Sea-level Studies. In: Tooley, M.J. and Shennan, I. (Eds) *Sea-level Changes,* Basil Blackwell, Oxford, 1-24.

Tooley, M.J. (1992) Recent Sea-level Changes. In: Allen, J.R.L and Pye, K. (Eds) *Saltmarsh; Morphodynamics, Conservation and Engineering Significance,* Cambridge University Press, Cambridge, 19-40.

Tooley, M.J. (1993) Long-term Changes in Eustatic Sea-level. In: Warrick, R.A., Barrow, E.M. and Wigley, T.M.L. (Eds) *Climate and Sea-level Change: Observations, Projections and Implications,* Cambridge Univ. Press, 81-107.

Troels-Smith, J. (1955) Characteristics of Unconsolidated Sediments. *Nanm. Geol. Unders.*, 3 (10), 1-73.

Umitsu, M. (1985) Natural Levées and Landform Evolutions in the Bengal Lowland. *Geog. Rev. Japan,* B58(2), 149-64.

Umitsu, M. (1987) Late Quaternary Sedimentary Environment and Landform Evolution in the Bengal Lowland. *Geog. Rev. Japan,* B60(2), 164-178.

Umitsu, M. (1993) Late Quaternary Sedimentary Environment and Landforms in the Ganges Delta. *Sedi. Geol.,* 83, 177-186.

UNDP (1992) *Multipurpose Cyclone Shelter Programme, Draft Final Report: Vol VII: Geotechnical Profile,* Govt. of Bangladesh.

van Campo, E. (1986) Monsoon Fluctuations in Two 20,000 yrs BP Oxygen Isotope/Pollen Records off Southwest India. *Quaternary Res.,* 26, 376-388.

van de Plassche, O. (1980) Compaction and Other Sources of Errors in Obtaining Sea-level Data; Some Results and Consequences. *Eisz. und. Geg.,* 30, 171-181.

van de Plassche, O. (1982) Sea-level Changes and Water Level Movement in the Netherlands During the Holocene. *Meded. Rijks Geol. Dienst.,* 36, 1-93.

van de Plassche O.(1986a) Introduction. In: van de Plassche O.(Ed.) *Sea Level Research; A Manual for Collection and Evaluation of Data,* Geo Books, Norwich, 1-26.

van de Plassche, O. (Ed.) (1986b) *Sea-level Research: A Manual for the Collection and Evaluation of Data,* Geo Books, Norwich.

van der Werff, H. and Huls, H. (1958-1974) *Diatomeenflora van Nederland.* 8 parts, Published Privately: De Hoef, The Netherlands.

van Straaten, L.M.J.U. (1954) Radiocarbon Dating and Changes of Sea-level at Velzen (Netherlands). *Geol. en Mijn.*, 16, 247-253.

Veres, A. Pienitz, R. and Smol, J.P. (1995) Lake Water Salinity and Periphytic Diatom Succession in the Three Subarctic lakes, Yukon Treeitory, Canada. *Arctic,* 48(1), 63-70.

Vishnu-Mittre (1972) Problems and Prospects of Quaternary Palynology in India. In: Ghosh, A.K., Chanda, S., Ghosh, T.K., Baksi, S.K. and Banerjee, M. (Eds) *Proc. of the Seminar on Palaeopalynology and Indian Stratigraphy,* Calcutta University, India, 348-356.

Vishnu-Mittre and Gupta, H.P. (1972) Pollen Analytical Study of Quaternary Deposits in the Bengal Basin. *Palaeobotanist,* 19(3), 297-306.

Vogel, J.C., Fuls, A.M. and Becker, B. (1993) Pretoria Calibration Curve for Short-Lived Sample, 1930-3350 BC. *Radiocarbon,* 35(1), 73-86.

von Post, L. (1916) Om skogsträdpollen i sydsvenska torfmosslagerföljder. *Geol. For. Stock. Forh.*, 38, 384-394.

Vos, P.C. and de Wolf, H.(1988) Methodological Aspects of Palaeoecological Diatom Research in Coastal Areas of the Netherlands. *Geol. en Mijn.* 67, 31-40.

Vos, P.C. and de Wolf, H. (1993a) Diatoms as a Tool for Reconstructing Sedimentary Environment in Coastal Wetland; Methodological Aspects. *Hydrobiologia,* 269/270, 285-296.

Vos, P.C. and de Wolf, H. (1993b) Reconstruction of Sedimentary Environments in Holocene Coastal Deposits of the South-west Netherlands; the Poortvliet Boring, a Case Study of Palaeoenvironmental Diatom Research. *Hydrobiologia,* 269/270, 297-306.

Vos, P.C. and de Wolf, H. (1994) Palaeoenvironmental Research on Diatoms in Early and Middle Holocene Deposits in Central North Holland (The Netherlands). *Neth. Jour. Aquat. Ecol.*, 28(1), 97-115.

Wakushima, S., Kuraishi, S. and Sakurai, N. (1994a) Soil Salinity and pH in Japanese Mangrove Forest and Growth of Cultivated Mangrove Plants in Different Conditions. *Jour. Plant Res.,* 107, 39-46.

Wakushima, S., Kuraishi, S., Sakurai, N., Supappibul, K. and Siripatanadilok, S. (1994b) Stable Soil pH of Thai Mangroves in Dry and Rainy Seasons and its Relation to Zonal Distribution of Mangroves. *Jour. Plant Res.,* 107, 47-52.

Walcott, R.I. (1972) Past Sea Levels, Eustasy and Deformation of the Earth. *Quaternary Res.,* 2, 1-14.

Walter, H. (1971) *Ecology of Tropical and Subtropical Vegetation.* Oliver and Boyd, Edinburgh.

Warrick, R. and Oerlemans, J. (1990) Sea Level Rise. In: Houghton, J.T., Jenkins, G.J. and Ephraums, J.J. (Eds) *Climate Change; The IPCC Scientific Assessment*, Cambridge Univ. Press, Cambridge, 257-282.

Warrick, R.A., Bhuiya, A.H. and Mirza, M.Q. (1993a) *Briefing Document No-1: The Greenhouse Effect and Climate Change*. Bang. Unnayan Parishad, Dhaka.

Warrick, R.A., Bhuiya, A.H., Mitchell, W.M., Murty, T.S. and Rasheed, K.S.B. (1993b) *Briefing Documents No.-2: Sea-Level Changes in the Bay of Bengal*. Bang. Unnayan Parishad, Dhaka.

Watson, R.T., Rodhe, H., Oeschger, H. and Siegenthaler, U. (1990) Greenhouse Gases and Aerosols. In: Houghton, J.T., Jenkins, G.J. and Ephraums, J.J. (Eds) *Climate Change: The IPCC Scientific Assessment,* Cambridge Univ. Press, Cambridge, 1-40.

Watts, W.A. and Hansen, B.C.S. (1994) Pre-Holocene and Holocene Pollen Records of Vegetation History from the Florida Peninsula and their Climatic Implications. *Palaeogeo. Palaeocli. Palaeoeco.,* 109, 163-176.

Webb, R.S. and Webb, T. (1988) Rates of Sediment Accumulation in Pollen Cores from Small Lakes and Mires of Eastern North America. *Quat. Res.,* 30, 284-297.

Wentworth, C.K. and Palmer, H.S. (1925) Eustatic Bench of Islands of the North Pacific. *Geol. Soc. Am. Bull,*. 35, 521-544.

Whittington, G. and Edwards, K. J. (1993) Vegetational Change on Papa Stour, Shetland, Scotland: a Response to Coastal Evolution and Human Interference. *The Holocene,* 3(1), 54-62.

Whittington, G., Edwards, K.J. and Cundill, P.R. (1990) *Palaeoenvironmental Investigations at Black Loch, in the Ochil Hills of Fife, Scotland.* O'Dell Memorial Monograph No. 22, Dept. of Geography, University of Aberdeen, Scotland.

Whittington, G., Hall, A.M. and Jarvis, J. (1993) A pre-Late Devensian Pollen Site from Camp Fauld, Buchan, North-east Scotland. *New Phytol.,* 125, 867-874.

Whitton, B.A., Aziz, A., Kawecka, B. and Rother, J.A. (1988) Ecology of Deepwater Rice-field in Bangladesh 3. Associated Algae and Macrophytes. *Hydrobiologia,* 169(1), 23-42.

Wigley, T.M.L. (1989) Possible Climate Change due to SO_2 Derived Cloud Condensation Nuclei. *Nature*, 339, 365-367.

Wolfe, A.P. (1994) Late Wisconsinan and Holocene Diatom Stratigraphy from Amarok Lake, Baffin Island, N.W.T., Canada, *Jour. Palaeolim.,* 10, 129-139.

Woodroffe, C.D. (1981) Mangrove Swamp Stratigraphy and Holocene Transgression, Grand Cayman Island, West Indies. *Mar. Geol.,* 41, 271-294.

Woodroffe, C.D. (1995) Response of Tide Dominated Mangrove Shorelines in Northern Australia to Anticipate Sea-level Rise. *Eart. Sci. Proc. Land.*, 20, 65-85.

Woodroffe, C.D., Thom, B.G. and Chappell, J. (1985) Development of Widespread Mangrove Swamps in Mid-Holocene Time in Northern Australia. *Nature,* 317, 711-713.

Woodworth, P.L. (1990) A Search for Acceleration in Records of European Mean Sea-level. *Int. Jour. Clim.,* 10, 129-143.

World Bank (1989) *Bangladesh: Action Plan For Flood Control.* World Bank Publication.

Wunderlich, J. and Andres, W. (1991) Late Pleistocene and Holocene Evolution of the Western Nile Delta and Implications for Its Future Development.In: Brückner, H. and Radtke, U. (Eds) *Von der Nordsee bis Zum Indischen Ozean.* Franz Steiner Verlag, Stuttgart, 105-120.

Zaher, M.A. (1962) *Peat Deposit of Kola Mauza, Khulna.* Geol. Survey of Pakistan, Quetta.

Zong, Y. (1992) Postglacial Stratigraphy and Sea-Level Changes in the Han River Delta, China. *Jour. Coastal Res.,* 8(1), 1-28.

Zong, Y. (1993) *Flandrian Sea-level Changes and Impacts of Projected Sea-level Rise on the Coastal Lowlands of Morecambe Bay and the Thames Estuary, U.K..* Unpub. Ph. D. Thesis, University of Durham, UK.

Zong, Y. and Tooley, M.J. (1996a) Holocene Sea-level Changes and Crustal Movement in Morecambe Bay, North-west England. *Jour. Quat. Sci.,* 11(1), 43-58

Zong, Y. and Tooley, M.J. (1996b) Evidence of Mid-Holocene Storm-Surge Deposits from Morecambe Bay, North-west England: A Biostratigraphic Approach. *Quat. Inter.,* (in press).

RELATIVE SEA-LEVEL CHANGES

IN BANGLADESH

DURING THE HOLOCENE

by

M. Shahidul Islam

Volume Two: Figures and Appendices

Thesis submitted for the degree of
Doctor of Philosophy

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Scotland, U.K.

May, 1996

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Location Map of Bangladesh

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Bangladesh in South Asian Region (Source: Khan, 1991)

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Administrative Districts of Bangladesh (Source: FAO, 1988)

Bottom (Left):
List of the Reconnaissance Sampling Sites

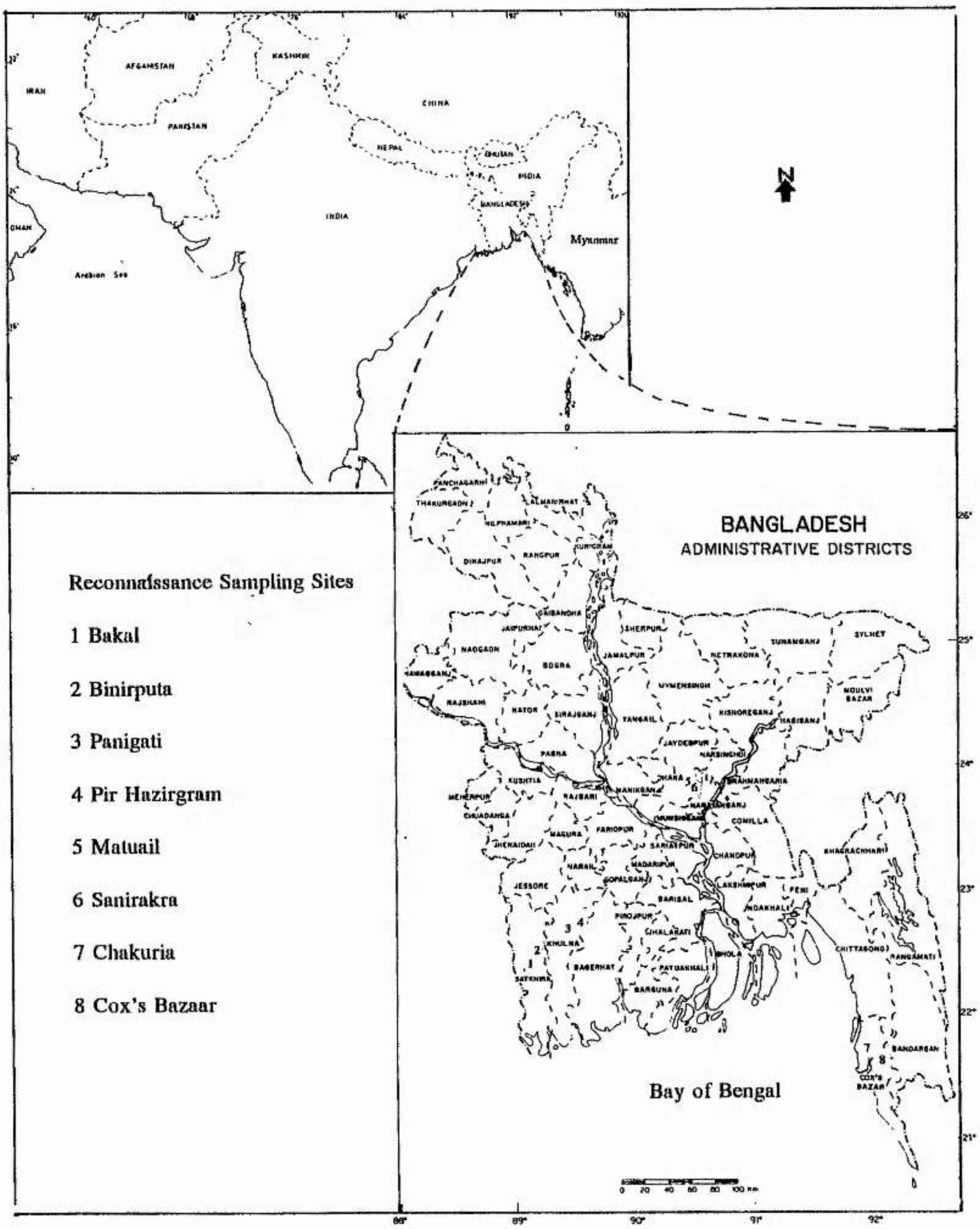
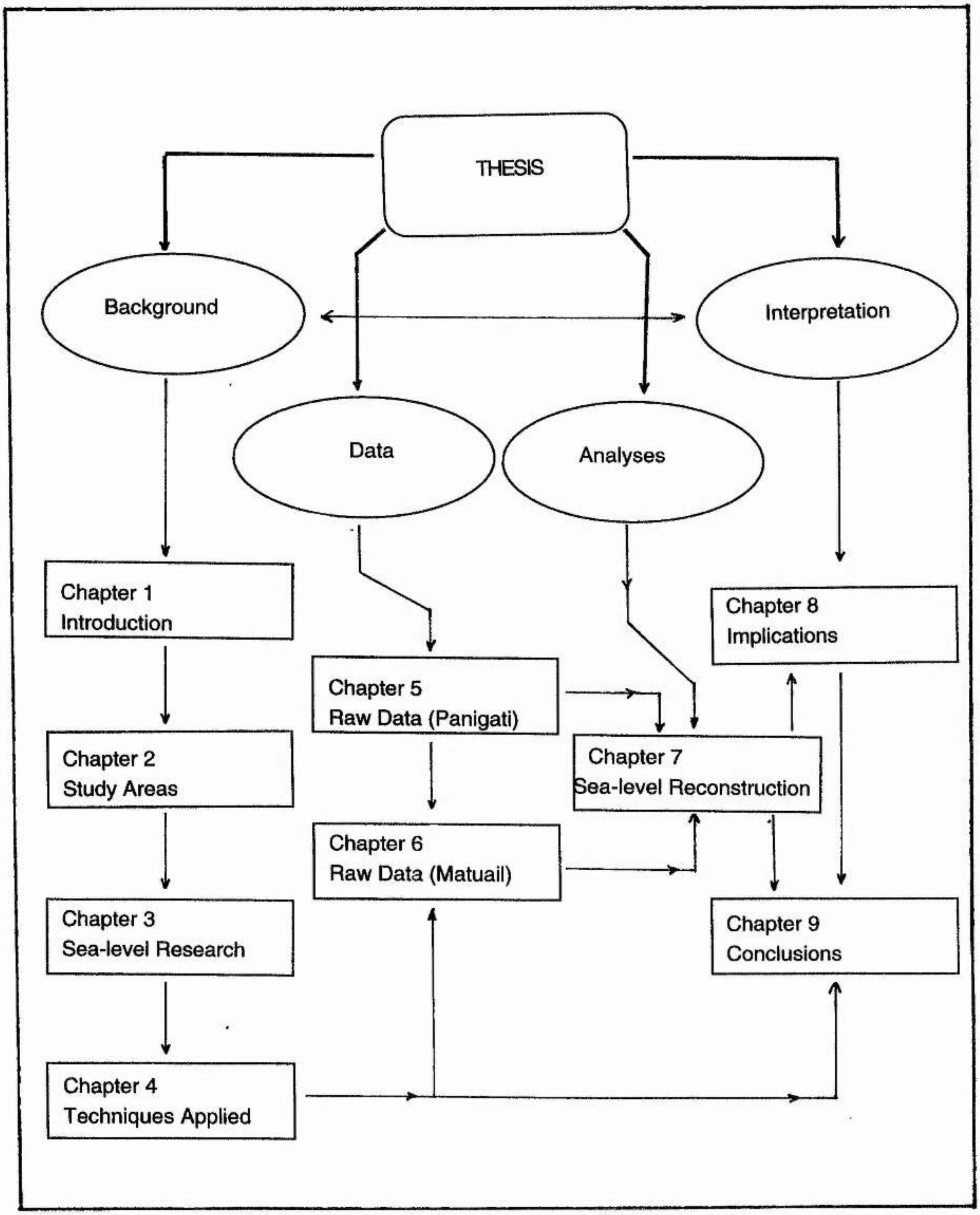

BANGLADESH
ADMINISTRATIVE DISTRICTS
Reconnaissance Sampling Sites
1 Bakal
2 Binirputa
3 Panigati
4 Pir Hazirgram
5 Matuail
6 Sanirakra
7 Chakuria
8 Cox's Bazaar
Bay of Bengal
Myanmar
INDIA
CHINA
PAKISTAN
AFGANISTAN
IRAN
NEPAL
Arabian Sea

Figure 1.2:

Structure of the Thesis


THESIS
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Chapter 6
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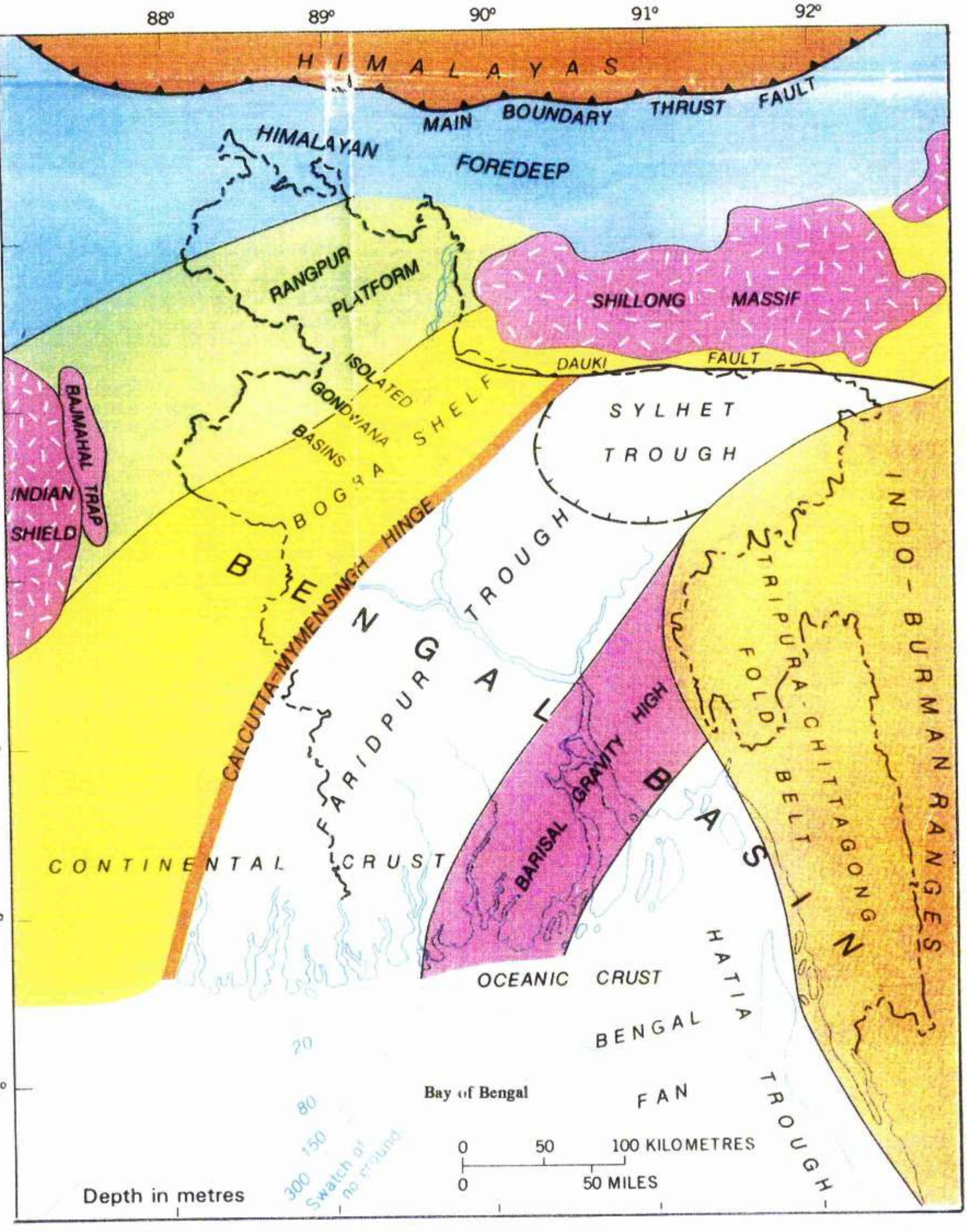
Figure 2.1:

Generalized Geometry of the Bengal Basin (Source: Alam *et al.*, 1990)



HIMALAYAS
MAIN BOUNDARY THRUST FAULT
HIMALAYAN FOREDEEP
RANGPUR PLATFORM
SHILLONG MASSIF
DAUKI FAULT
ISOLATED GONDWANA BASINS
BOGRA SHELF
RAJMAHAL TRAP
INDIAN SHIELD
SYLHET TROUGH
CALCUTTA-MYMENSINGH HINGE
BENGAL BASIN
FARIDPUR TROUGH
BARISAL GRAVITY HIGH
TRIPURA-CHITTAGONG FOLD BELT
INDO-BURMAN RANGES
CONTINENTAL CRUST
OCEANIC CRUST
BENGAL FAN
HATIA TROUGH
Bay of Bengal
88° 89° 90° 91° 92°
27° 26° 25° 24° 23° 22° 21°
0 50 100 KILOMETRES
0 50 MILES
Depth in metres
20
80
150
300
Swatch of no ground

Figure 2.2:

Regional Geology and Tectonic Setting of the Bengal Basin Showing Major Faults (Source: Khandoker, 1987) and Earthquake Zones (CEEHM, 1979)

Zone-I: Maximum Magnitude 7.0 (Richter Scale)

Zone-II: Maximum Magnitude 6.5-7.0 (Richter Scale)

Zone-III: Maximum Magnitude 6.0-6.5 (Richter Scale)

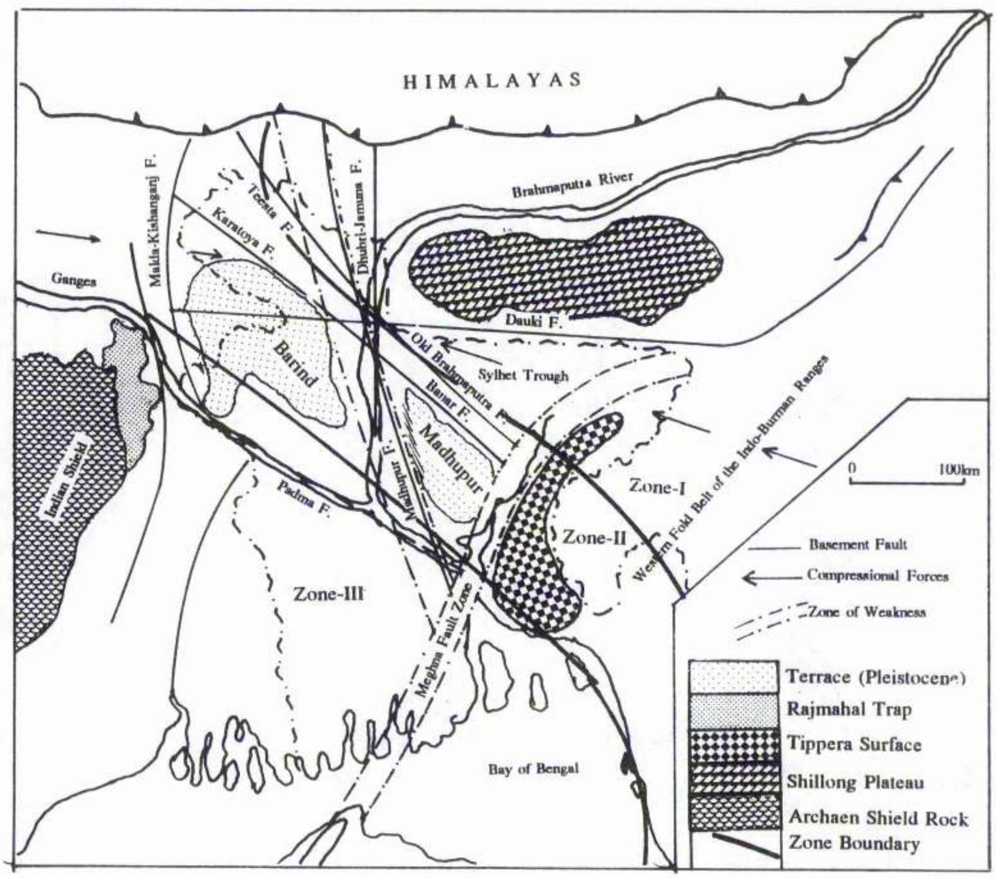

HIMALAYAS
Brahmaputra River
Ganges
Malda-Kishanganj F.
Teesta F.
Karatoya F.
Dhubri-Jamuna F.
Dauki F.
Barind
Old Brahmaputra F.
Sylhet Trough
Bansar F.
Madhupur
Madhupur F.
Padma F.
Indian Shield
Zone-I
Zone-II
Zone-III
Western Fold Belt of the Indo-Burman Ranges
Meghna Fault Zone
Bay of Bengal
0
100km
Basement Fault
Compressional Forces
Zone of Weakness
Terrace (Pleistocene)
Rajmahal Trap
Tippera Surface
Shillong Plateau
Archaen Shield Rock
Zone Boundary

Figure 2.3:

Generalized Physiographic and Drainage Map of Bangladesh **(Source: Alam *et al.*, 1990)**

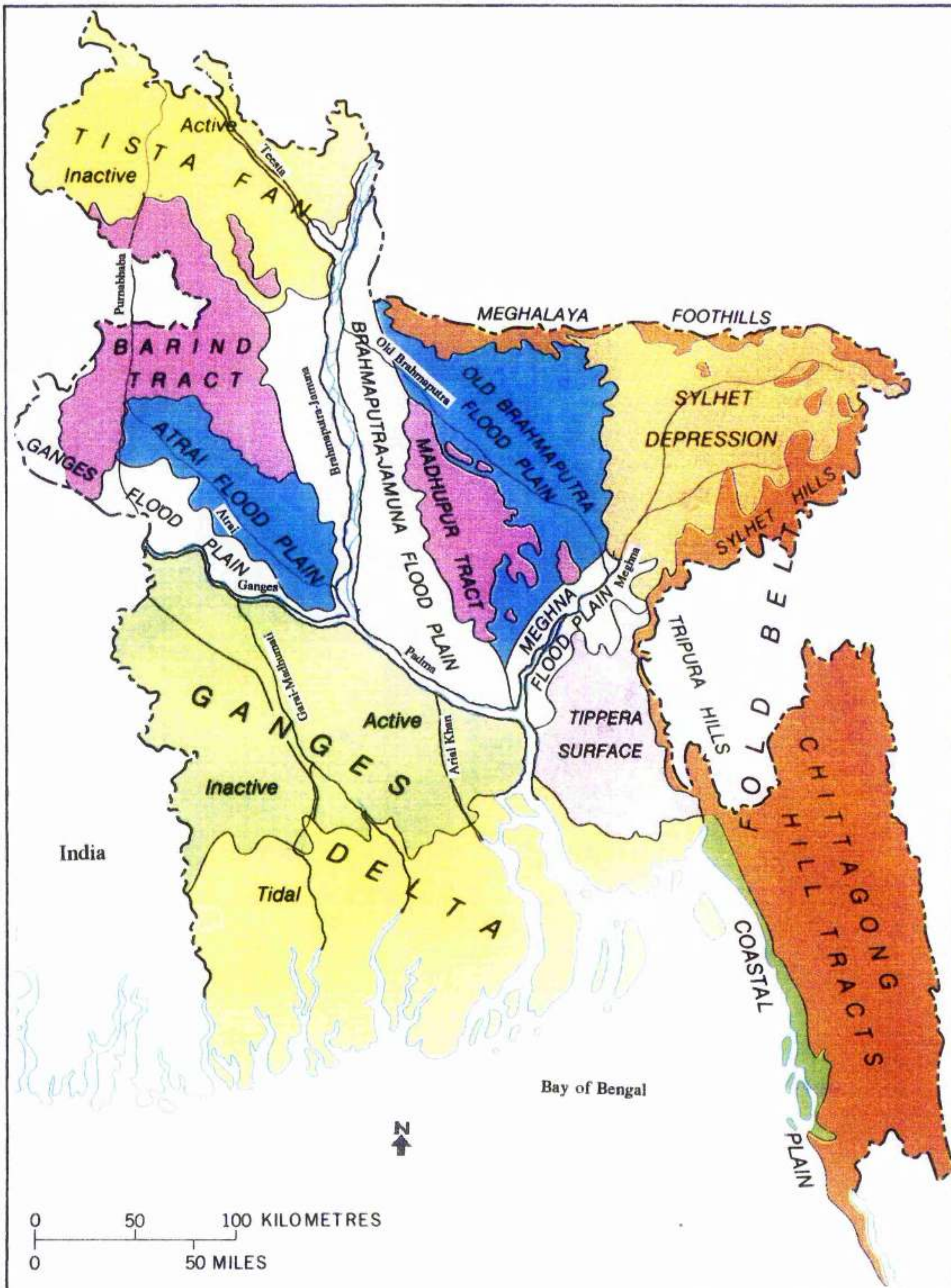

TISTA FAN
Active
Inactive
Teesta
Purnabhaba
BARIND TRACT
GANGES
ATRAI FLOOD PLAIN
Atrai
FLOOD PLAIN
Ganges
Brahmaputra-Jamuna
BRAHMAPUTRA-JAMUNA FLOOD PLAIN
Old Brahmaputra
OLD BRAHMAPUTRA FLOOD PLAIN
MADHUPUR TRACT
MEGHALAYA FOOTHILLS
SYLHET DEPRESSION
SYLHET HILLS
FOLD BELT
MEGHNA FLOOD PLAIN
Meghna
TRIPURA HILLS
TIPPERA SURFACE
Padma
Garai-Madhumati
Arial Khan
GANGES DELTA
Active
Inactive
Tidal
CHITTAGONG HILL TRACTS
COASTAL PLAIN
India
Bay of Bengal
N
0 50 100 KILOMETRES
0 50 MILES

Figure 2.4:

Map of the Coastal Belt of Bangladesh Showing Three Different Coastal Zones

1. The Sundarbans of the Western Region
2. The Area of Rapid Sedimentation in the Central Region
3. The Narrow Coastal Belt of the Eastern Region

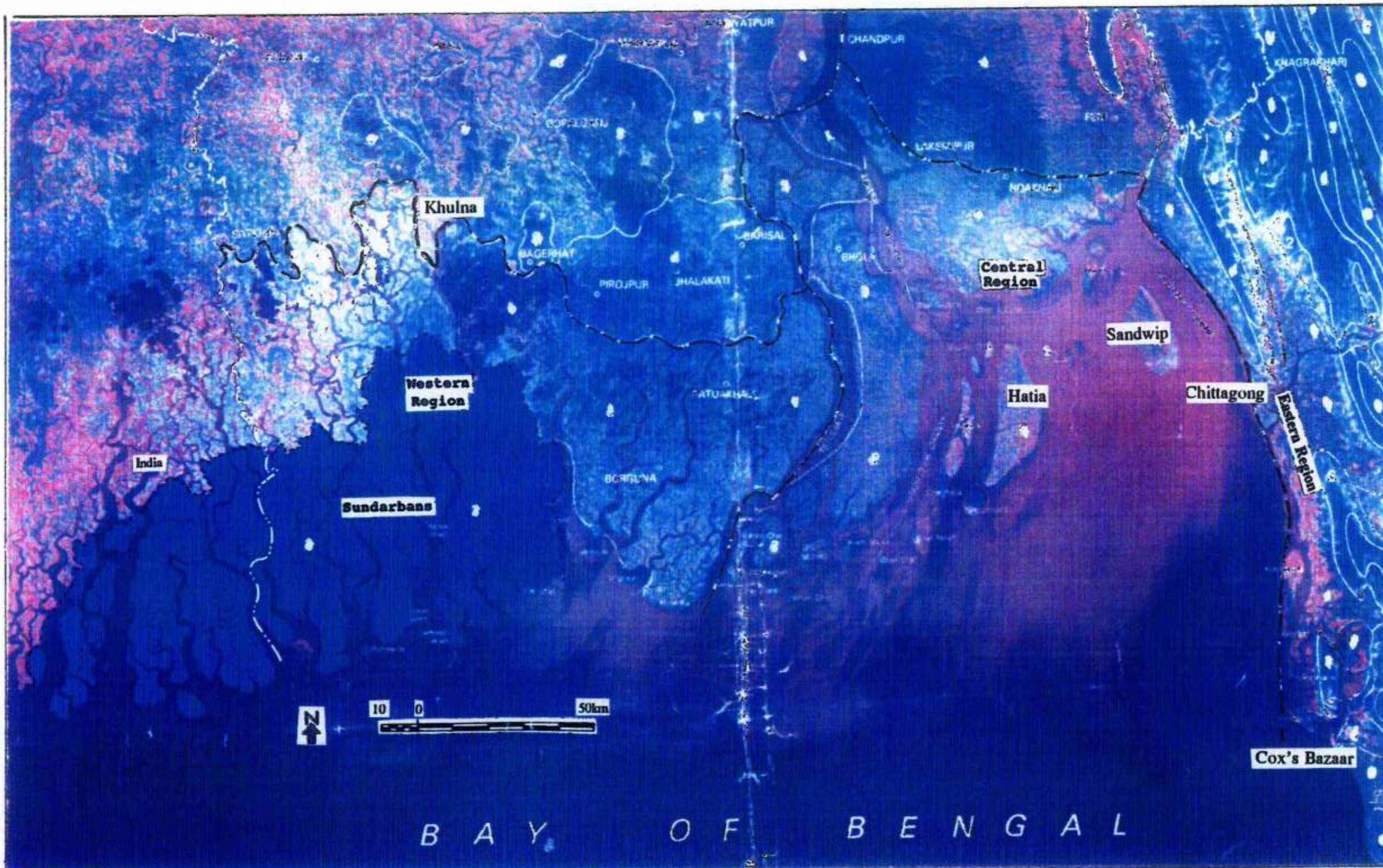

Khulna
Western Region
Sundarbans
India
Central Region
Sandwip
Hatia
Chittagong
Eastern Region
Cox's Bazaar
CHANDPUR
LAKSHMIPUR
NOAKHALI
KHAGRACHHARI
BARISAL
BAGERHAT
PIROJPUR
JHALAKATI
PATUAKHALI
BORGUNA
N
10
0
50km
B A Y O F B E N G A L

Figure 2.5:

Saline Water Limit (Source: Huq and Ali, 1990) and Major Cyclone Paths (Source: Warrick *et al.*, 1993b)

(Map Source: SPARRSO, 1984)

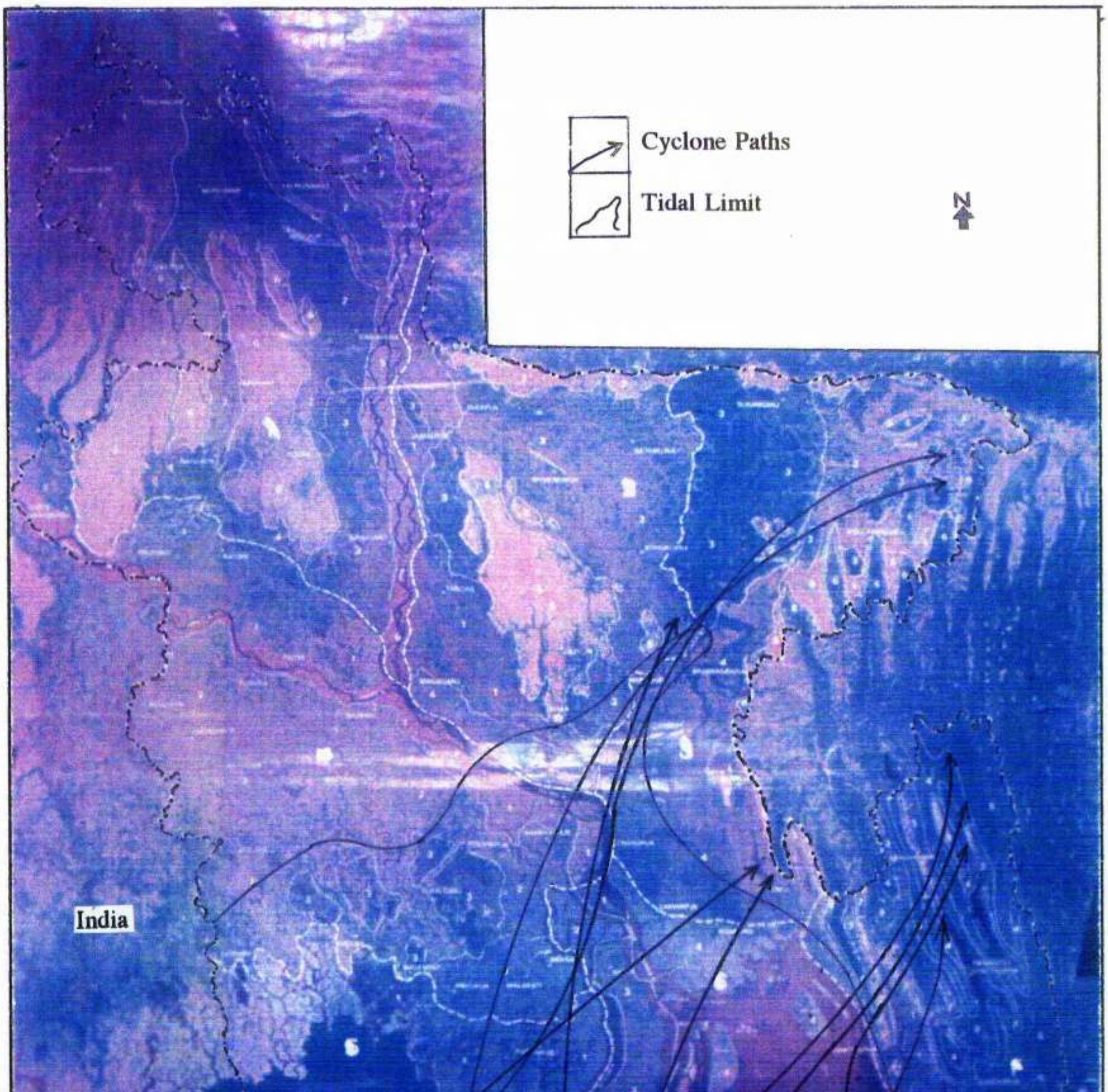

Cyclone Paths
Tidal Limit
N
India
1970
1991
1965
1958
1961
1961
1980
1985
1963

Figure 2.6:

Salinity Zones in Sundarbans Forest

For River Water Salinity:

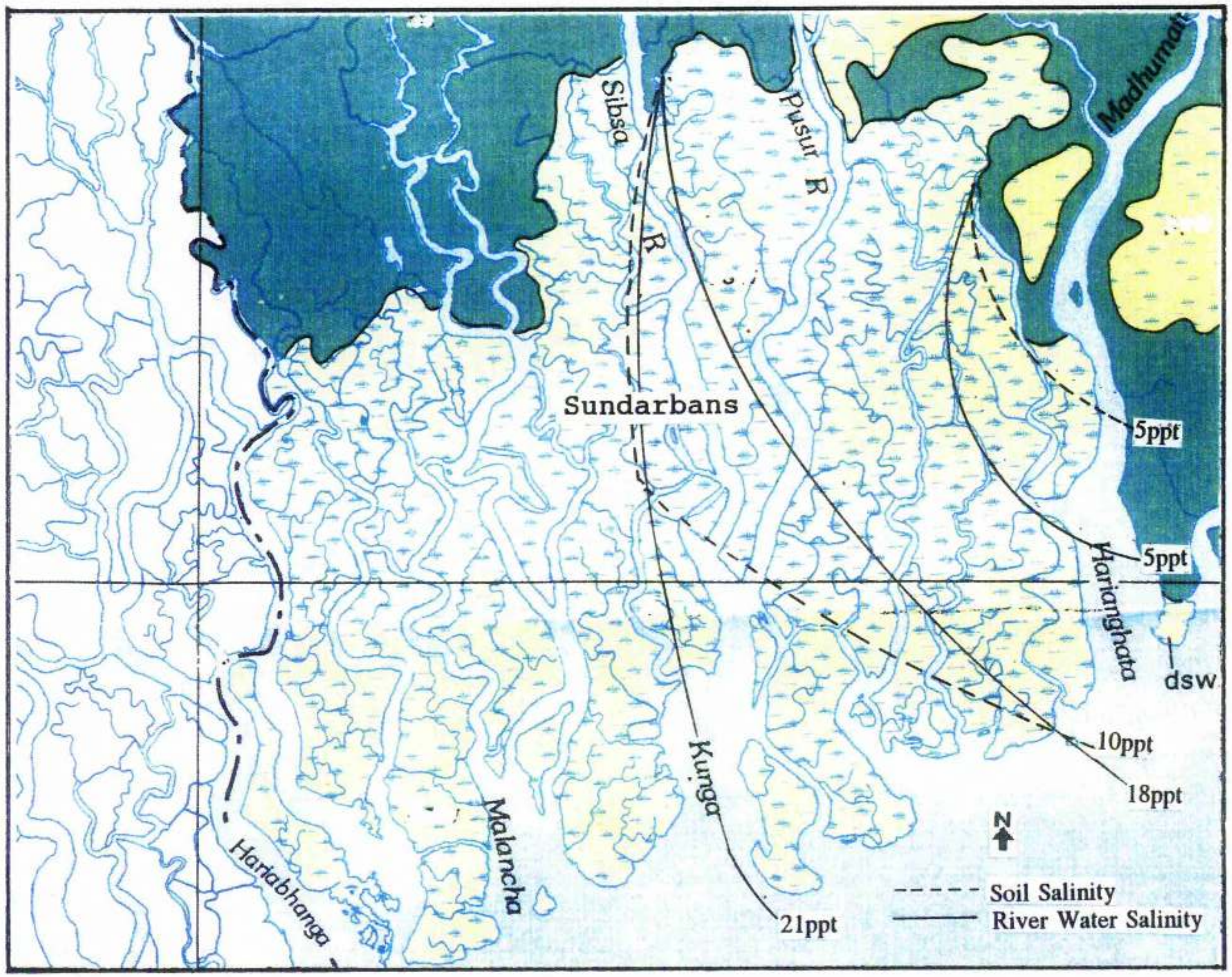
Oligohaline (Salinity 0-5 ppt)
Mesohaline (Salinity 5-18 ppt)
Polyhaline (Salinity >18 ppt)

For Soil Salinity:

Oligohaline (Salinity 0-5 ppt)
Mesohaline (Salinity 5-10 ppt)
Polyhaline (Salinity >10 ppt)

ppt=parts per thousand

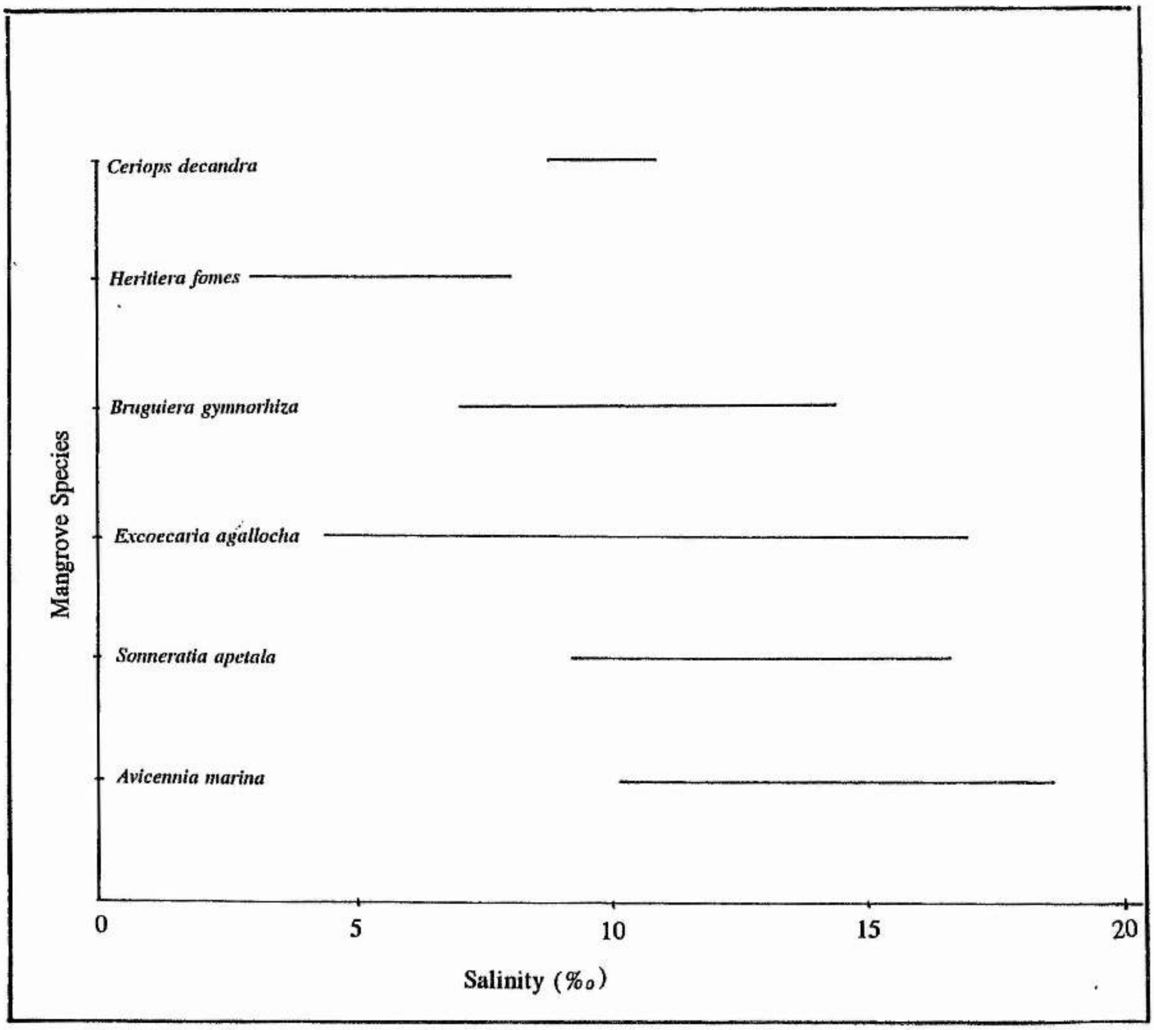
(Source: Karim, 1994)



Madhumati
Sibsa
Pusur R
R
Sundarbans
5ppt
5ppt
Harianghata
dsw
10ppt
18ppt
Kunga
21ppt
Malancha
Hariabhanga
N
Soil Salinity
River Water Salinity

Figure 2.7:

Range of Salinity Tolerance of Some Common Mangrove Species in Sundarbans (Source: Karim, 1988)



Ceriops decandra
Heritiera fomes
Bruguiera gymnorhiza
Excoecaria agallocha
Sonneratia apetala
Avicennia marina
Mangrove Species
0
5
10
15
20
Salinity (‰)

Figure 2.8:

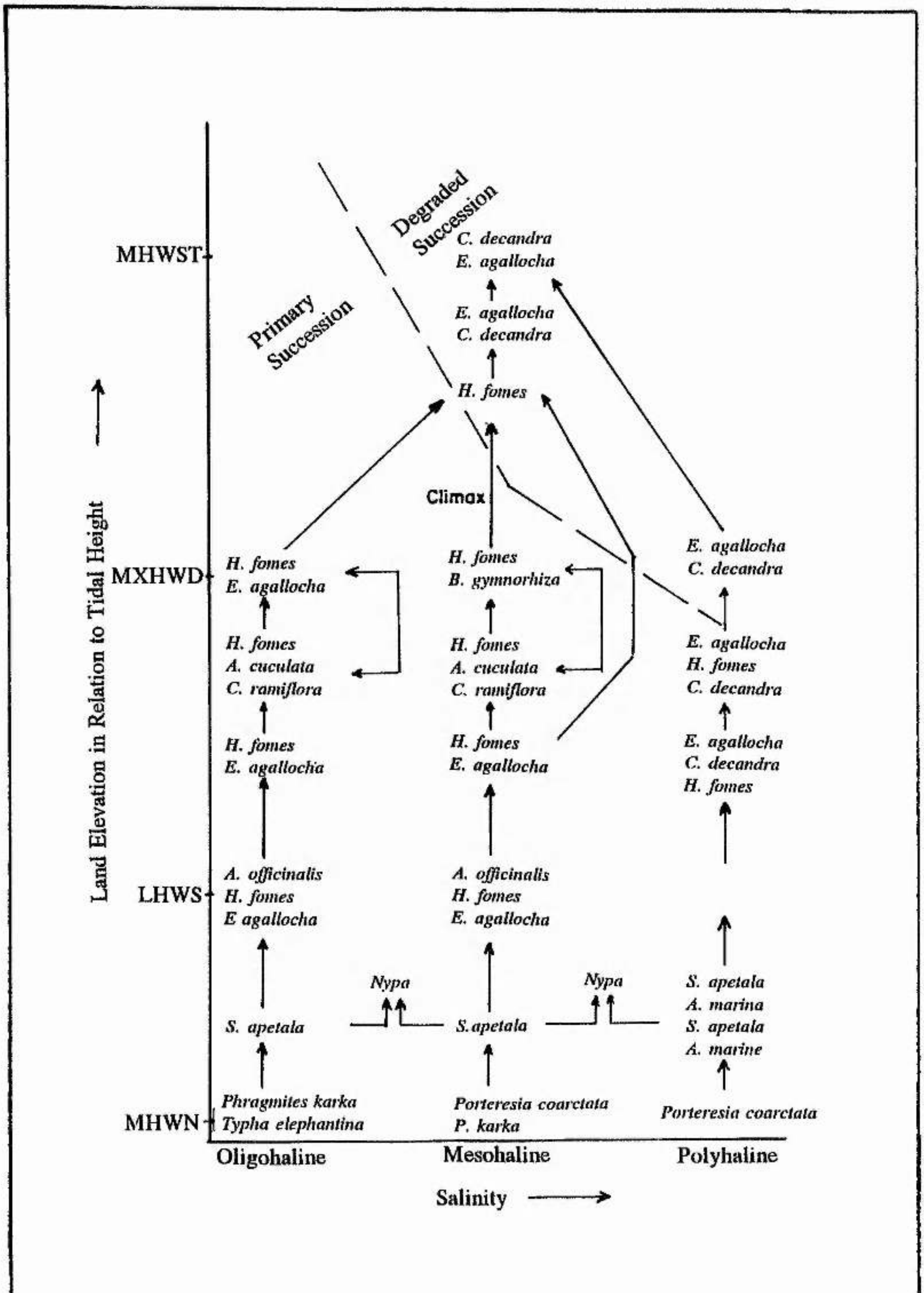
Model Showing Mangrove Succession and Tidal Range in Sundarbans (Source: Karim, 1994)

MHWN= Mean High Water Neap Tide

LHWS= Low High Water Spring Tide During Dry Season

MXHWD= Maximum High water Spring Tide During Dry Season

MHWST= Mean High water Spring Tide



Degraded Succession
Primary Succession
C. decandra
E. agallocha
E. agallocha
C. decandra
H. fomes
Climax
MHWST
MXHWD
LHWS
MHWN
Land Elevation in Relation to Tidal Height
H. fomes
E. agallocha
H. fomes
A. cuculata
C. ramiflora
H. fomes
E. agallocha
A. officinalis
H. fomes
E agallocha
S. apetala
Phragmites karka
Typha elephantina
Nypa
H. fomes
B. gymnorhiza
H. fomes
A. cuculata
C. ramiflora
H. fomes
E. agallocha
A. officinalis
H. fomes
E. agallocha
S.apetala
Porteresia coarctata
P. karka
Nypa
E. agallocha
C. decandra
E. agallocha
H. fomes
C. decandra
E. agallocha
C. decandra
H. fomes
S. apetala
A. marina
S. apetala
A. marine
Porteresia coarctata
Oligohaline
Mesohaline
Polyhaline
Salinity

Figure 2.9:

Mangrove Zonation at Different Geomorphic Units in Sundarbans

A. Mudflat Unit in Polyhaline Zone

B. Inclined Slope Unit in Oligohaline Zone

C. Backswamp Unit in Mesohaline Zone

(Source: Karim, 1994)

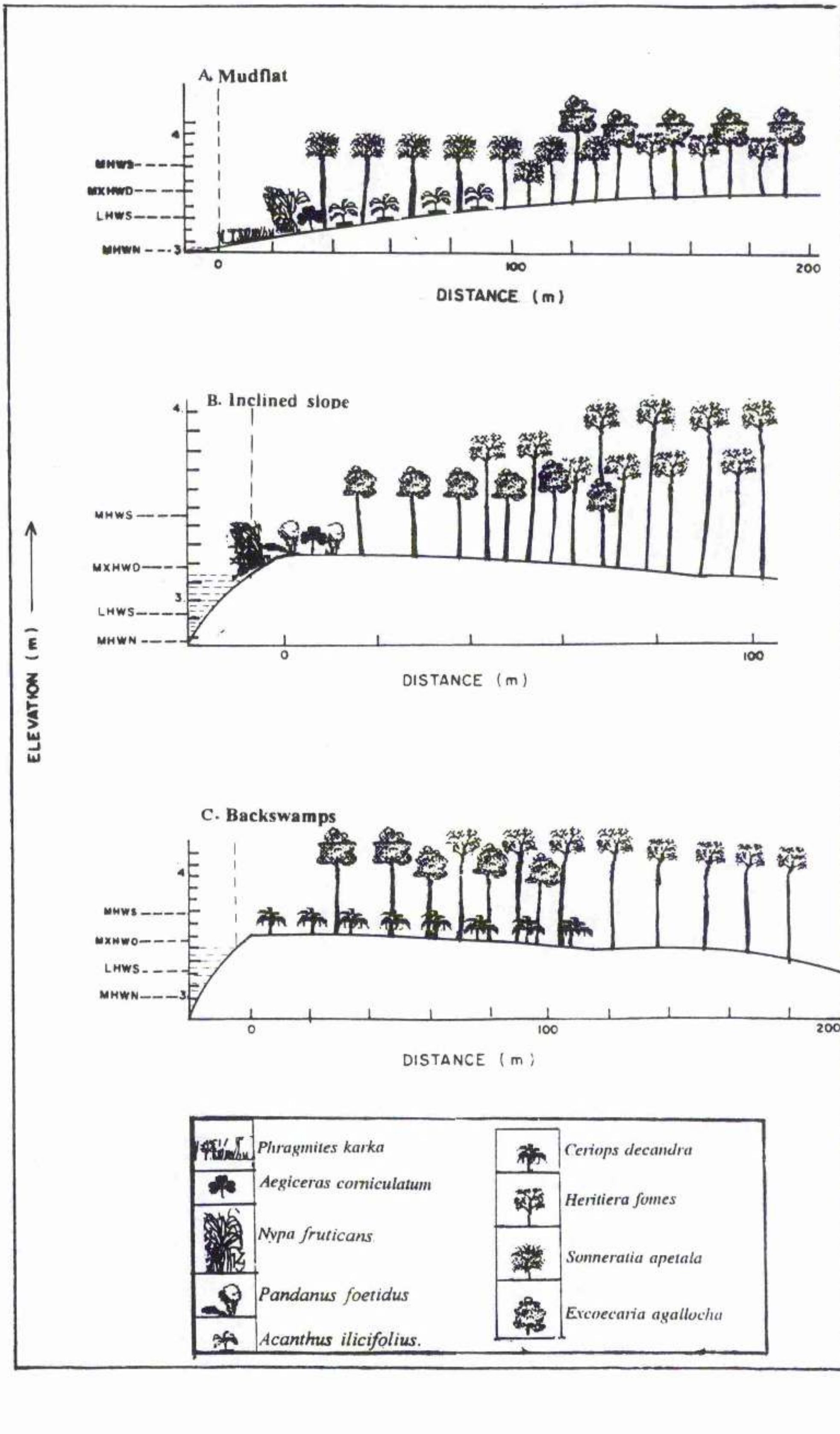

A. Mudflat
MHWS
MXHWD
LHWS
MHWN
4
3
0
100
200
DISTANCE (m)
B. Inclined slope
4
MHWS
MXHWD
3
LHWS
MHWN
0
100
DISTANCE (m)
ELEVATION (m)
C. Backswamps
4
MHWS
MXHWD
LHWS
MHWN
3
0
100
200
DISTANCE (m)
Phragmites karka
Aegiceras corniculatum
Nypa fruticans
Pandanus foetidus
Acanthus ilicifolius.
Ceriops decandra
Heritiera fomes
Sonneratia apetala
Excoecaria agallocha

Figure 2.10:

Map of Panigati Showing Different Geomorphic Units and Site Location

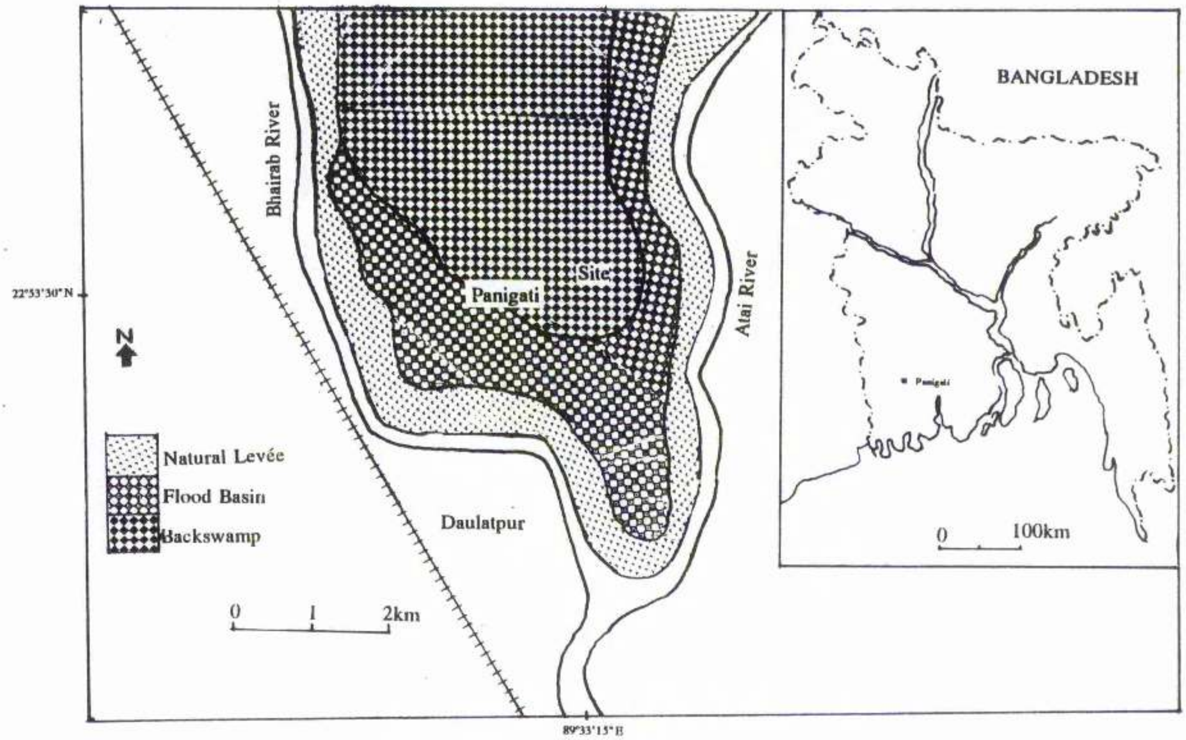

Bhairab River
Atai River
Site
Panigati
Daulatpur
22°53'30"N
89°33'15"E
N
Natural Levée
Flood Basin
Backswamp
0
1
2km
BANGLADESH
0
100km

Figure 2.11:

Map of Matuail Showing Site Location

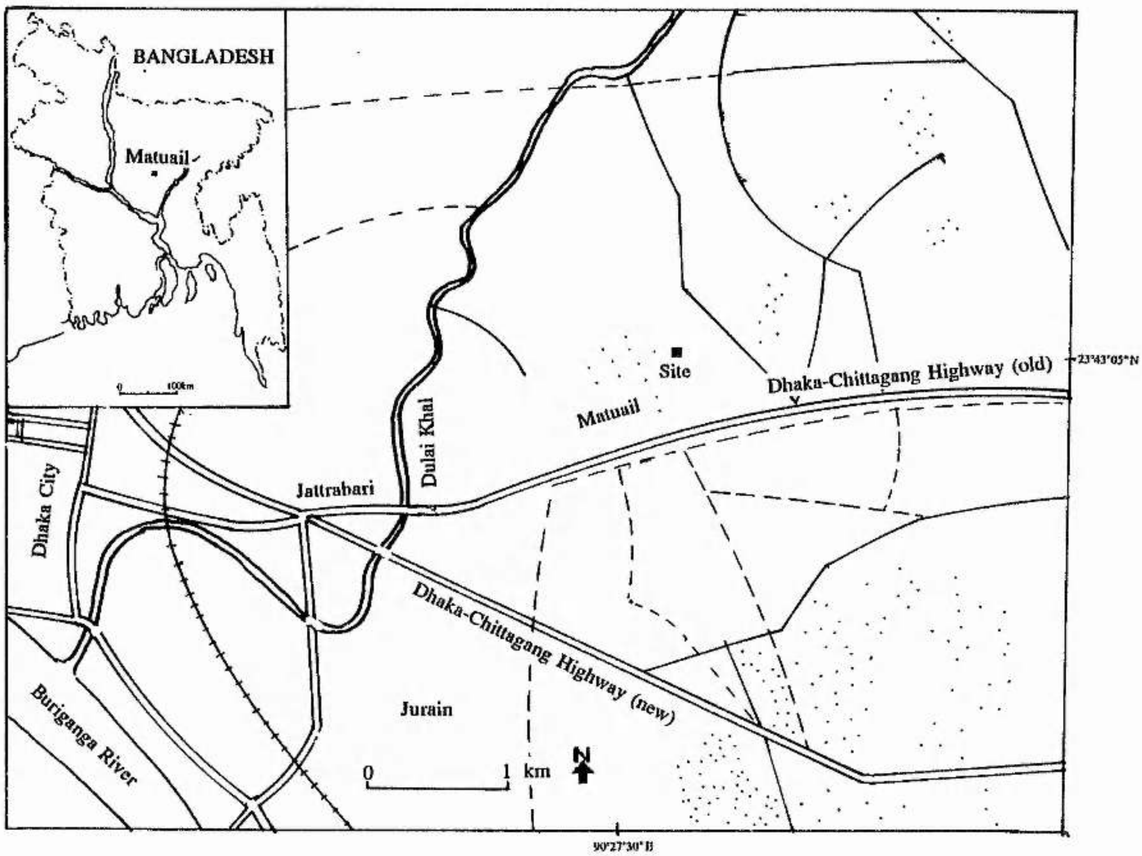
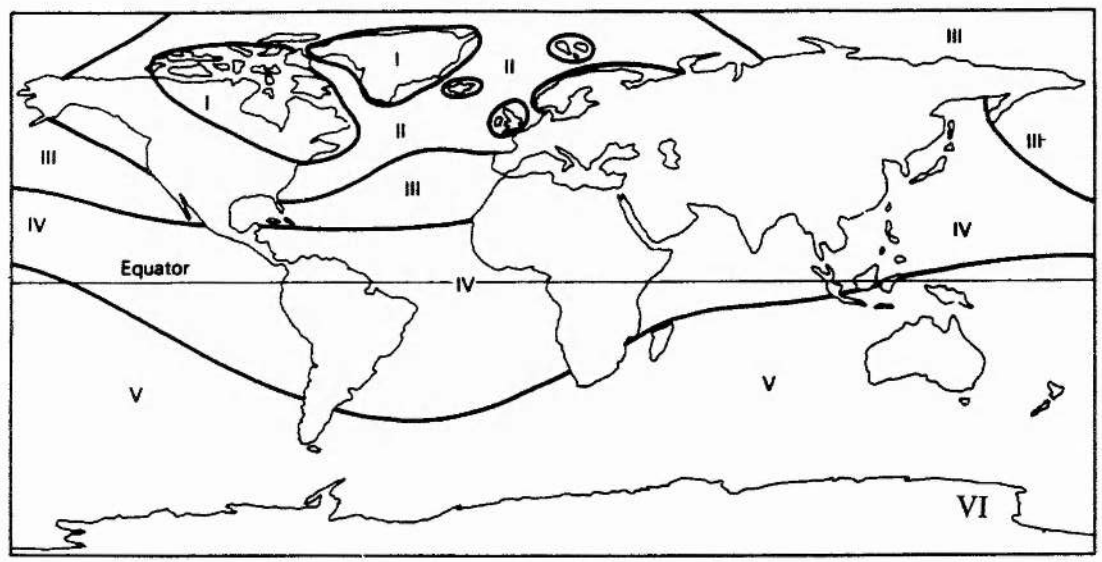

BANGLADESH
Matuail
Site
Matuail
Dhaka-Chittagang Highway (old)
23°43'05"N
Dulai Khal
Jattrabari
Dhaka City
Dhaka-Chittagang Highway (new)
Jurain
Buriganga River
0
1 km
N

Figure 3.1:

Six Zones of Predicted Sea-level Change of the Earth
(Source: Clark *et al.*, 1978)

Emerged Beaches are predicted for Zones I, III, V, and VI

Submerged Beaches are predicted in Zones II and IV



III
I
I
II
II
III
III
IV
Equator
IV
IV
V
V
VI

Figure 3.2:

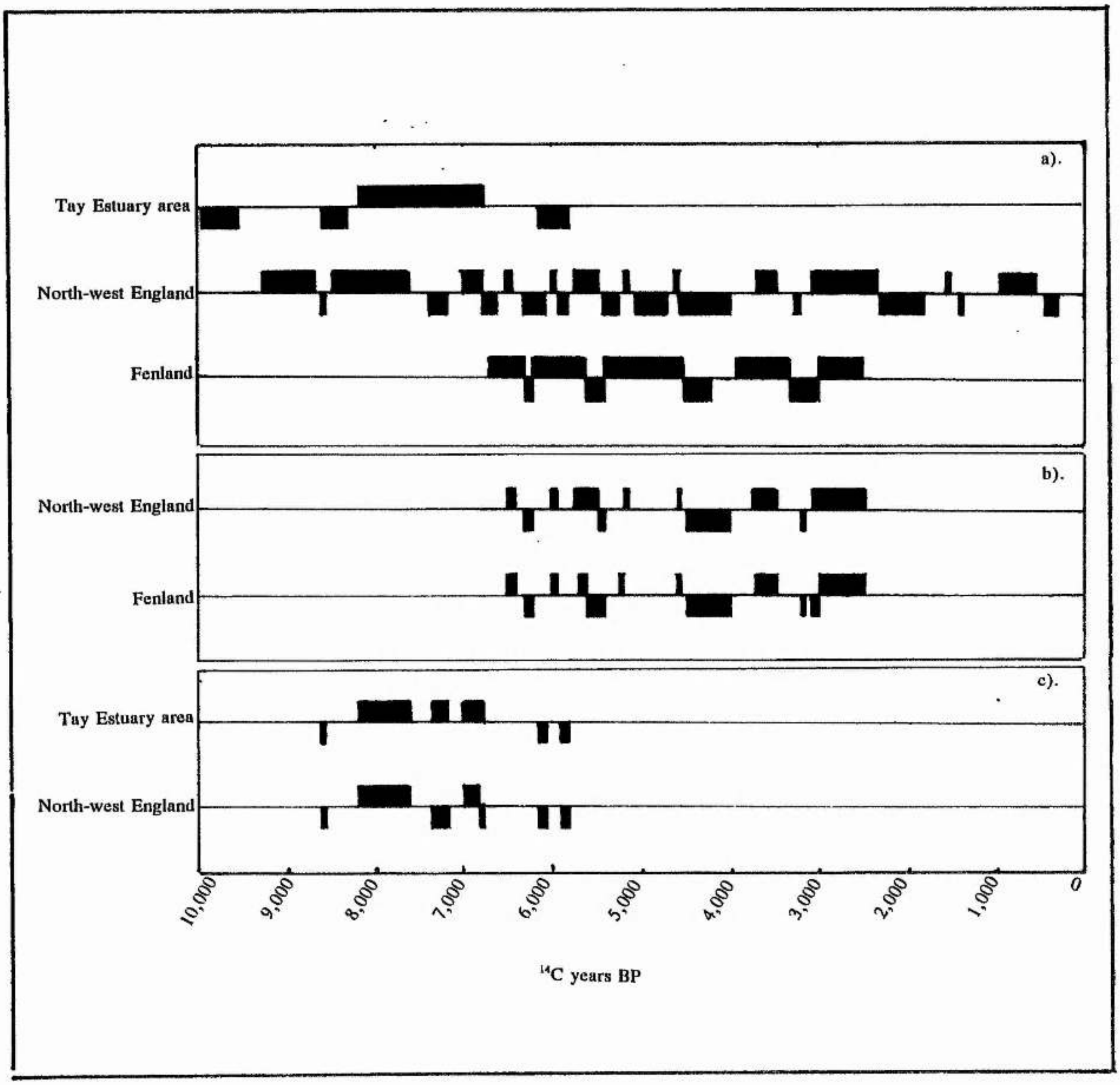
Chronologies of Tendencies of Sea-level Movement: An Example

a). Chronologies from the Tay Estuary area, North-west England and the Fenlands,

b). Partial Chronologies from North-west England and the Fenland for tendencies of more than local significance,

c). Partial Chronologies from the Tay Estuary area and North-west England for tendencies of more than local significance.

(Source: Shennan *et al.*, 1983)

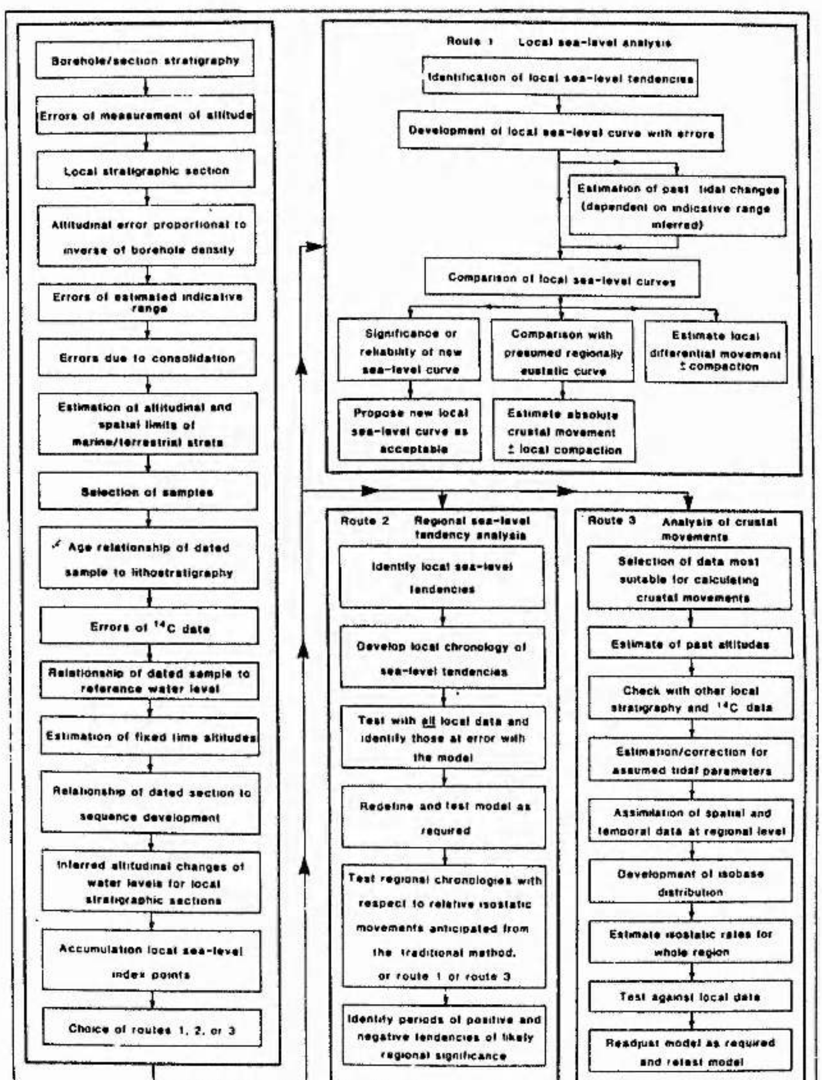


a).
Tay Estuary area
North-west England
Fenland
b).
North-west England
Fenland
c).
Tay Estuary area
North-west England
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
¹⁴C years BP

Figure 3.3:

A Model of Sea-level Research Methods with Routes to be Followed as a Necessary Prerequisite for Correlation

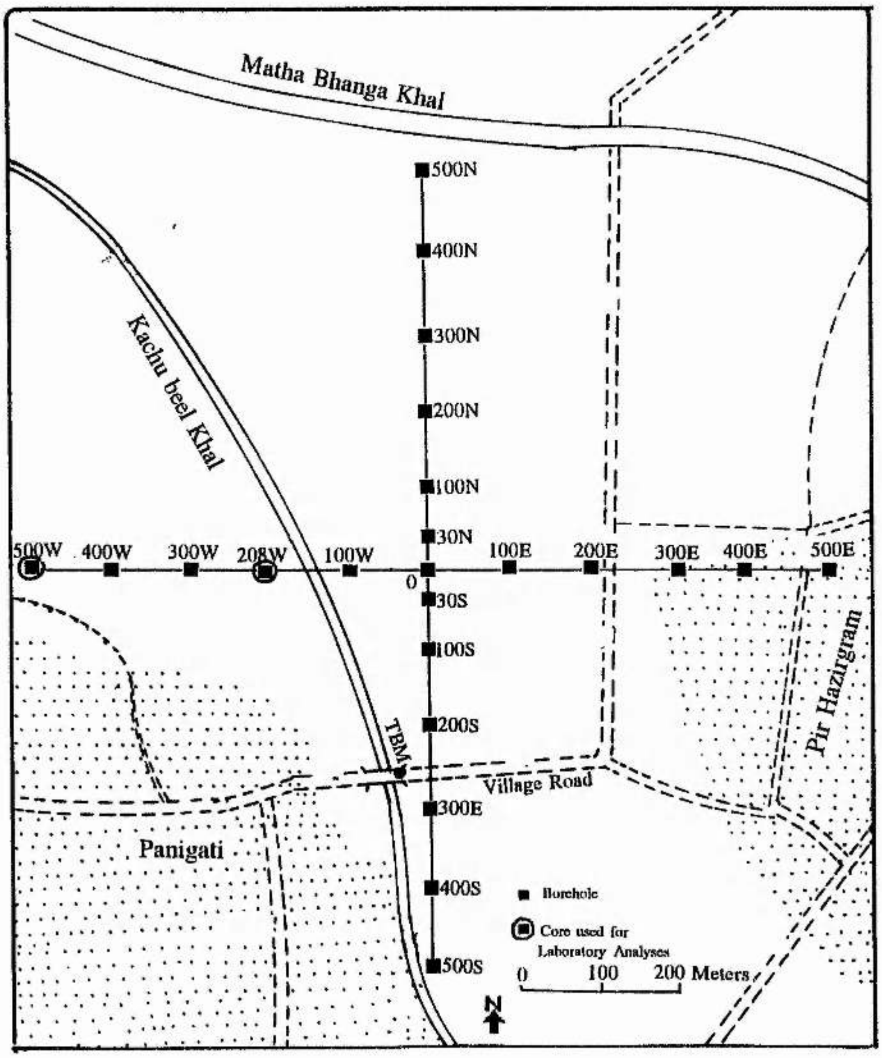
(Source: Shennan, 1983b)



Borehole/section stratigraphy
Errors of measurement of altitude
Local stratigraphic section
Altitudinal error proportional to inverse of borehole density
Errors of estimated indicative range
Errors due to consolidation
Estimation of altitudinal and spatial limits of marine/terrestrial strata
Selection of samples
Age relationship of dated sample to lithostratigraphy
Errors of 14C date
Relationship of dated sample to reference water level
Estimation of fixed time altitudes
Relationship of dated section to sequence development
Inferred altitudinal changes of water levels for local stratigraphic sections
Accumulation local sea-level index points
Choice of routes 1, 2, or 3
Route 1 Local sea-level analysis
Identification of local sea-level tendencies
Development of local sea-level curve with errors
Estimation of past tidal changes (dependent on indicative range inferred)
Comparison of local sea-level curves
Significance or reliability of new sea-level curve
Comparison with presumed regionally eustatic curve
Estimate local differential movement ± compaction
Propose new local sea-level curve as acceptable
Estimate absolute crustal movement ± local compaction
Route 2 Regional sea-level tendency analysis
Identify local sea-level tendencies
Develop local chronology of sea-level tendencies
Test with all local data and identify those at error with the model
Redefine and test model as required
Test regional chronologies with respect to relative isostatic movements anticipated from the traditional method, or route 1 or route 3
Identify periods of positive and negative tendencies of likely regional significance
Route 3 Analysis of crustal movements
Selection of data most suitable for calculating crustal movements
Estimate of past altitudes
Check with other local stratigraphy and 14C data
Estimation/correction for assumed tidal parameters
Assimilation of spatial and temporal data at regional level
Development of isobase distribution
Estimate isostatic rates for whole region
Test against local data
Readjust model as required and retest model

Figure 5.1:

Location of Boreholes at Panigati

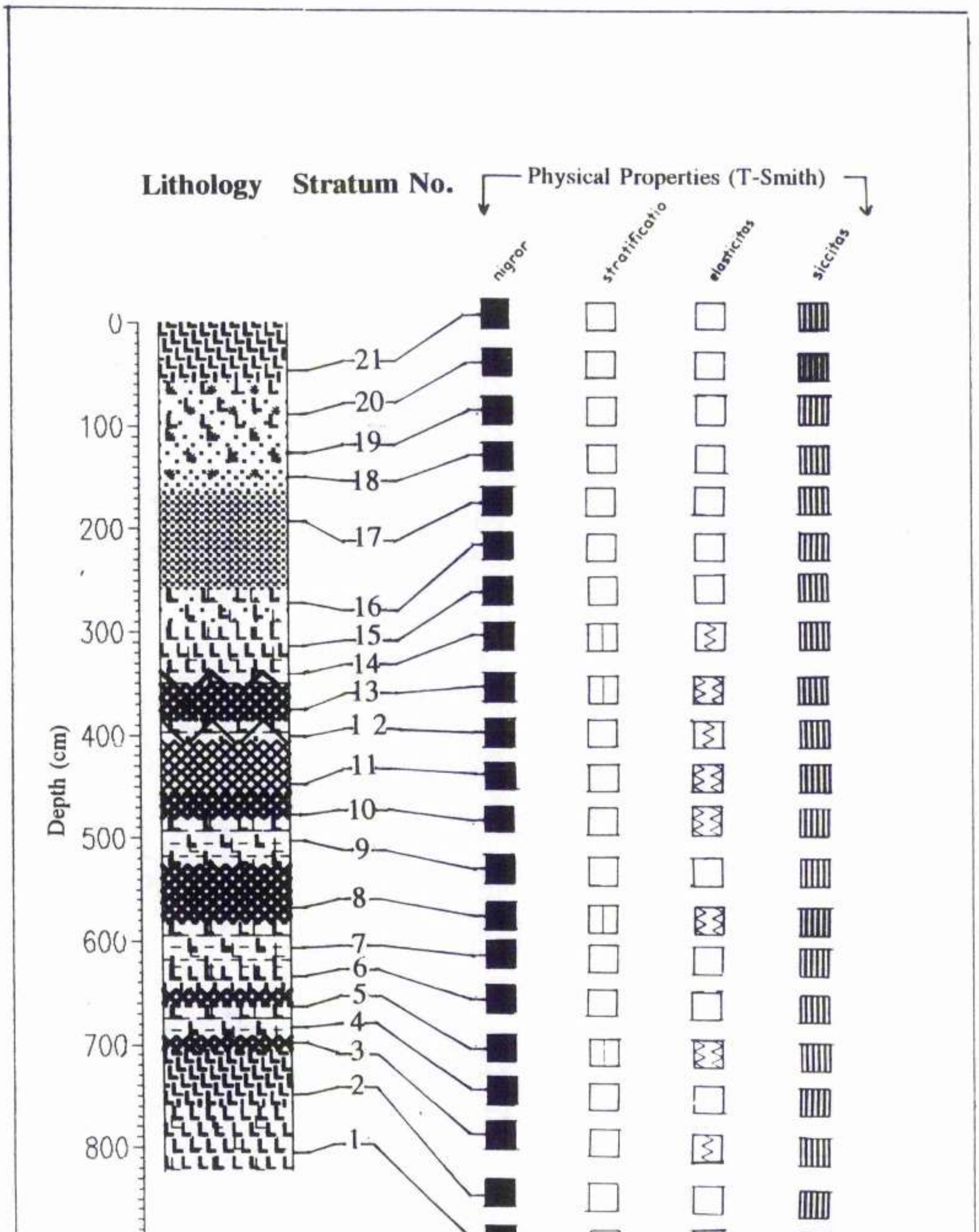


Matha Bhanga Khal
Kachu beel Khal
500N
400N
300N
200N
100N
30N
500W
400W
300W
208W
100W
0
100E
200E
300E
400E
500E
30S
100S
200S
TBM
Village Road
300E
400S
500S
Panigati
Pir Hazirgram
Borehole
Core used for Laboratory Analyses
0 100 200 Meters
N

Figure 5.2:

Lithostratigraphy of the Core P-208W

Symbols for the Lithology and Physical Properties Follows the Troels-Smith Scheme (1955)

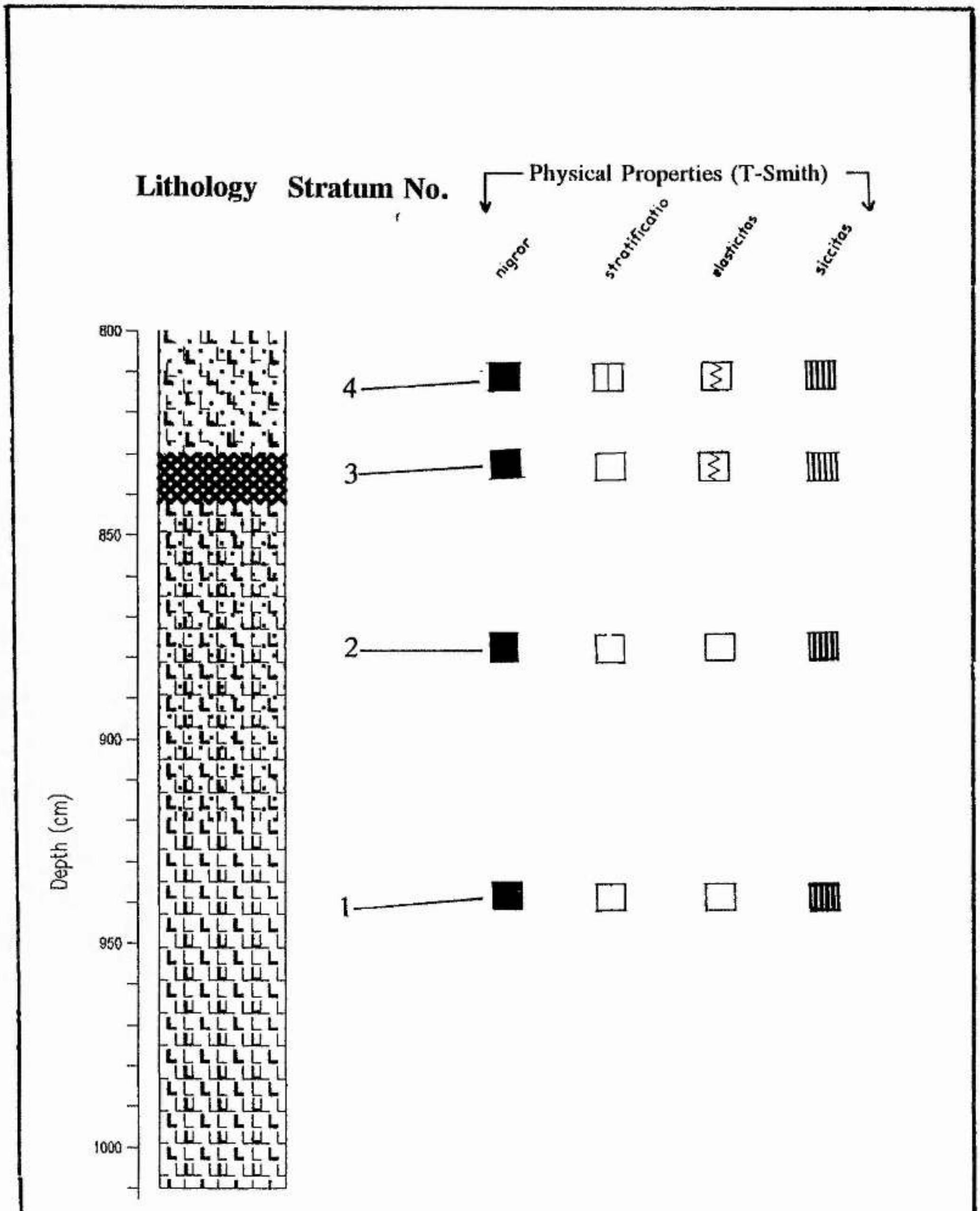


Lithology
Stratum No.
Physical Properties (T-Smith)
nigror
stratificatio
elasticitas
siccitas
Depth (cm)
0
100
200
300
400
500
600
700
800
900
21
20
19
18
17
16
15
14
13
1 2
11
10
9
8
7
6
5
4
3
2
1

Figure 5.3:

Lithostratigraphy of Part of the Core P-500W (800-1010 cm)

Symbols for the Lithology and Physical Properties Follows the Troels-Smith Scheme (1955)



Lithology
Stratum No.
Physical Properties (T-Smith)
nigror
stratificatio
elasticitas
siccitas
Depth (cm)
800
850
900
950
1000
4
3
2
1

Figure 5.4:

Borehole Records at Panigati

I. Lithostratigraphy

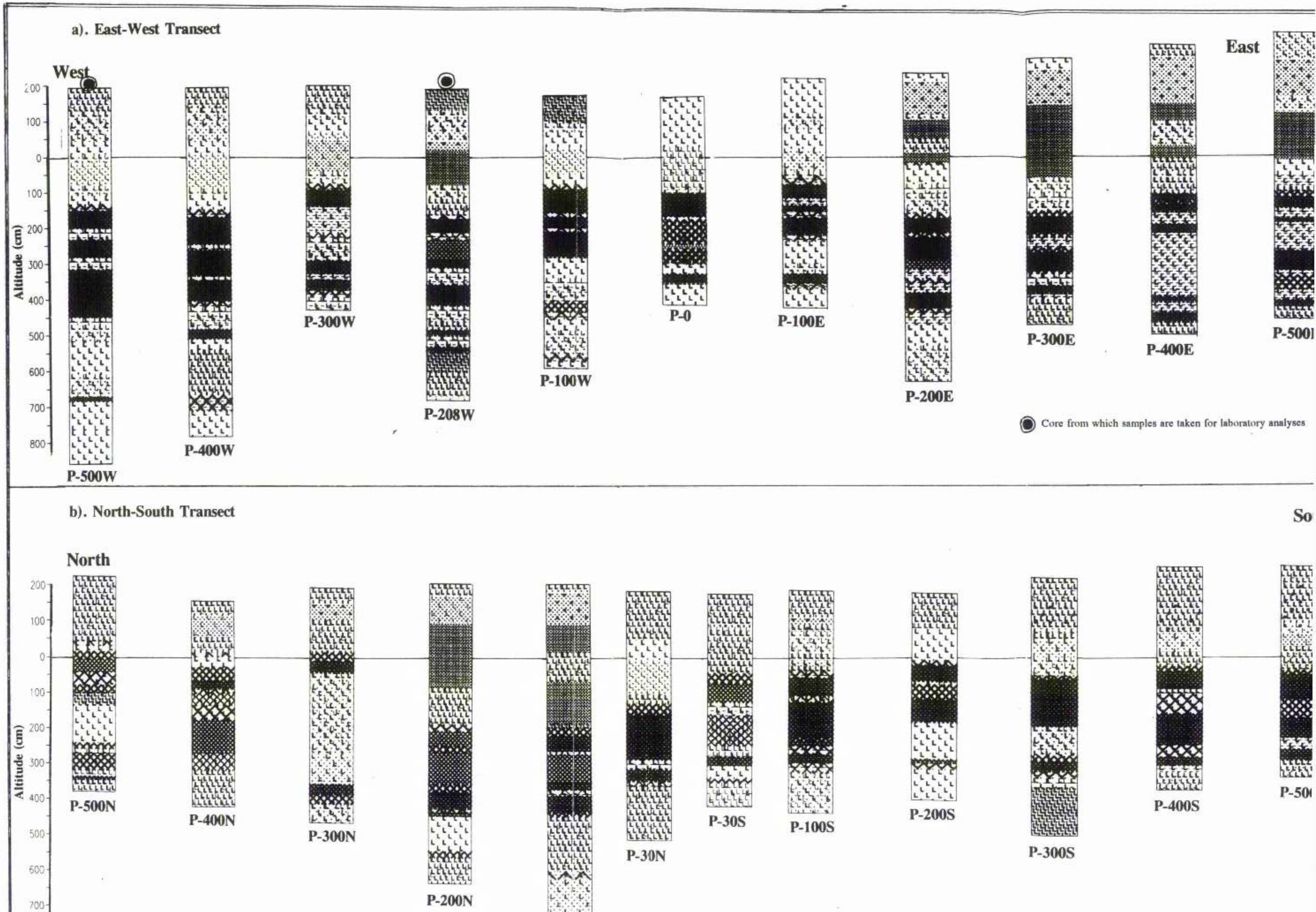
II. Tentative Correlation

a). East-West Transect Showing the Lithology of 11 Cores

b). North-South Transect Showing the Lithology of 12 Cores

(also see appendix 7)

I. Lithostratigraphy



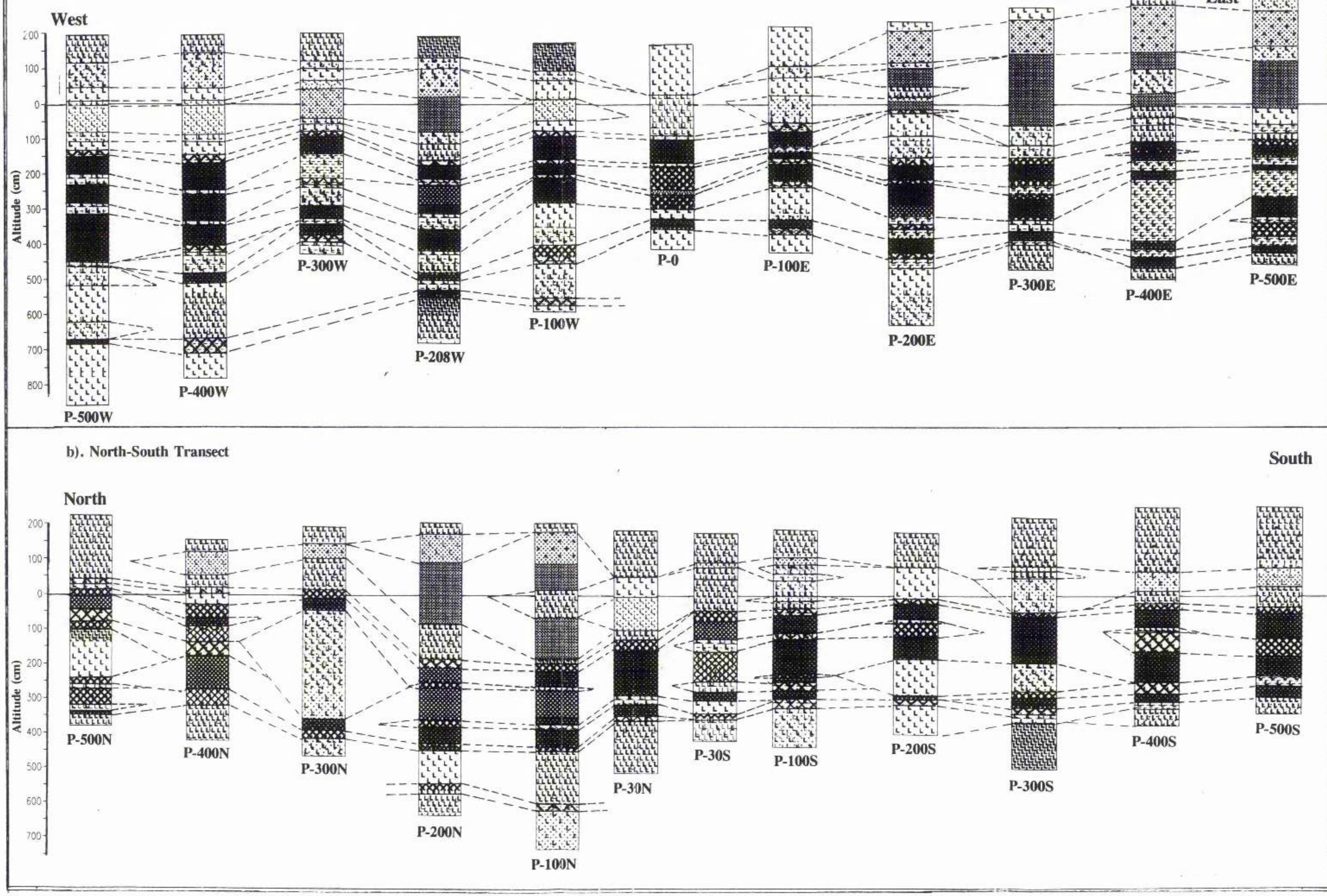

West
East
Altitude (cm)
P-500W
P-400W
P-300W
P-208W
P-100W
P-0
P-100E
P-200E
P-300E
P-400E
P-500E
b). North-South Transect
North
South
Altitude (cm)
P-500N
P-400N
P-300N
P-200N
P-100N
P-30N
P-30S
P-100S
P-200S
P-300S
P-400S
P-500S

Figure 5.5:

Organic Content of Sediments at Different Depths: Panigati.

Core P-208W (Left)

Core P-500W (Right)

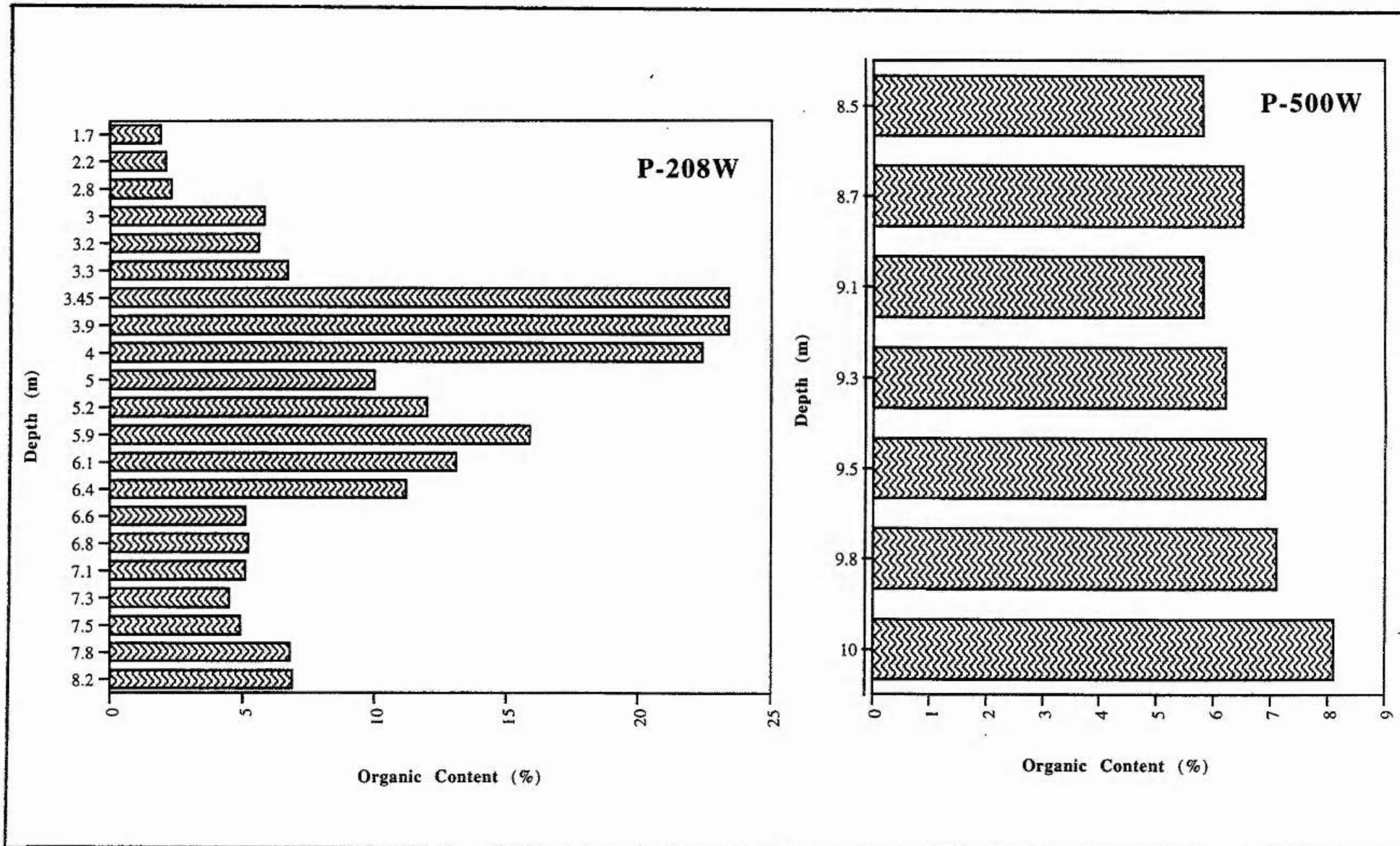
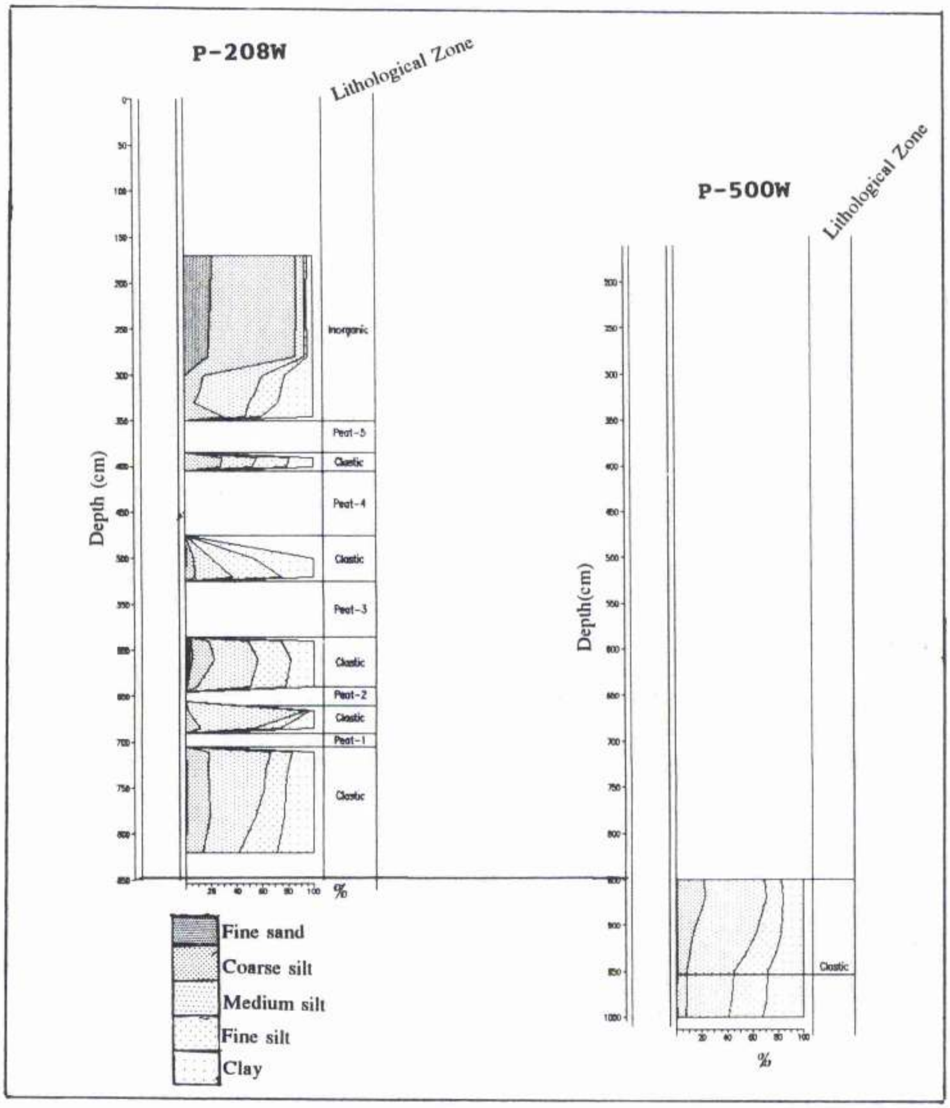

P-208W
Depth (m)
1.7
2.2
2.8
3
3.2
3.3
3.45
3.9
4
5
5.2
5.9
6.1
6.4
6.6
6.8
7.1
7.3
7.5
7.8
8.2
0
5
10
15
20
25
Organic Content (%)
P-500W
Depth (m)
8.5
8.7
9.1
9.3
9.5
9.8
10
0
1
2
3
4
5
6
7
8
9
Organic Content (%)

Figure 5.6:

Particle Size Distributions at Different Depths: Panigati

Core P-208W (Left)

Core P-500W (Right)



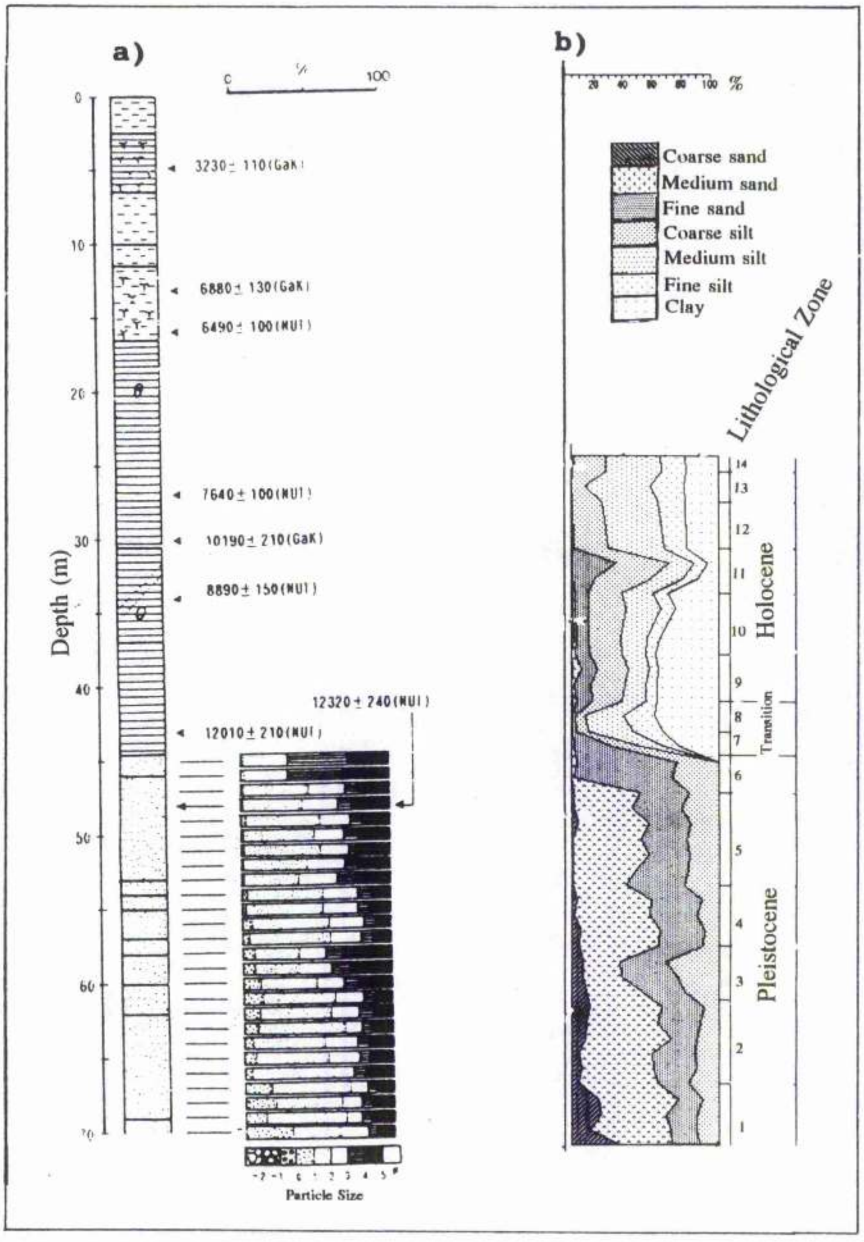
P-208W
Lithological Zone
Depth (cm)
Inorganic
Peat-5
Clastic
Peat-4
Clastic
Peat-3
Clastic
Peat-2
Clastic
Peat-1
Clastic
%
Fine sand
Coarse silt
Medium silt
Fine silt
Clay
P-500W
Lithological Zone
Depth(cm)
Clastic
%

Figure 5.7:

Particle Size Distributions at Different depths for the Core Collected by Umitsu (in 1987): Daulatpur

a). Results from Umitsu (1987)

b). Results from the present author



a)
0
%
100
3230± 110(GaK)
6880± 130(GaK)
6490± 100(NUI)
7640± 100(NUI)
10190± 210(GaK)
8890± 150(NUI)
12320± 240(NUI)
12010± 210(NUI)
Depth (m)
0
10
20
30
40
50
60
70
-2 -1 0 1 2 3 4 5
Particle Size
b)
20 40 60 80 100 %
Coarse sand
Medium sand
Fine sand
Coarse silt
Medium silt
Fine silt
Clay
Lithological Zone
Holocene
Transition
Pleistocene
14
13
12
11
10
9
8
7
6
5
4
3
2
1

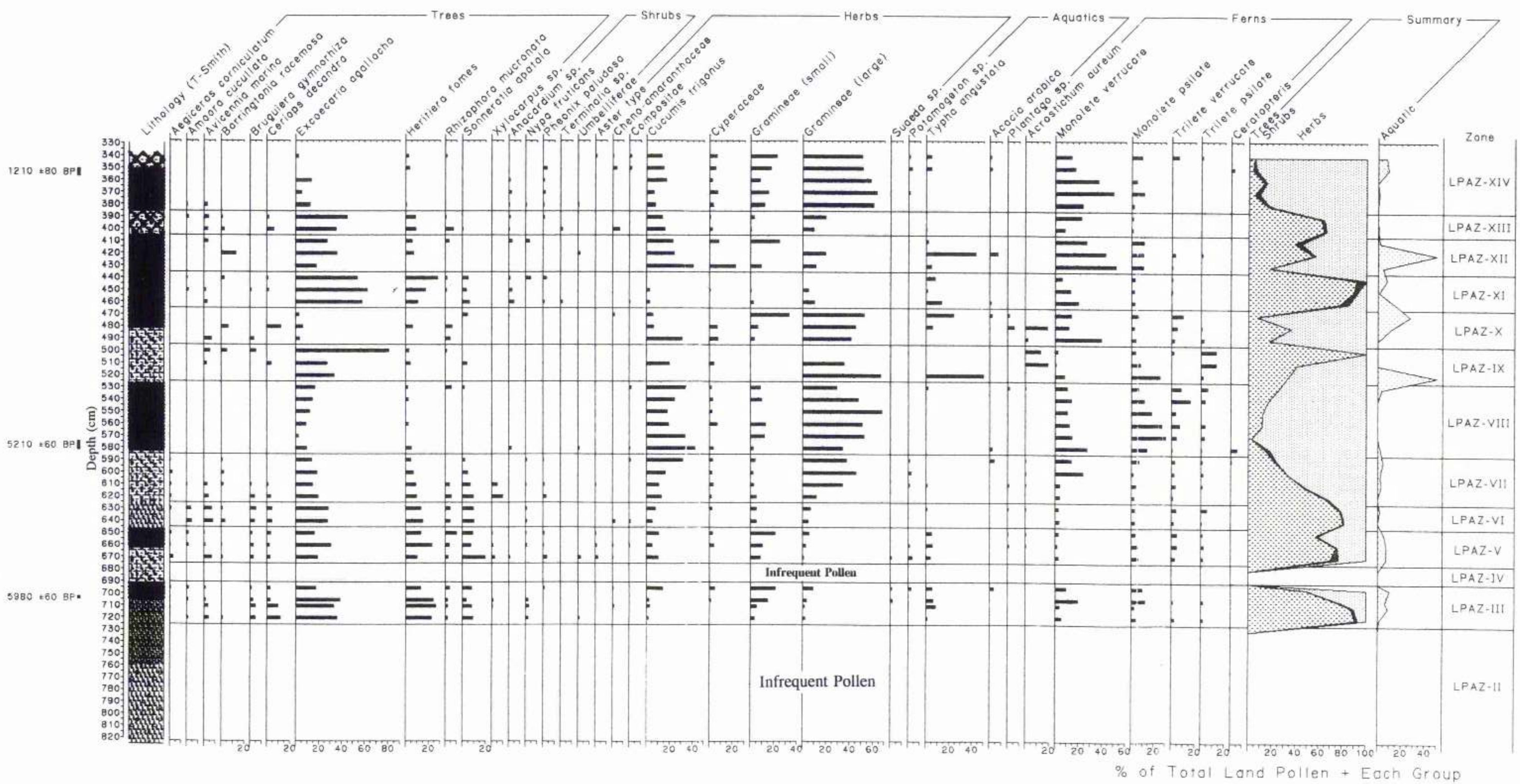
Figure 5.8:

Pollen Diagram at Panigati: P-208W

Tree, shrub or herb pollen are expressed as percentages of total land pollen, aquatic pollen as percentage of total land pollen plus total aquatic, and fern spores as percentage of total land pollen plus total fern spores.

LPAZ= Local Pollen Assemblage Zone

For Lithological Symbol see Appendix 2



Trees
Shrubs
Herbs
Aquatics
Ferns
Summary
Lithology (T-Smith)
Aegiceras corniculatum
Amoora cucullata
Avicennia marina
Barringtonia racemosa
Bruguiera gymnorhiza
Ceriops decandra
Excoecaria agallocha
Heritiera fomes
Rhizophora mucronata
Sonneratia apatala
Xylocarpus sp.
Anacardium sp.
Nypa fruticans
Pheonix paludosa
Terminalia sp.
Umbelliferae
Aster type
Cheno-amaranthaceae
Compositae
Cucumis trigonus
Cyperaceae
Gramineae (small)
Gramineae (large)
Suaeda sp.
Potamogeton sp.
Typha angustata
Acacia arabica
Plantago sp.
Acrostichum aureum
Monolete verrucate
Monolete psilate
Trilete verrucate
Trilete psilate
Ceratopteris
Trees
Shrubs
Herbs
Aquatic
Zone
Depth (cm)
1210 ±80 BP
5210 ±60 BP
5980 ±60 BP
Infrequent Pollen
Infrequent Pollen
LPAZ-XIV
LPAZ-XIII
LPAZ-XII
LPAZ-XI
LPAZ-X
LPAZ-IX
LPAZ-VIII
LPAZ-VII
LPAZ-VI
LPAZ-V
LPAZ-IV
LPAZ-III
LPAZ-II
% of Total Land Pollen + Each Group

Figure 5.9:

Pollen Diagram at Panigati: P-500W

Tree, shrub or herb pollen are expressed as percentages of total land pollen, aquatic pollen as percentage of total land pollen plus total aquatic, and fern spores as percentage of total land pollen plus total fern spores.

LPAZ= Local Pollen Assemblage Zone

For Lithological Symbol see Appendix 2

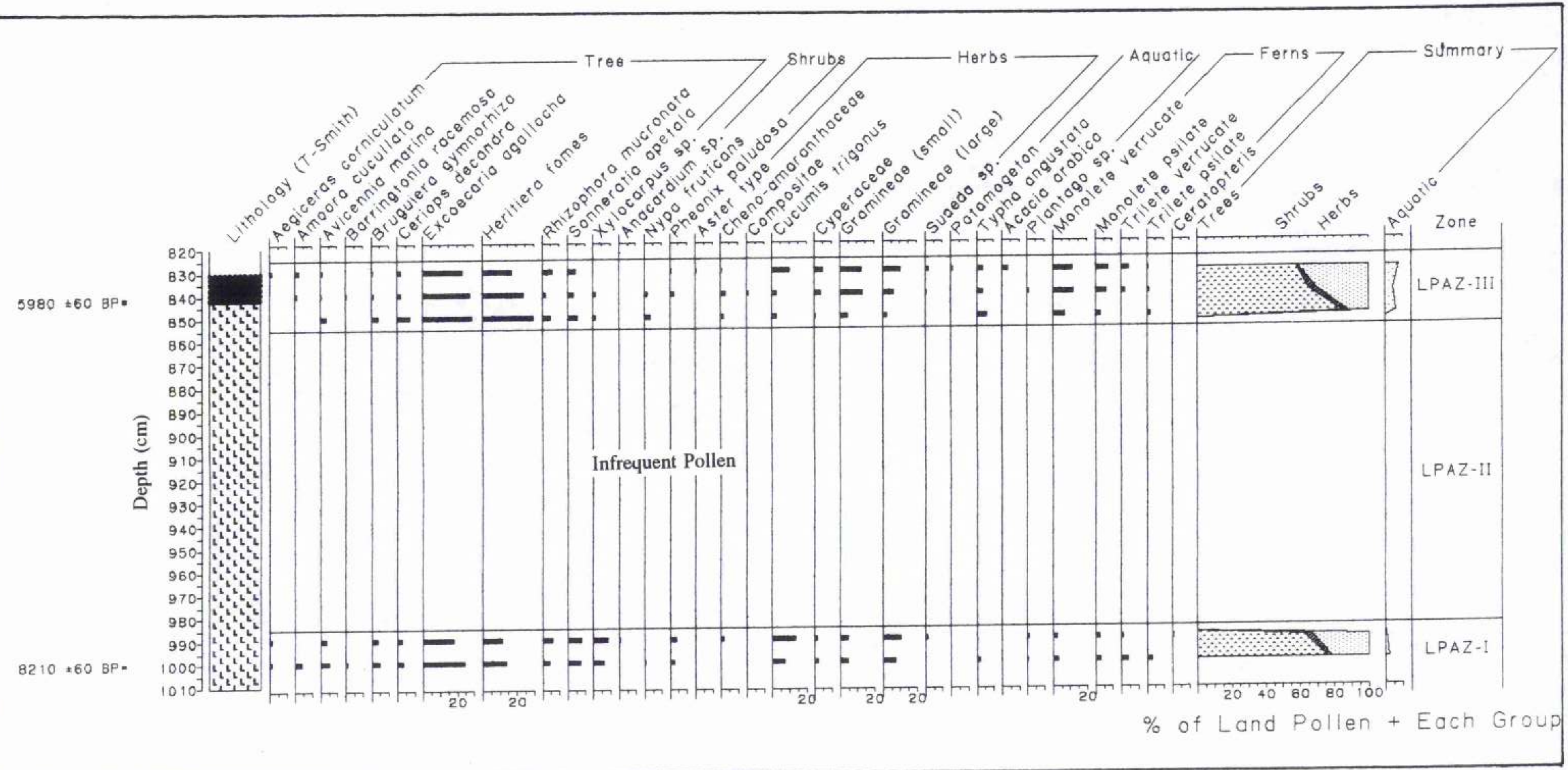
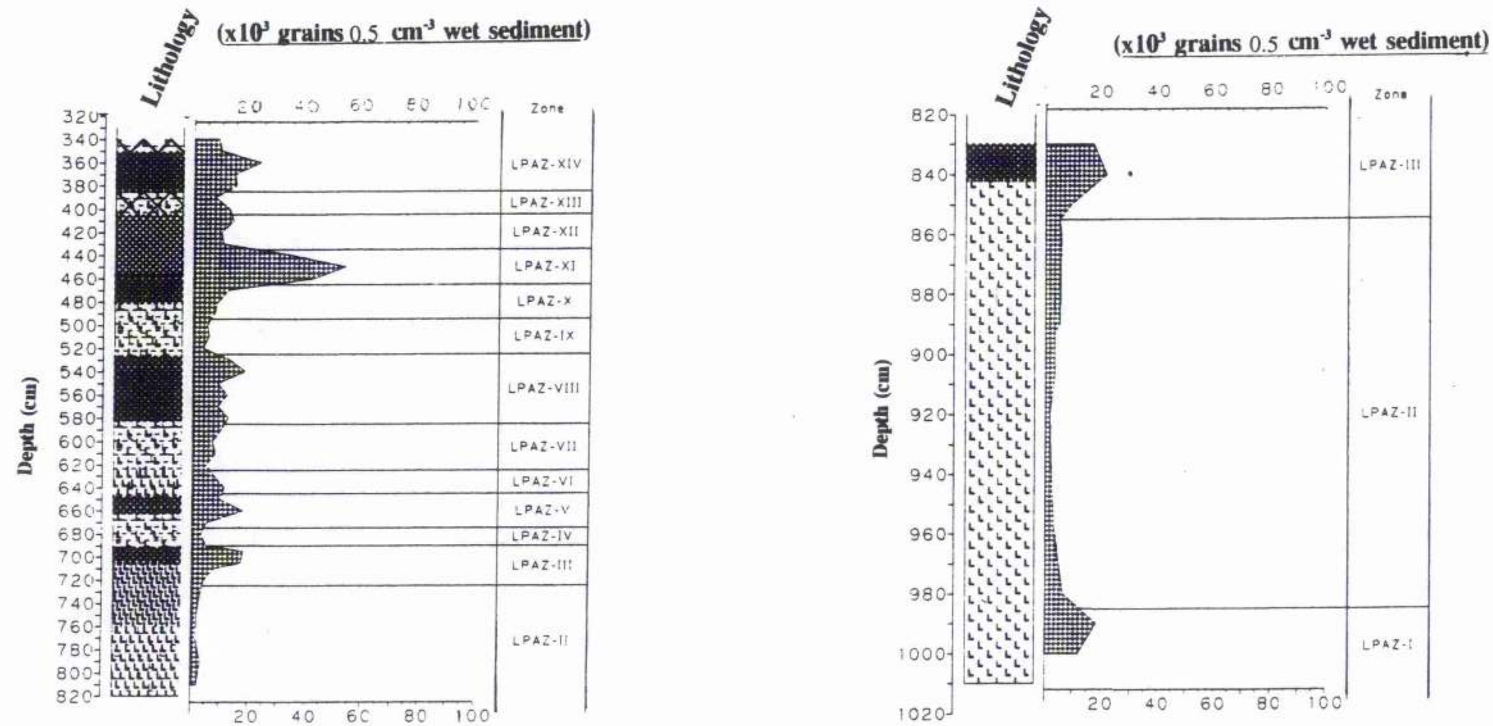

Tree
Shrubs
Herbs
Aquatic
Ferns
Summary
Lithology (T-Smith)
Aegiceras corniculatum
Amoora cucullata
Avicennia marina
Barringtonia racemosa
Bruguiera gymnorhiza
Ceriops decandra
Excoecaria agallocha
Heritiera fomes
Rhizophora mucronata
Sonneratia apetala
Xylocarpus sp.
Anacardium sp.
Nypa fruticans
Pheonix paludosa
Aster type
Cheno-amaranthaceae
Compositae
Cucumis trigonus
Cyperaceae
Gramineae (small)
Gramineae (large)
Suaeda sp.
Potamogeton
Typha angustata
Acacia arabica
Plantago sp.
Monolete verrucate
Monolete psilate
Trilete verrucate
Trilete psilate
Ceratopteris
Trees
Shrubs
Herbs
Aquatic
Zone
5980 ±60 BP
8210 ±60 BP
Depth (cm)
820
830
840
850
860
870
880
890
900
910
920
930
940
950
960
970
980
990
1000
1010
Infrequent Pollen
LPAZ-III
LPAZ-II
LPAZ-I
20
20 40 60 80 100
% of Land Pollen + Each Group

Figure 5.10:

Land Pollen Concentration at Different Depths: Panigati

a). Core P-208W

b). Core P-500W

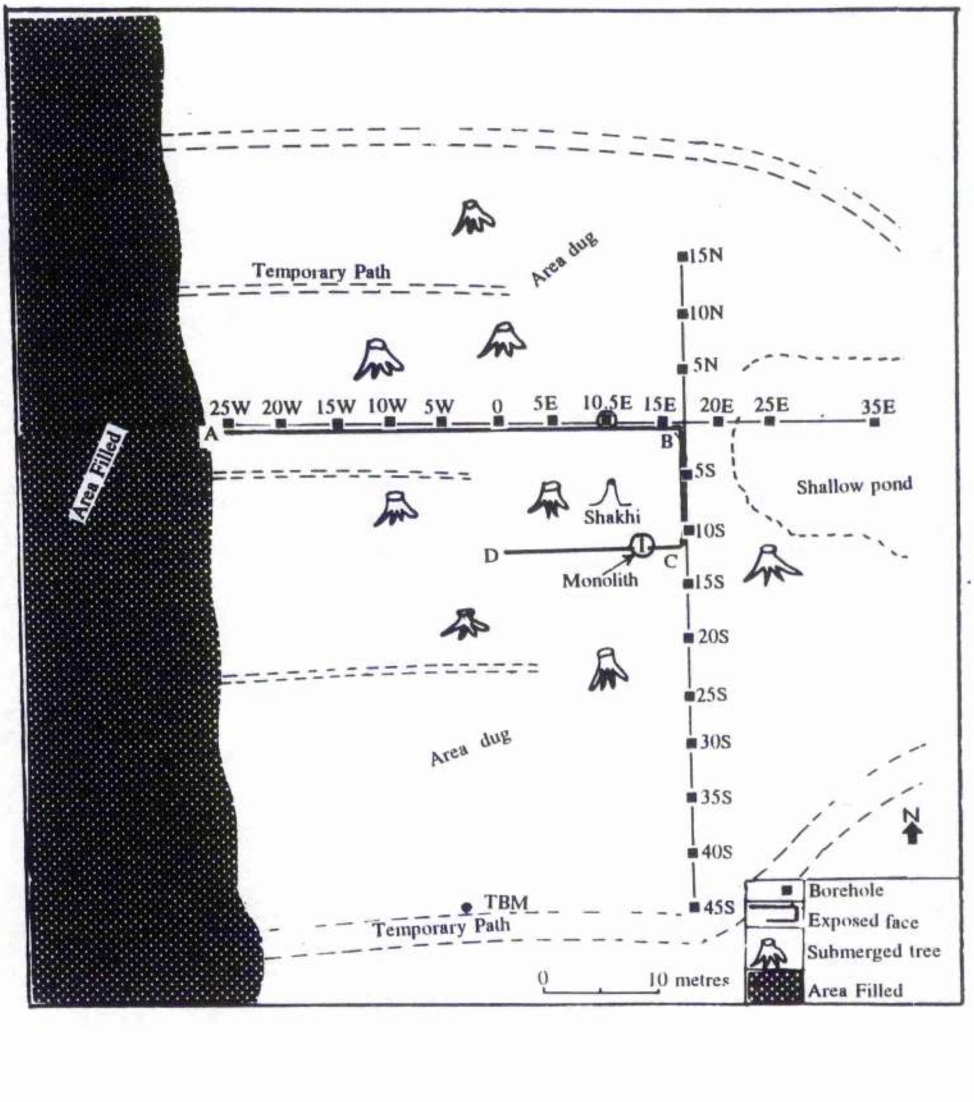


a). P-208W

b). P-500W

Figure 6.1:

Location of Boreholes, Monolith and Exposed Faces at Matuail



Area Filled
Temporary Path
Area dug
15N
10N
5N
25W
20W
15W
10W
5W
0
5E
10.5E
15E
20E
25E
35E
A
B
5S
Shakhi
Shallow pond
10S
D
C
Monolith
15S
20S
25S
30S
35S
40S
45S
Area dug
N
TBM
Temporary Path
0
10 metres
Borehole
Exposed face
Submerged tree
Area Filled

Figure 6.2:

Lithostratigraphy of Core M-10.5E: Matuail

Symbols for the Lithology and Physical Properties Follows the Troels-Smith Scheme (1955)

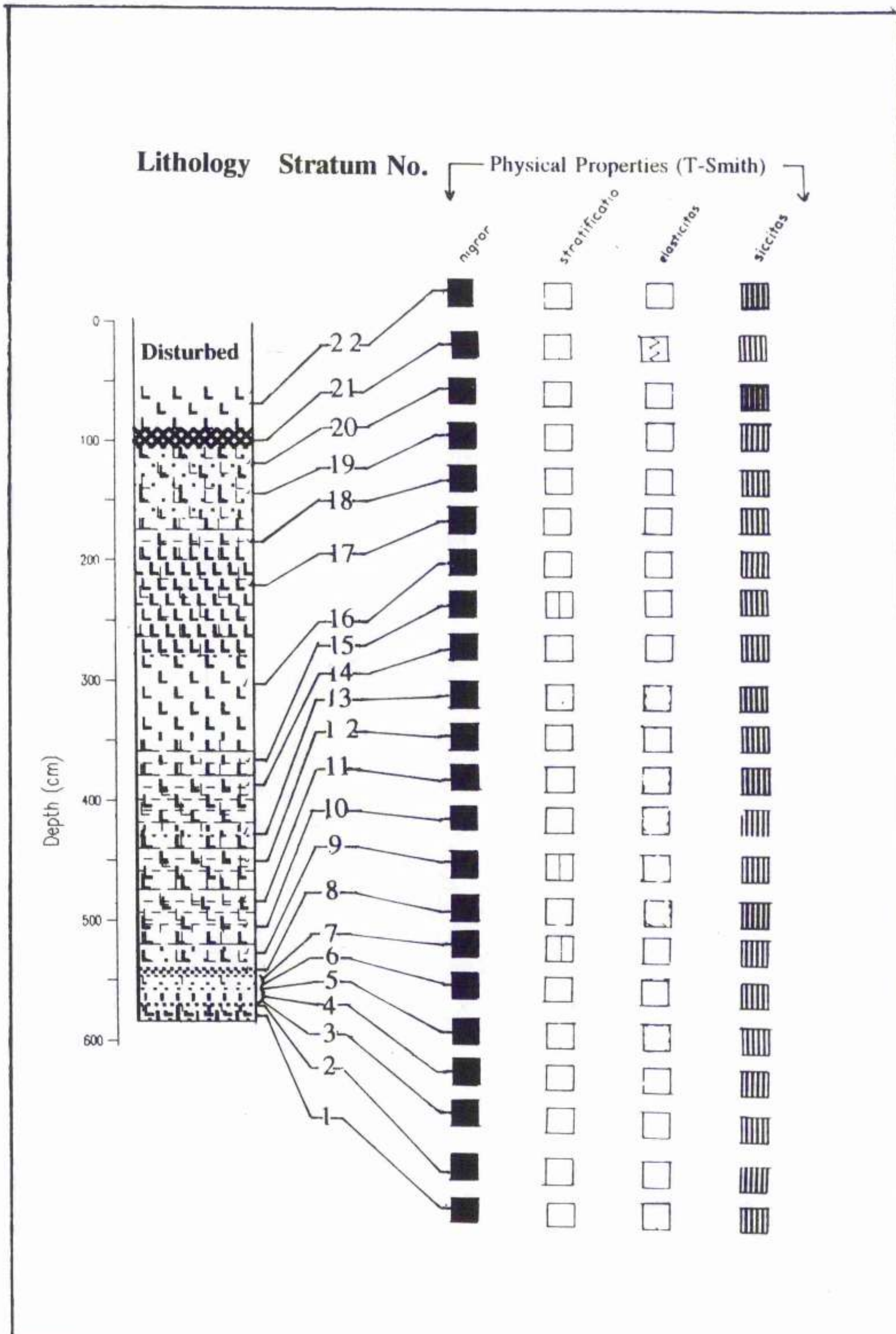
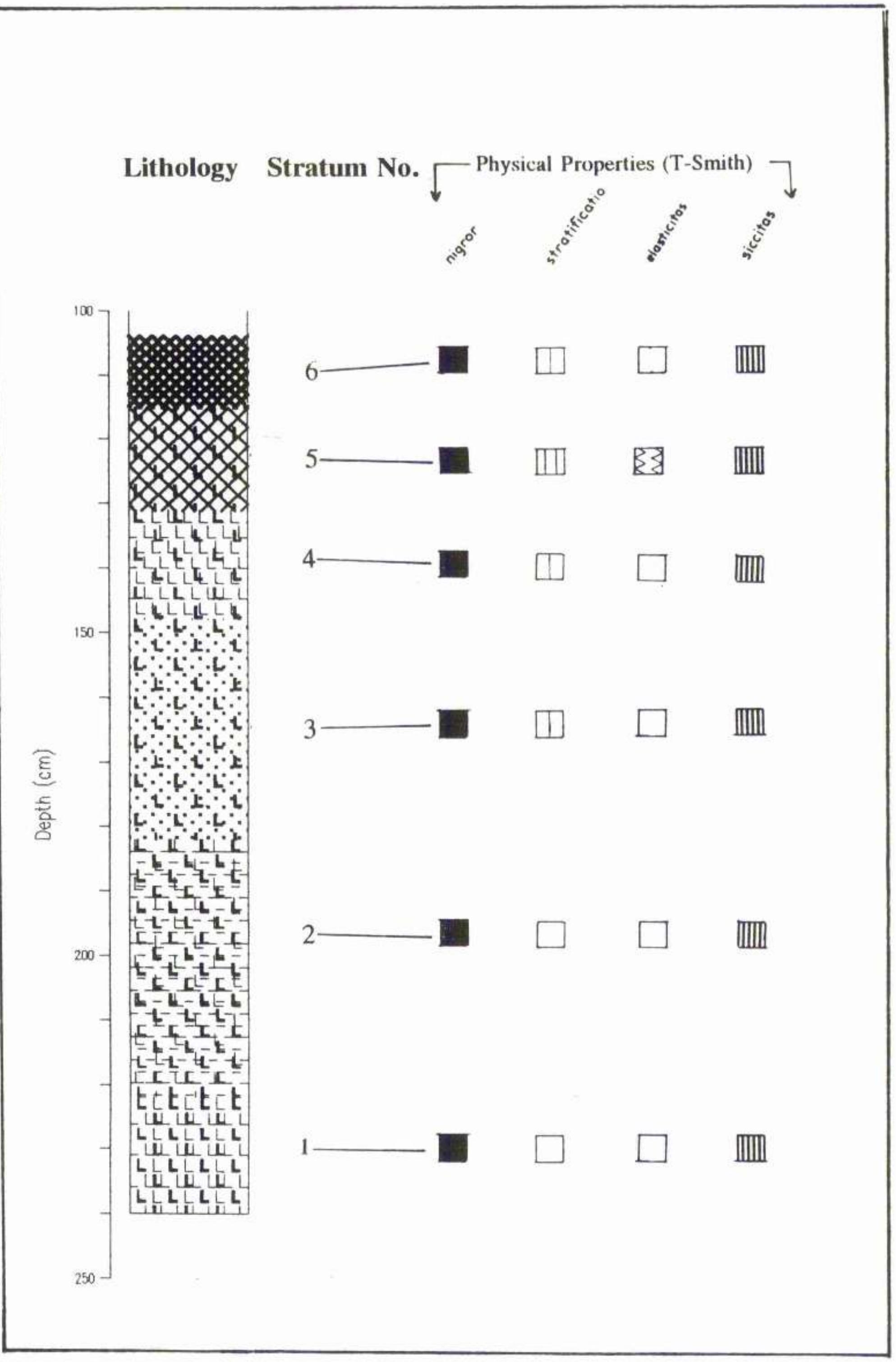

Lithology
Stratum No.
Physical Properties (T-Smith)
nigror
stratificatio
elasticitas
siccitas
Disturbed
Depth (cm)
0
100
200
300
400
500
600
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1

Figure 6.3:

Lithostratigraphy of the Monolith: Matuail

Symbols for the Lithology and Physical Properties Follows the Troels-Smith Scheme (1955)



Lithology
Stratum No.
Physical Properties (T-Smith)
nigror
stratificatio
elasticitas
siccitas
Depth (cm)
100
150
200
250
6
5
4
3
2
1

Figure 6.4:

Borehole Records at Matuail

I. Lithostratigraphy

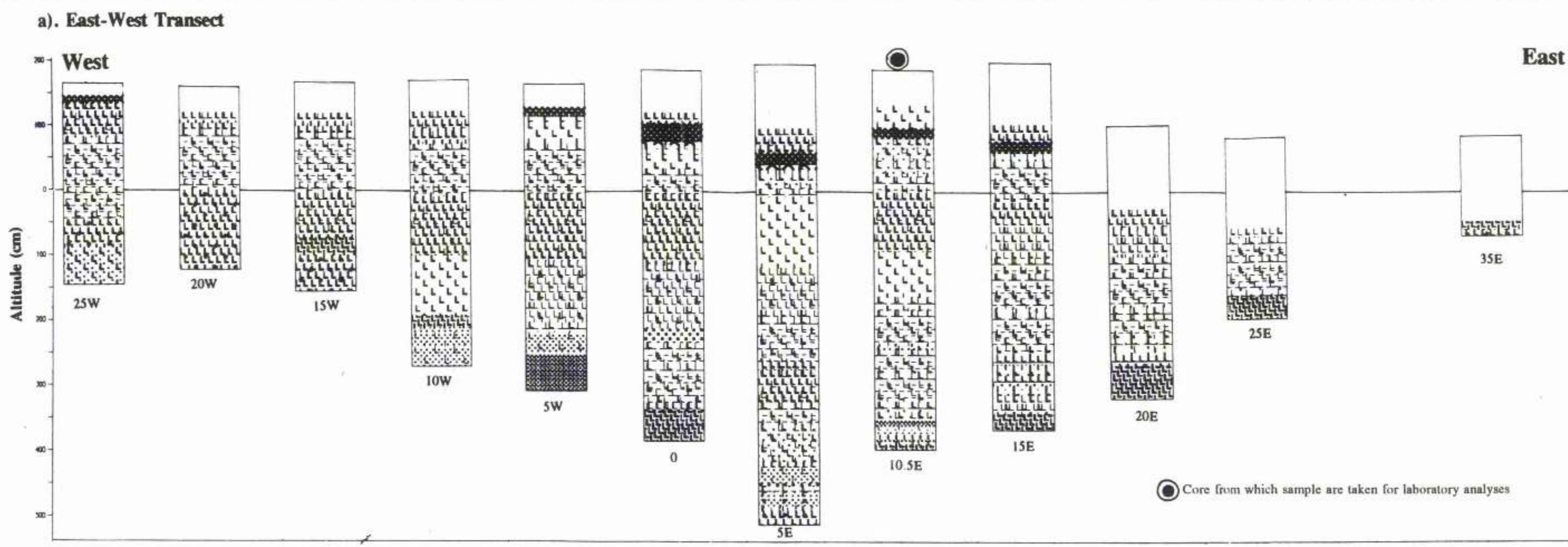
II. Tentative Correlation

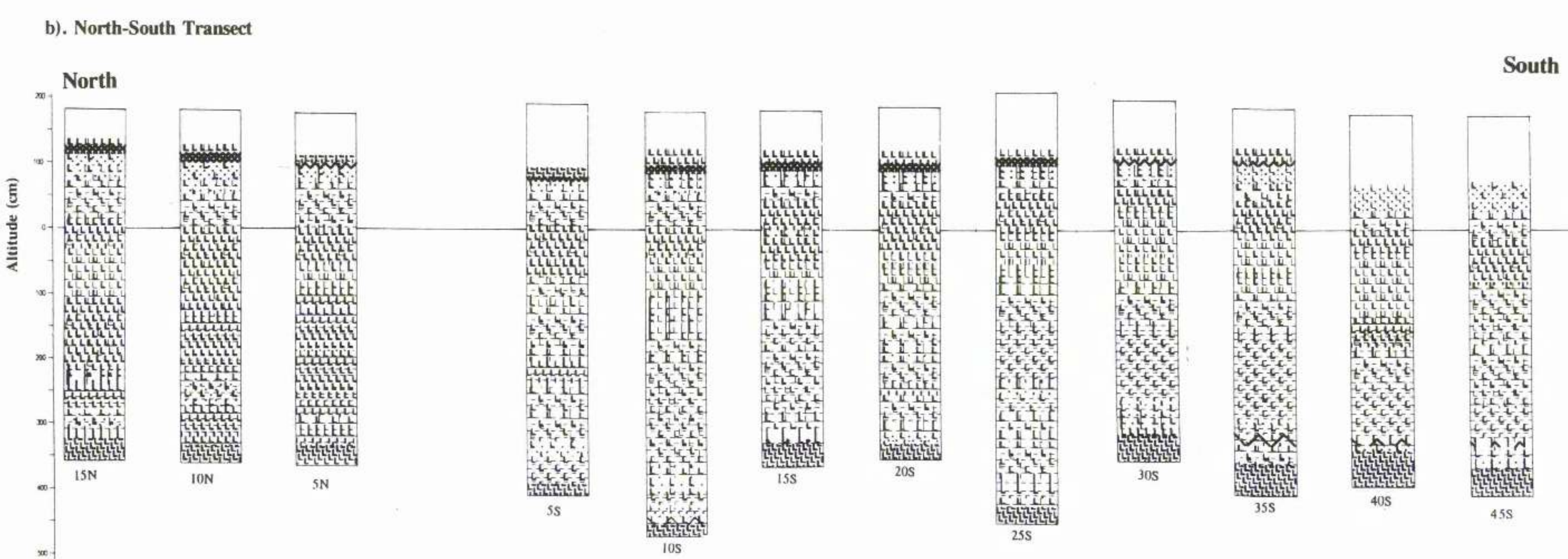
a). East-West Transect Showing the Lithology of 12 Cores

b). North-South Transect Showing the Lithology of 12 Cores

(also see Appendix 8)

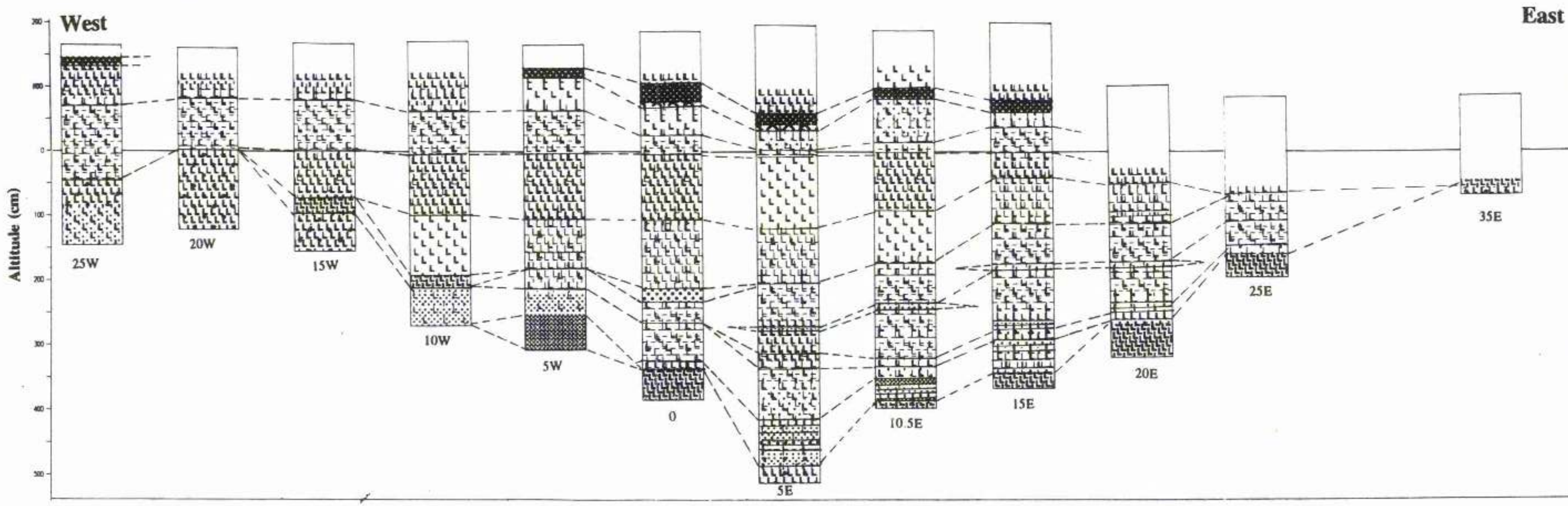
I. Lithostratigraphy





II. Tentative Correlation (Dashed lines)

a). East-West Transect



b). North-South Transect

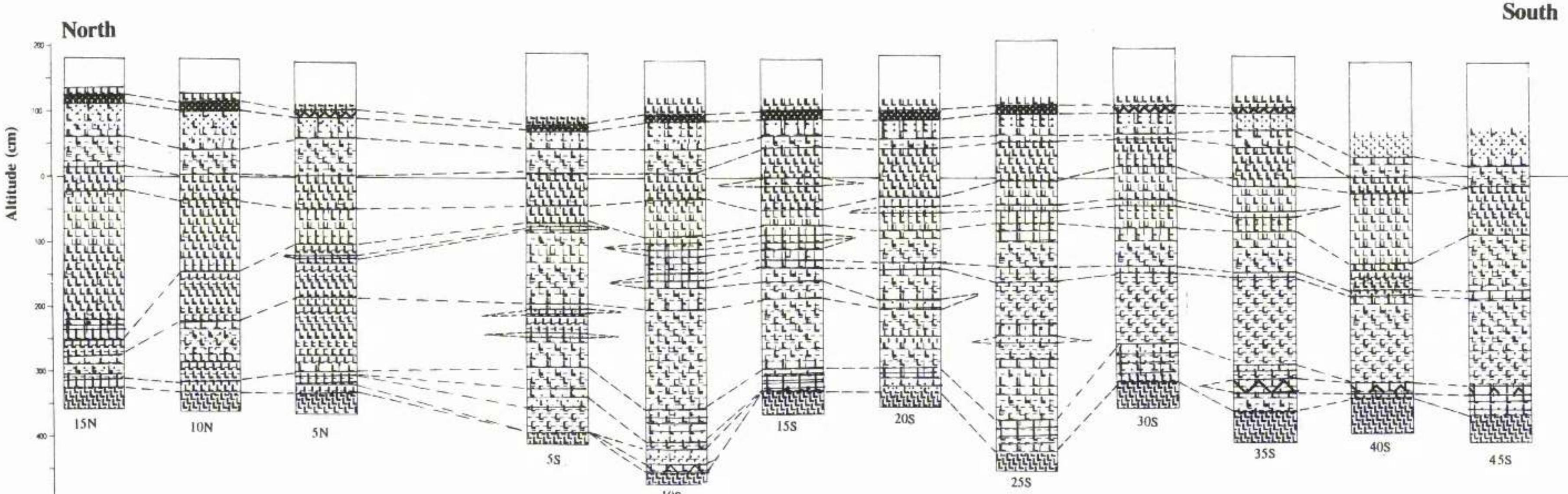


Figure 6.5:

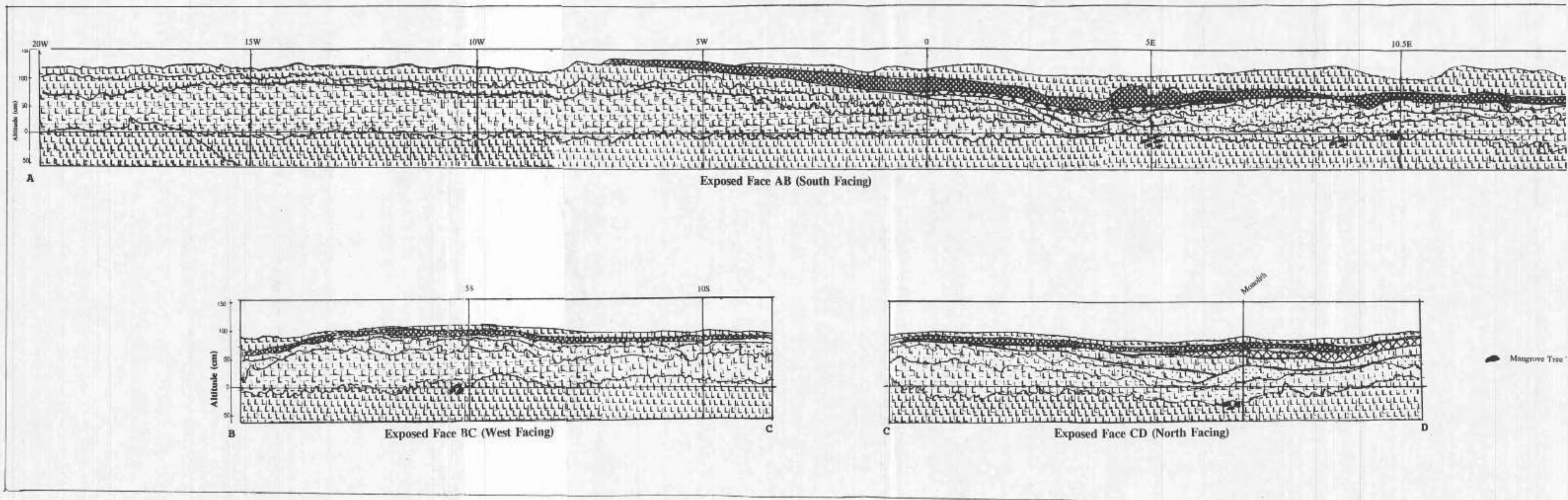
Lithostratigraphy of Exposed Faces at Matuail

Top: Exposed Face AB (South Facing)

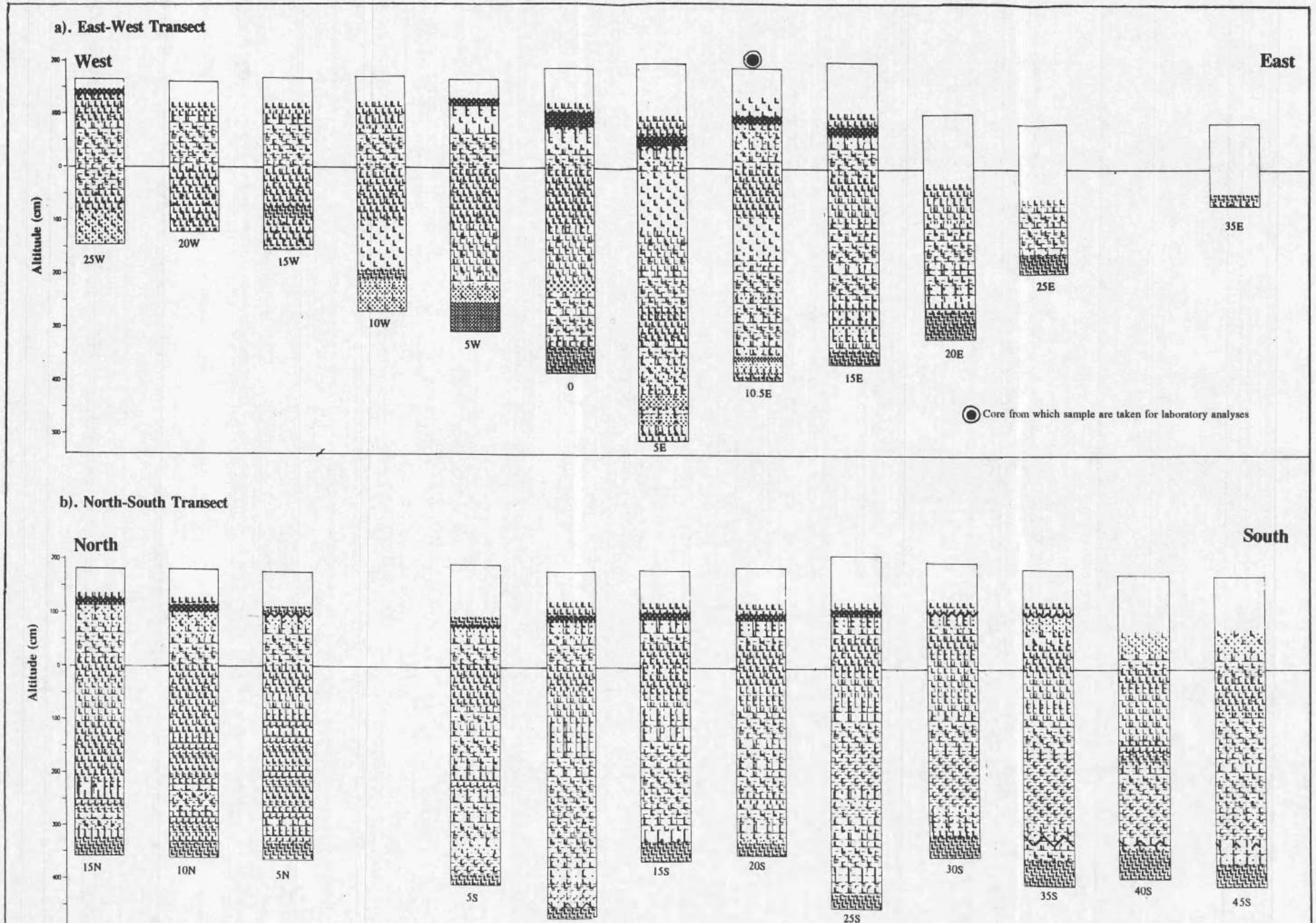
Bottom (Left): Exposed Face BC (West Facing)

Bottom (Right) Exposed Face CD (North Facing)

Symbols for the lithology Follows the Troels-Smith Scheme (1955)


20W
15W
10W
5W
0
5E
10.5E
Altitude (cm)
A
Exposed Face AB (South Facing)
5S
10S
Monolith
B
C
Exposed Face BC (West Facing)
C
D
Exposed Face CD (North Facing)
Mangrove Tree

I. Lithostratigraphy



II. Tentative Correlation (Dashed lines)

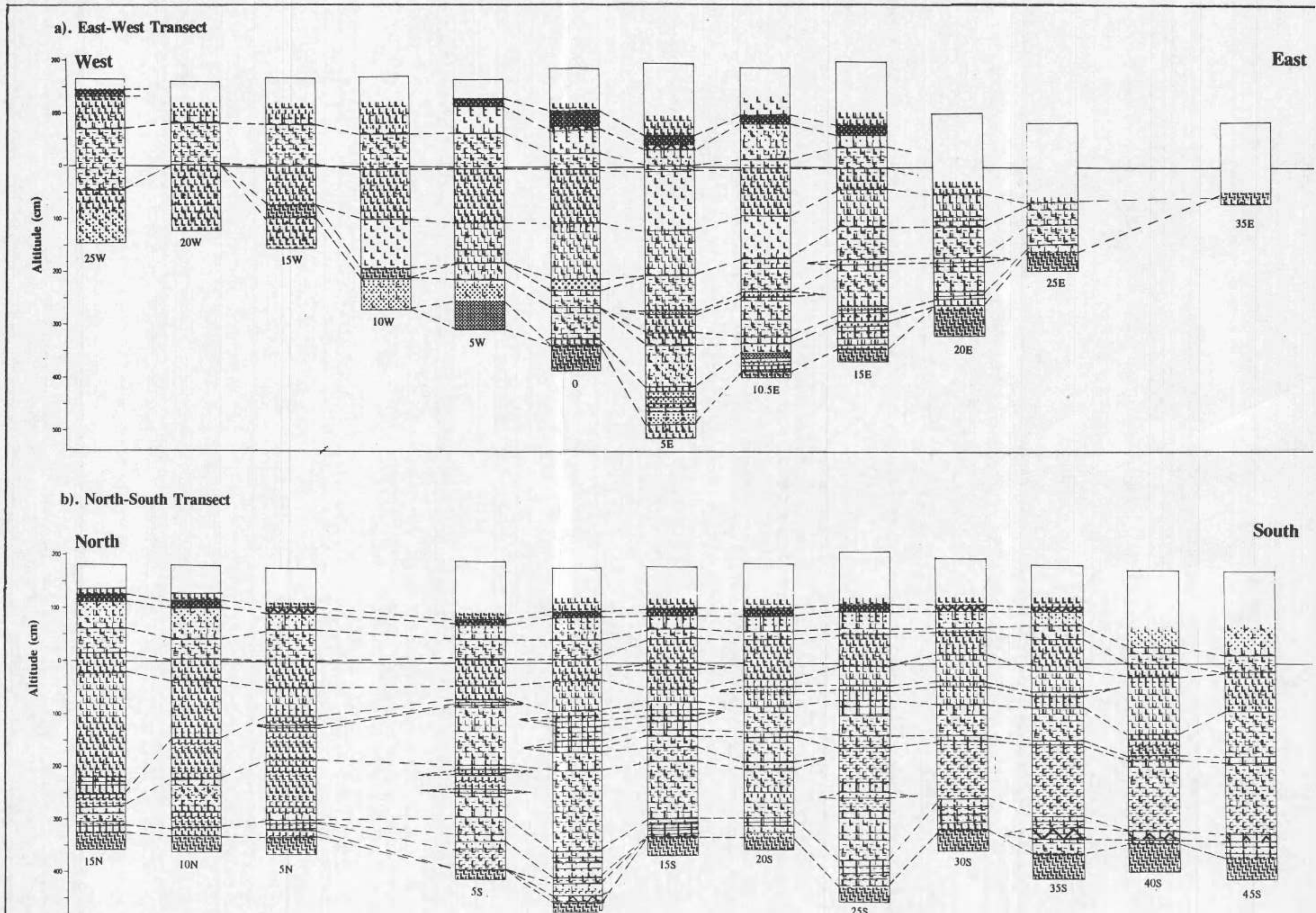
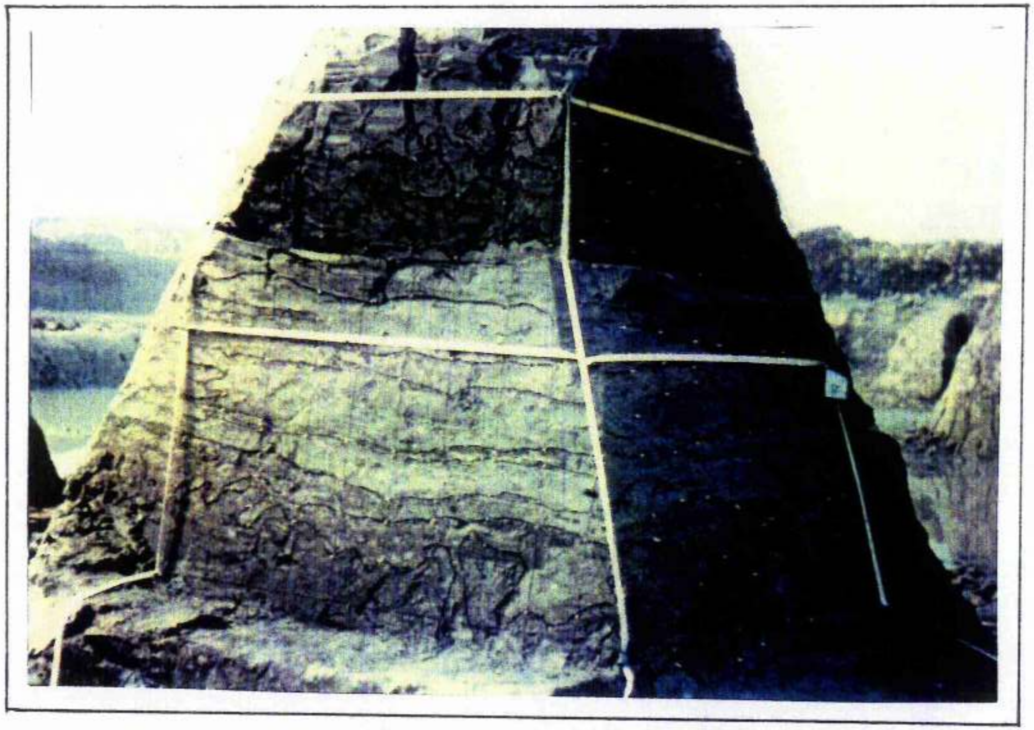


Figure 6.6:

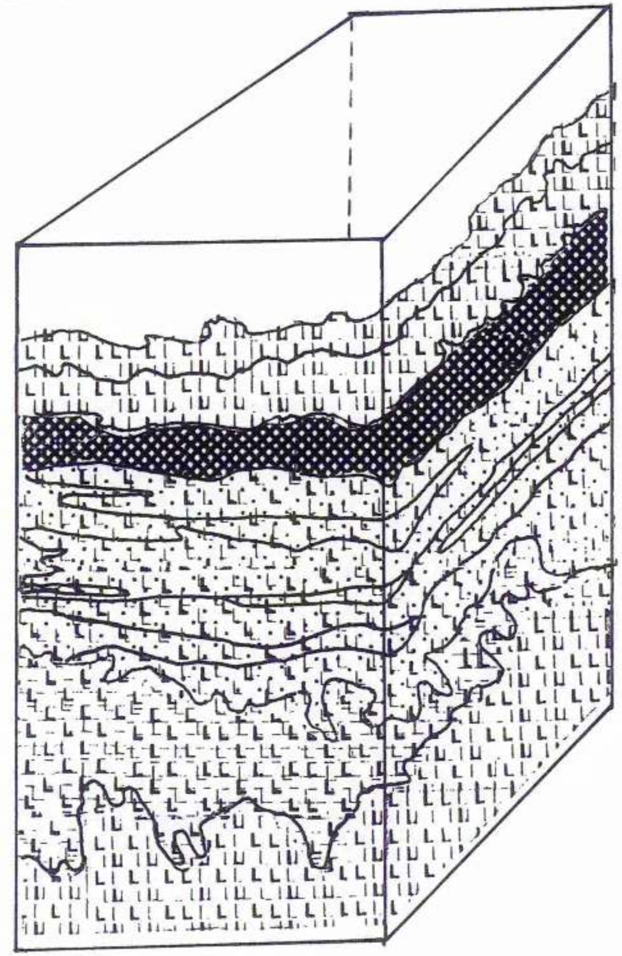
Lithostratigraphy of the *Shakhi*

Left: Three Dimensional View of the *Shakhi* (Photograph) Showing Different Lithological Boundaries

Right: Description of Lithology of the *Shakhi* Follows the Troels-Smith Scheme (1955)



Lithology of the *Shakhi*



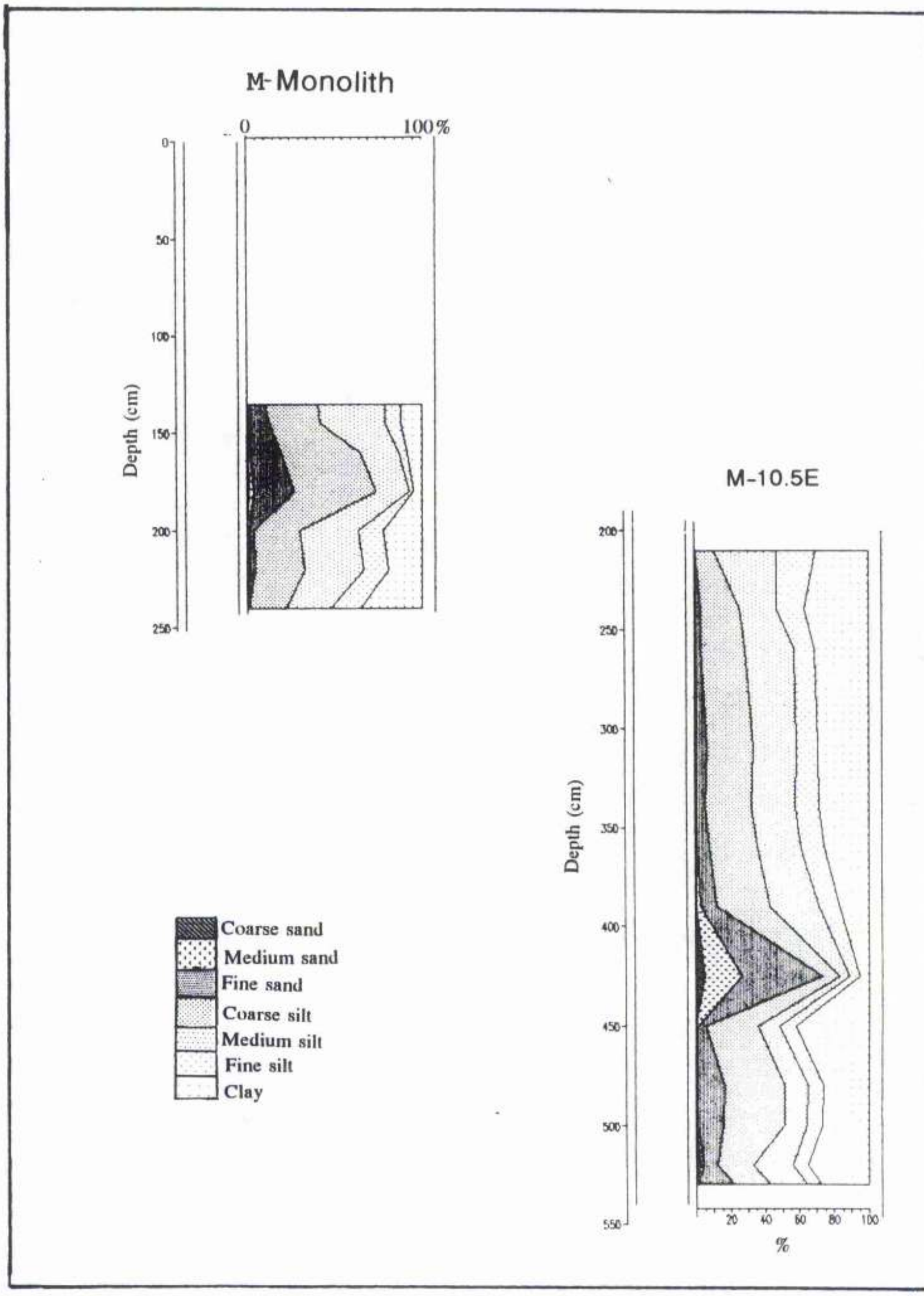
Three Dimensional Exposed Faces

Figure 6.7:

Particle Size Distributions at Different Depths: Matuail

Left: Core M-Monolith

Right: Core M-10.5E



M-Monolith
0
100%
Depth (cm)
0
50
100
150
200
250
M-10.5E
Depth (cm)
200
250
300
350
400
450
500
550
20
40
60
80
100
%
Coarse sand
Medium sand
Fine sand
Coarse silt
Medium silt
Fine silt
Clay

Figure 6.8:

Organic Content of Sediments at Different Depths: Matuail

Left: Core M-Monolith

Right: Core M-10.5E

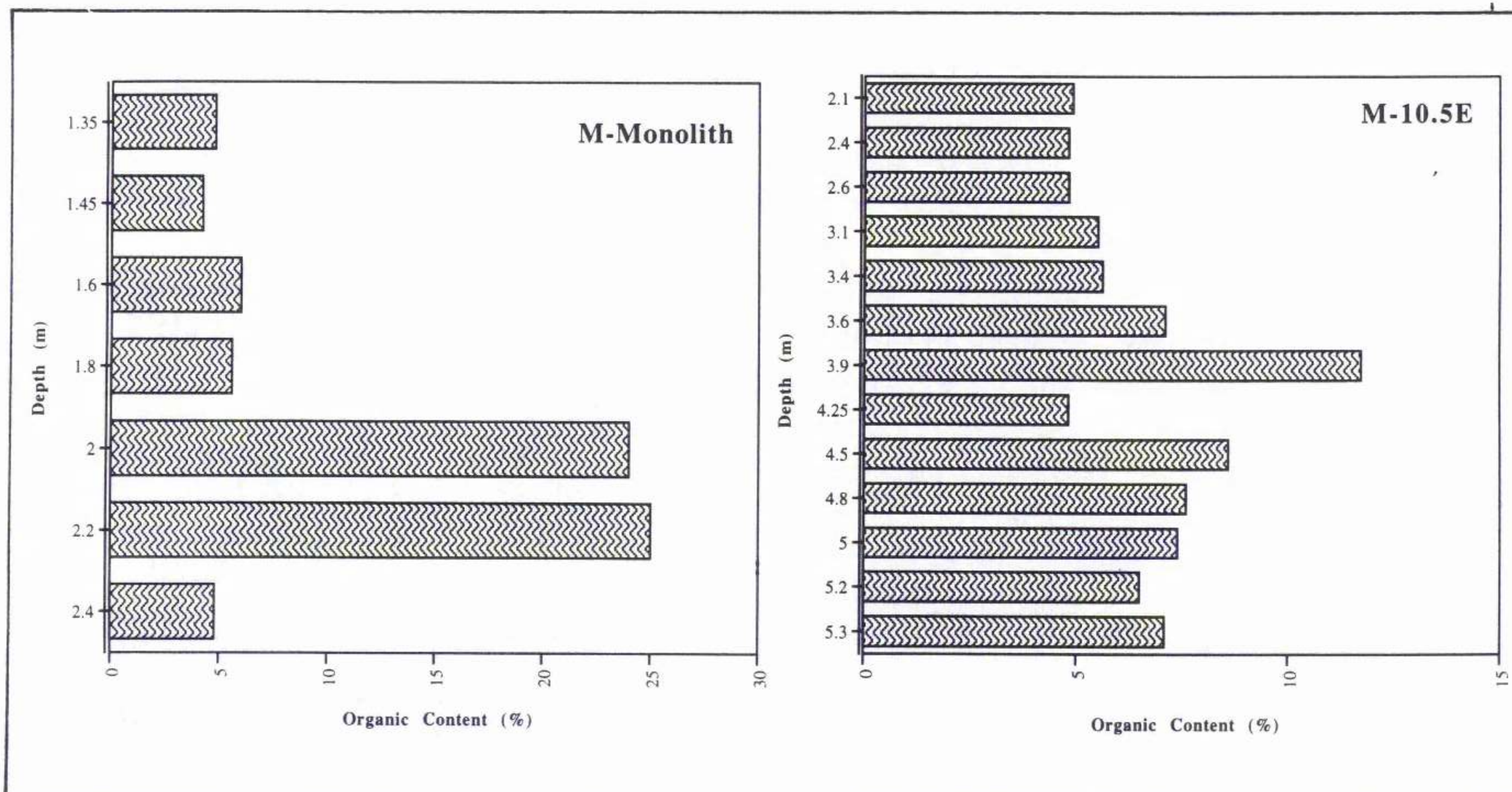

M-Monolith
Depth (m)
1.35
1.45
1.6
1.8
2
2.2
2.4
0
5
10
15
20
25
30
Organic Content (%)
M-10.5E
Depth (m)
2.1
2.4
2.6
3.1
3.4
3.6
3.9
4.25
4.5
4.8
5
5.2
5.3
0
5
10
15
Organic Content (%)

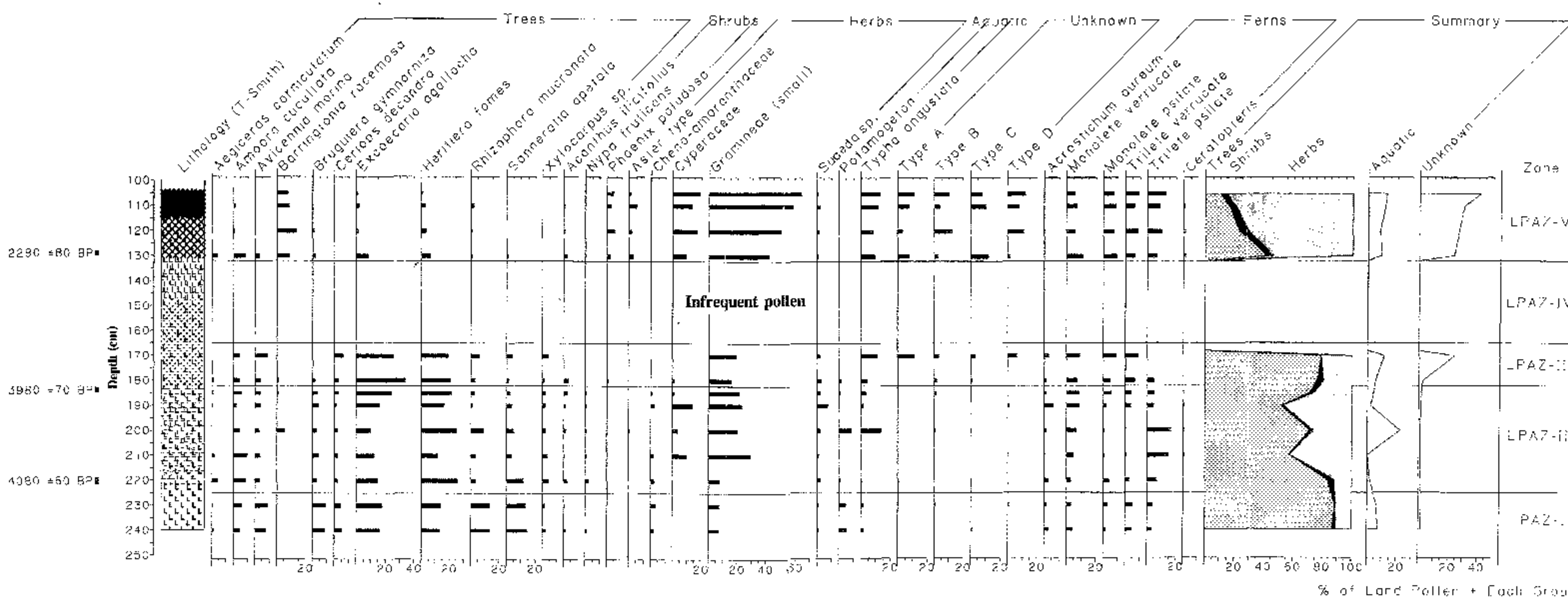
Figure 6.9:

Pollen Diagram at Matuail: M-Monolith

Tree, shrub or herb pollen are expressed as percentages of total land pollen, aquatic pollen as percentage of total land pollen plus total aquatic, unknown type pollen as percentage of total land pollen plus total unknown type, and fern spores as percentage of total land pollen plus total spores.

LPAZ= Local Pollen Assemblage Zone

For Lithological Symbol see Appendix 2



Trees
Shrubs
Herbs
Aquatic
Unknown
Ferns
Summary
Lithology (T-Smith)
Aegiceras corniculatum
Amoora cucullata
Avicennia marina
Barringtonia racemosa
Bruguiera gymnorrhiza
Ceriops decandra
Excoecaria agallocha
Heritiera fomes
Rhizophora mucronata
Sonneratia apetala
Xylocarpus sp.
Acanthus ilicifolius
Nypa fruticans
Phoenix paludosa
Aster type
Cheno-amaranthaceae
Cyperaceae
Gramineae (small)
Suaeda sp.
Potamogeton
Typha angustata
Type A
Type B
Type C
Type D
Acrostichum aureum
Monolete verrucate
Monolete psilate
Trilete verrucate
Trilete psilate
Ceratopteris
Trees
Shrubs
Herbs
Aquatic
Unknown
Zone
Depth (cm)
2290 ±80 BP
3960 ±70 BP
4080 ±60 BP
Infrequent pollen
LPAZ-V
LPAZ-IV
LPAZ-III
LPAZ-II
% of Land Pollen + Each Group

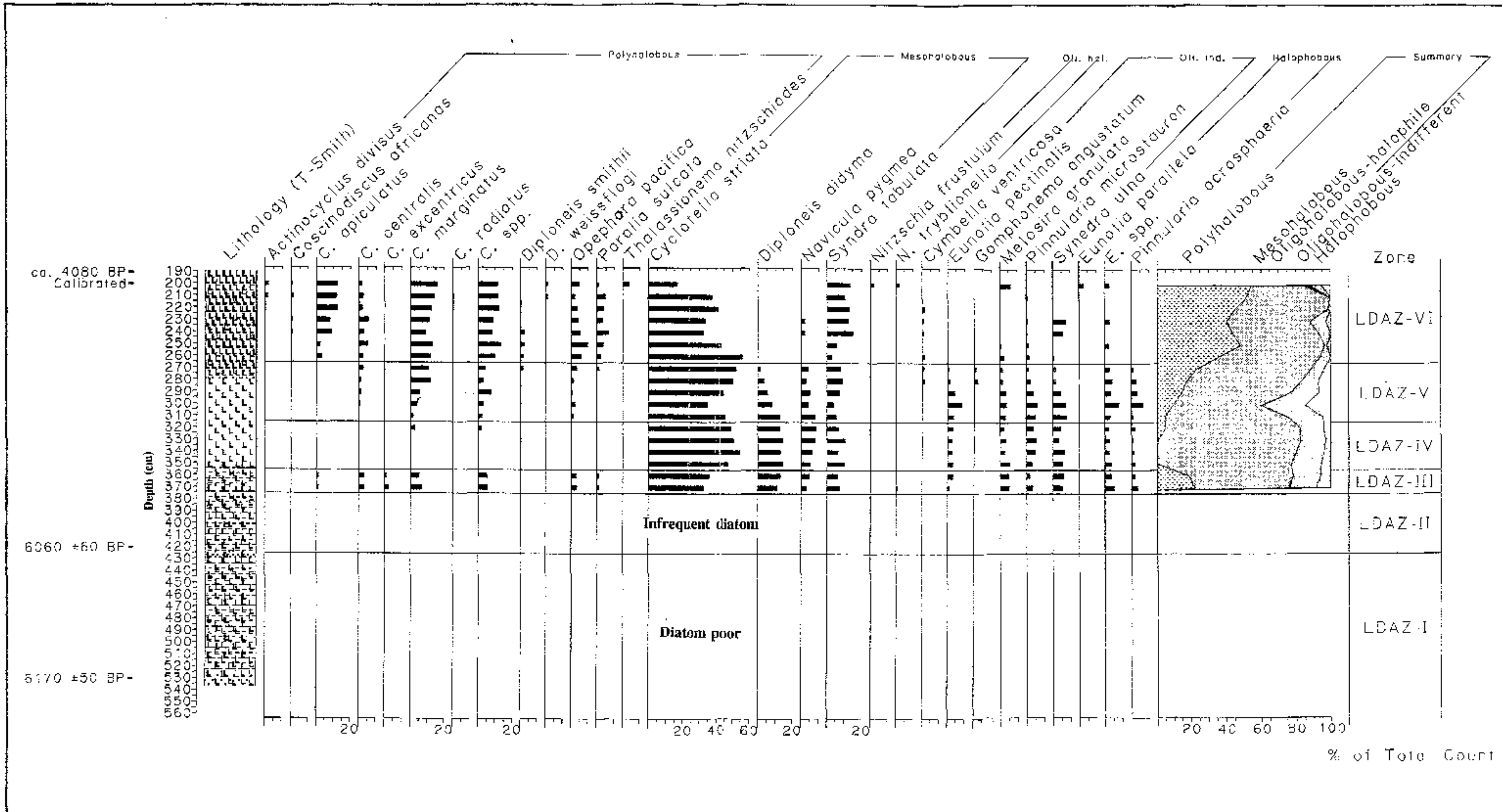
Figure 6.10:

Diatom Diagram at Matuail: M-10.5E

Polyhalobous, Mesohalobous, Oligohalobous-halophilous, Oligohalobous-indifferent or Halophobous diatoms are expressed as percentages of total diatom count at each level.

LDAZ= Local Diatom Assemblage Zone

For Lithological Symbol see Appendix 2



Polyhalobous
Mesohalobous
Oli. hal.
Oli. ind.
Halophobous
Summary
Lithology (T-Smith)
Actinocyclus divisus
Coscinodiscus africanas
C. apiculatus
C. centralis
C. excentricus
C. marginatus
C. radiatus
C. spp.
Diploneis smithii
D. weissflogi
Opephora pacifica
Paralia sulcata
Thalassionema nitzschiodes
Cyclotella striata
Diploneis didyma
Navicula pygmea
Syndra tabulata
Nitzschia frustulum
N. tryblionella
Cymbella ventricosa
Eunotia pectinalis
Gomphonema angustatum
Melosira granulata
Pinnularia microstauron
Synedra ulna
Eunotia parallela
E. spp.
Pinnularia acrosphaeria
Polyhalobous
Mesohalobous
Oligohalobous-halophile
Oligohalobous-indifferent
Halophobous
Zone
ca. 4080 BP-
Calibrated-
6060 ±60 BP-
5170 ±50 BP-
Depth (cm)
Infrequent diatom
Diatom poor
LDAZ-VI
LDAZ-V
LDAZ-IV
LDAZ-III
LDAZ-II
LDAZ-I
% of Total Count

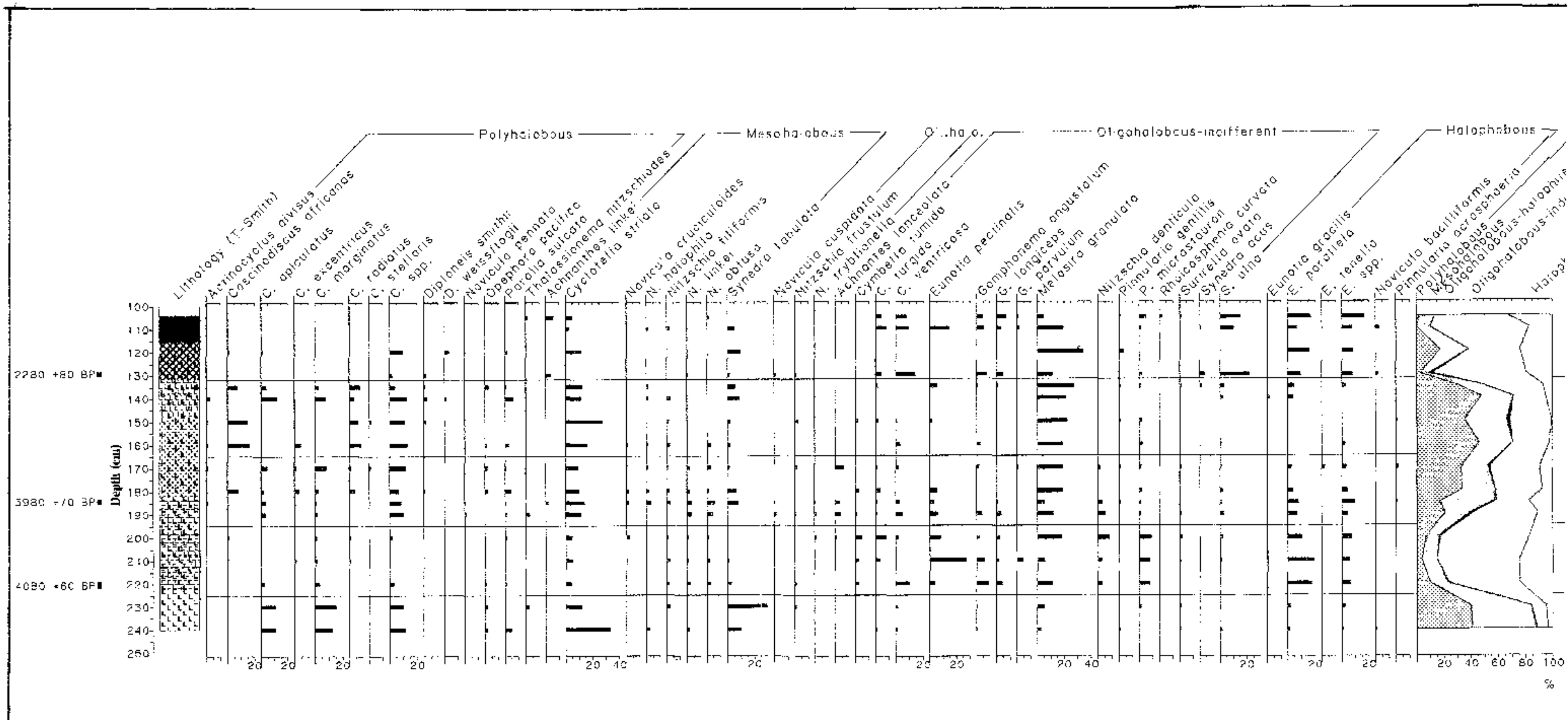
Figure 6.11:

Diatom Diagram at Matuail: M-Monolith

Polyhalobous, Mesohalobous, Oligohalobous-halophilous, Oligohalobous-indifferent or Halophobous diatoms are expressed as percentages of total diatom count at each level.

LDAZ= Local Diatom Assemblage Zone

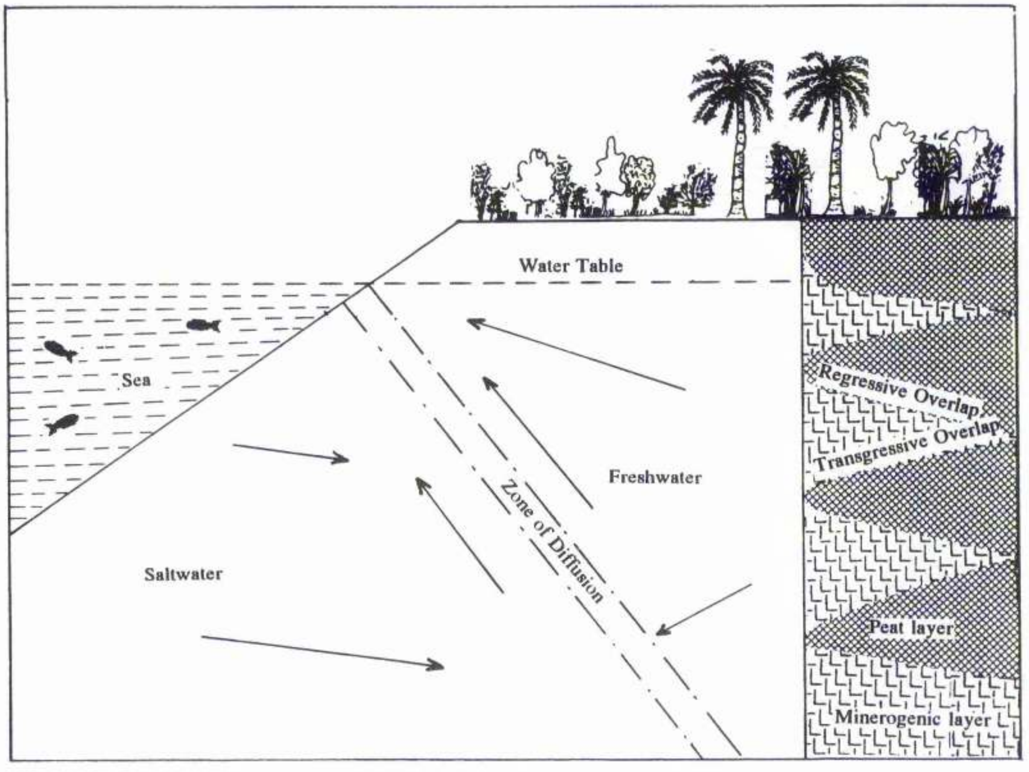
For Lithological Symbol see Appendix 2



Polyhalobous
Mesohalobous
Ol..halo.
Oligohalobous-indifferent
Halophobous
Lithology (T-Smith)
Actinocyclus divisus
Coscinodiscus africanus
C. apiculatus
C. excentricus
C. marginatus
C. radiatus
C. stellaris
C. spp.
Diploneis smithii
D. weissflogii
Navicula pennata
Opephora pacifica
Paralia sulcata
Thalassionema nitzschioides
Achnanthes linkei
Cyclotella striata
Navicula cruciculoides
N. halophila
Nitzschia filiformis
N. linkei
N. obtusa
Synedra tabulata
Navicula cuspidata
Nitzschia frustulum
N. tryblionella
Achnanthes lanceolata
Cymbella tumida
C. turgida
C. ventricosa
Eunotia pectinalis
Gomphonema angustatum
G. longiceps
G. parvulum
Melosira granulata
Nitzschia denticula
Pinnularia gentilis
P. microstauron
Rhoicosphenia curvata
Surirella ovata
Synedra acus
S. ulna
Eunotia gracilis
E. paralleia
E. tenella
E. spp.
Navicula bacilliformis
Pinnularia acrosphaeria
Polyhalobous
Mesohalobous
Oligohalobous-halophile
Oligohalobous-indifferent
Halophobous
Depth (cm)
2280 ±80 BP
3980 ±70 BP
4080 ±60 BP
%

Figure 7.1:

A Simple Model of Freshwater/Salinewater Interface and Peat Growth in Relation to Sea-level Movements



Water Table
Sea
Saltwater
Freshwater
Zone of Diffusion
Regressive Overlap
Transgressive Overlap
Peat layer
Minerogenic layer

Figure 7.2:

Sea-level Curve at Panigati

Each Error Box Shows Altitudinal Error Range on the Vertical Axis and Age Error Range on the Horizontal Axis

Each Arrowed Line Shows the Tendency of Sea-level Movement

The Belt Shows the Envelope within which the Sea-levels Oscillate

An Assumption of a Constant 2 m Palaeo-tidal Range is Considered

Each Dashed Line in the Curve Shows that it is an Approximate

(see section 7.6 for derivation of curve between index points)

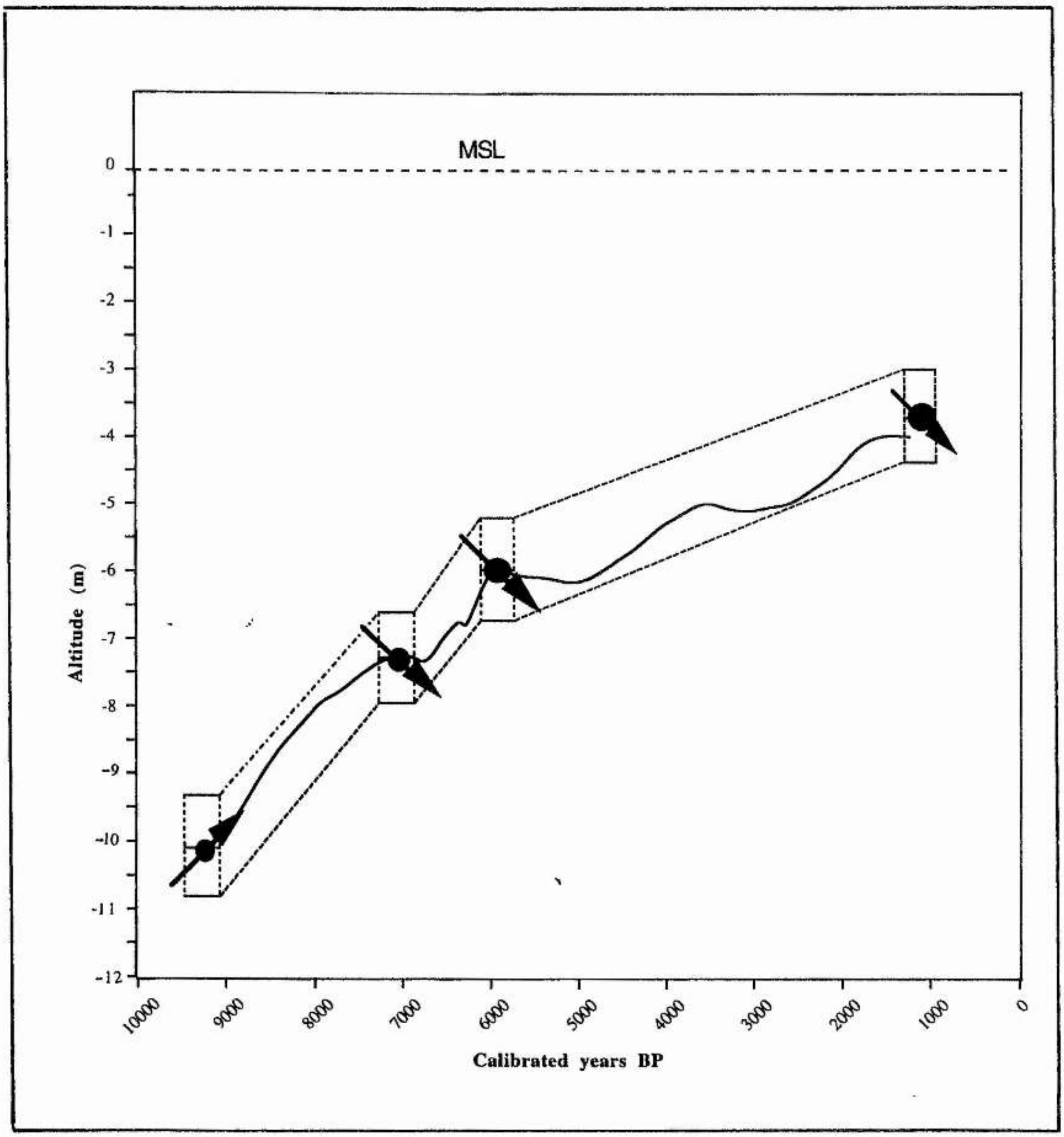

MSL
Altitude (m)
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Calibrated years BP

Figure 7.3:

Sea-level Curve at Matuail

Each Error Box Shows Altitudinal Error Range on the Vertical Axis and Age Error Range on the Horizontal Axis

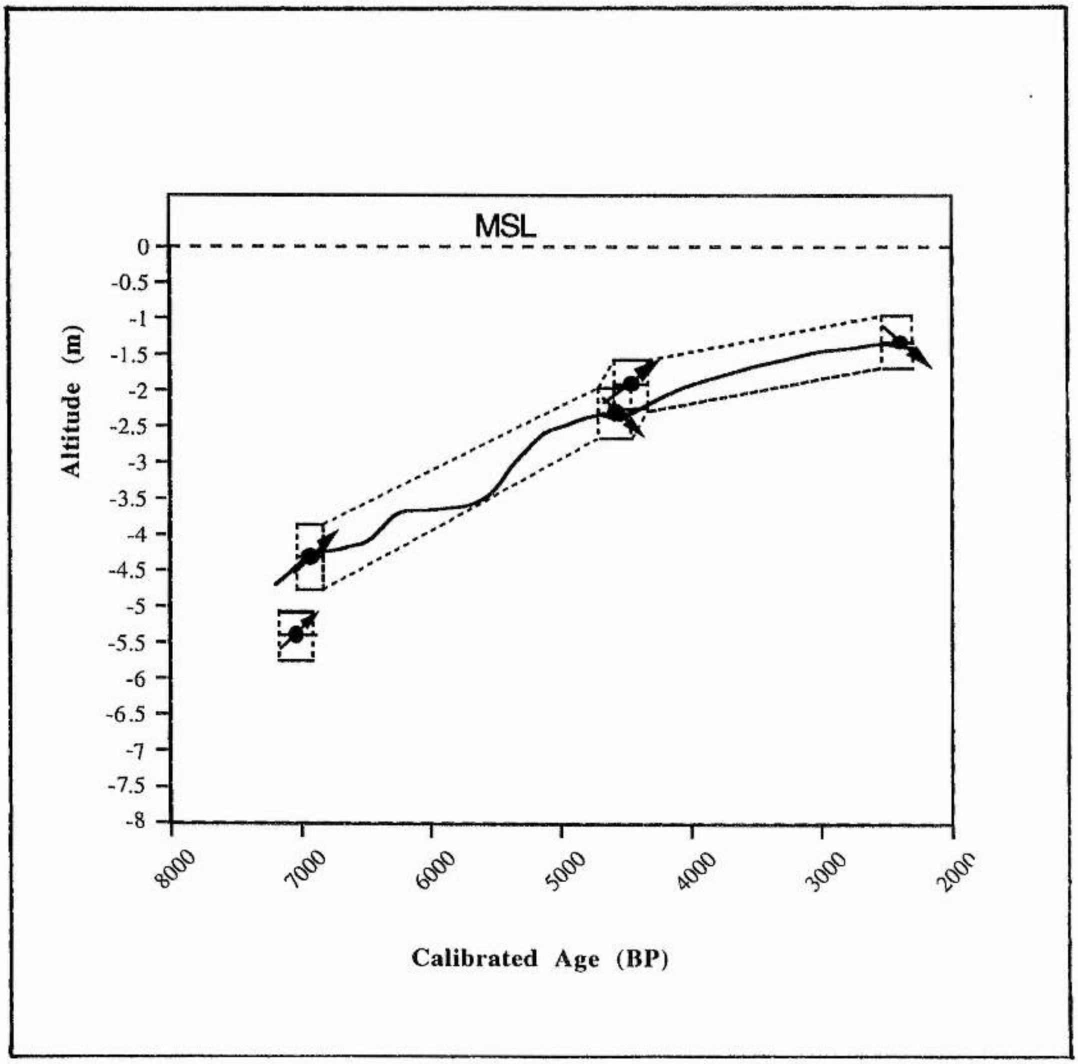
Each Arrowed Line Shows the Tendency of Sea-level Movement

The Belt Shows the Envelope within which the Sea-levels Oscillate

An Assumption of a Constant 2 m Palaeo-tidal Range is Considered

Each Dashed Line in the Curve Shows that it is an Approximate

(see section 7.6 for derivation of curve between index points)



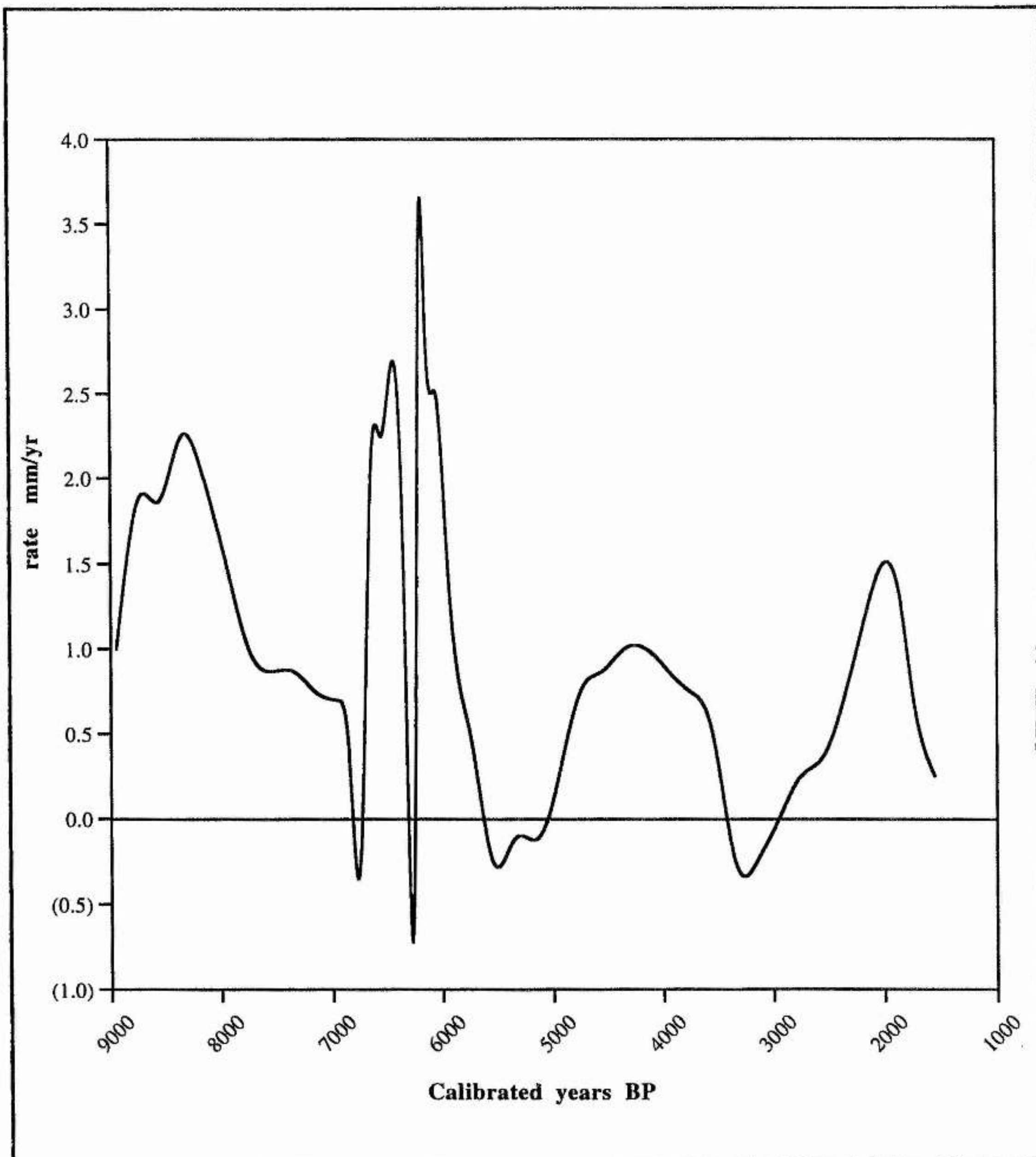
MSL
Altitude (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
-6
-6.5
-7
-7.5
-8
8000
7000
6000
5000
4000
3000
2000
Calibrated Age (BP)

Figure 7.4:

Rates of Sea-level Movement at Panigati

Rates have been Calculated at 100 years Intervals from the Calibrated Radiocarbon Dates, Assuming a Uniform Sedimentation Rate Between Dates.

Rates Above the Zero Line are Relative Rises and Below are Relative Falls of Sea-levels



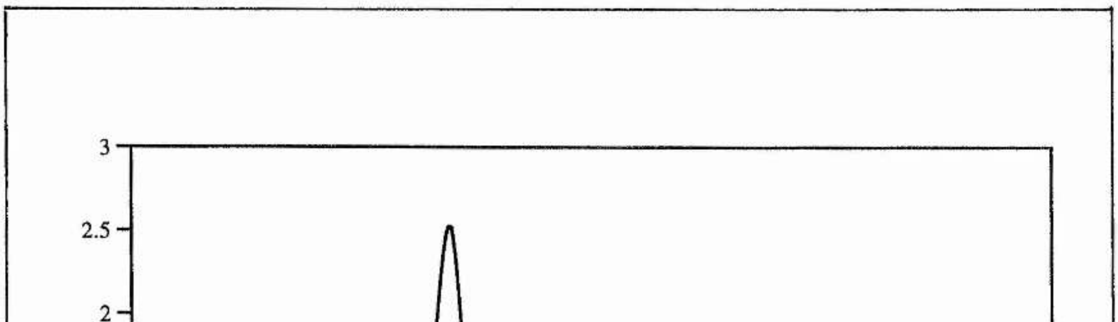
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
(0.5)
(1.0)
rate mm/yr
9000
8000
7000
6000
5000
4000
3000
2000
1000
Calibrated years BP

Figure 7.5:

Rates of Sea-level Movement at Matuail

Rates have been Calculated at 100 years Intervals from the Calibrated Radiocarbon Dates, Assuming a Uniform Sedimentation Rate Between Dates.

Rates Above the Zero line are Relative Rises and Below are Relative Falls of Sea-levels



Rate (mm/yr)
3
2.5
2
1.5
1
0.5
0
-0.5
-1
7000
6000
5000
4000
3000
2000
Calibrated Age (BP)

Figure 7.6:

Index Points at Transgressive, and Regressive Overlap which are Related to Positive and Negative Tendencies of Sea-level Movements-^{14}C Time Scale

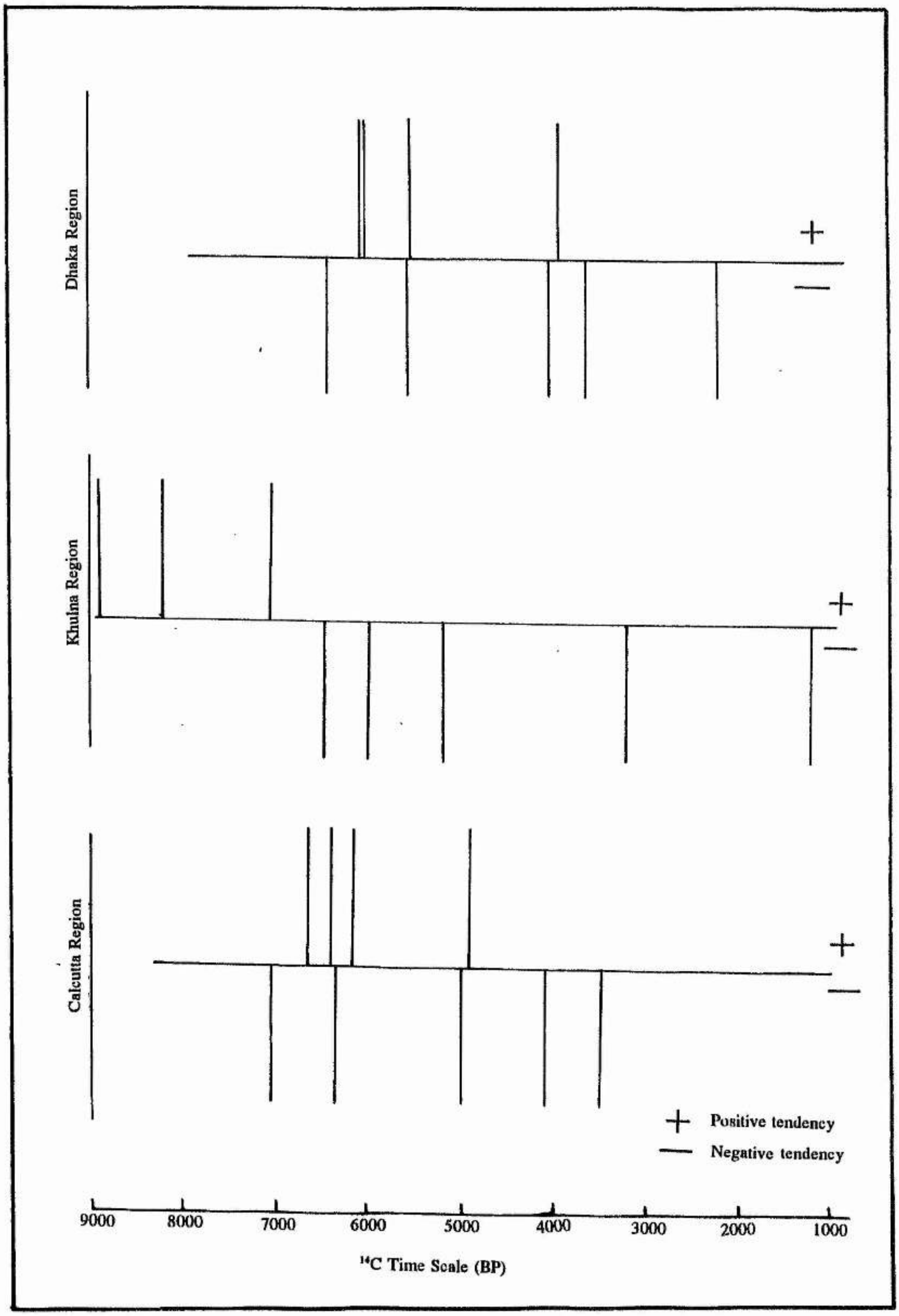
Uppermost: Dhaka Region

Middle: Khulna Region

Lowermost: Calcutta Region

Each ^{14}C dating point is shown by a vertical line

Each Upward Line Shows Transgression Overlap and Downward Line Shows Regressive overlap



Dhaka Region
Khulna Region
Calcutta Region
+ Positive tendency
— Negative tendency
9000
8000
7000
6000
5000
4000
3000
2000
1000
¹⁴C Time Scale (BP)

Figure 7.7:

Index Points at Transgressive, and Regressive Overlap which are Related to Positive and Negative Tendencies of Sea-level Movements- Sidereal Time Scale

Uppermost: Dhaka Region

Middle: Khulna Region

Lowermost: Calcutta Region

Each Calibrated dating point is shown by a vertical line

Each Upward Line Shows Transgression Overlap and Downward Line Shows Regressive overlap

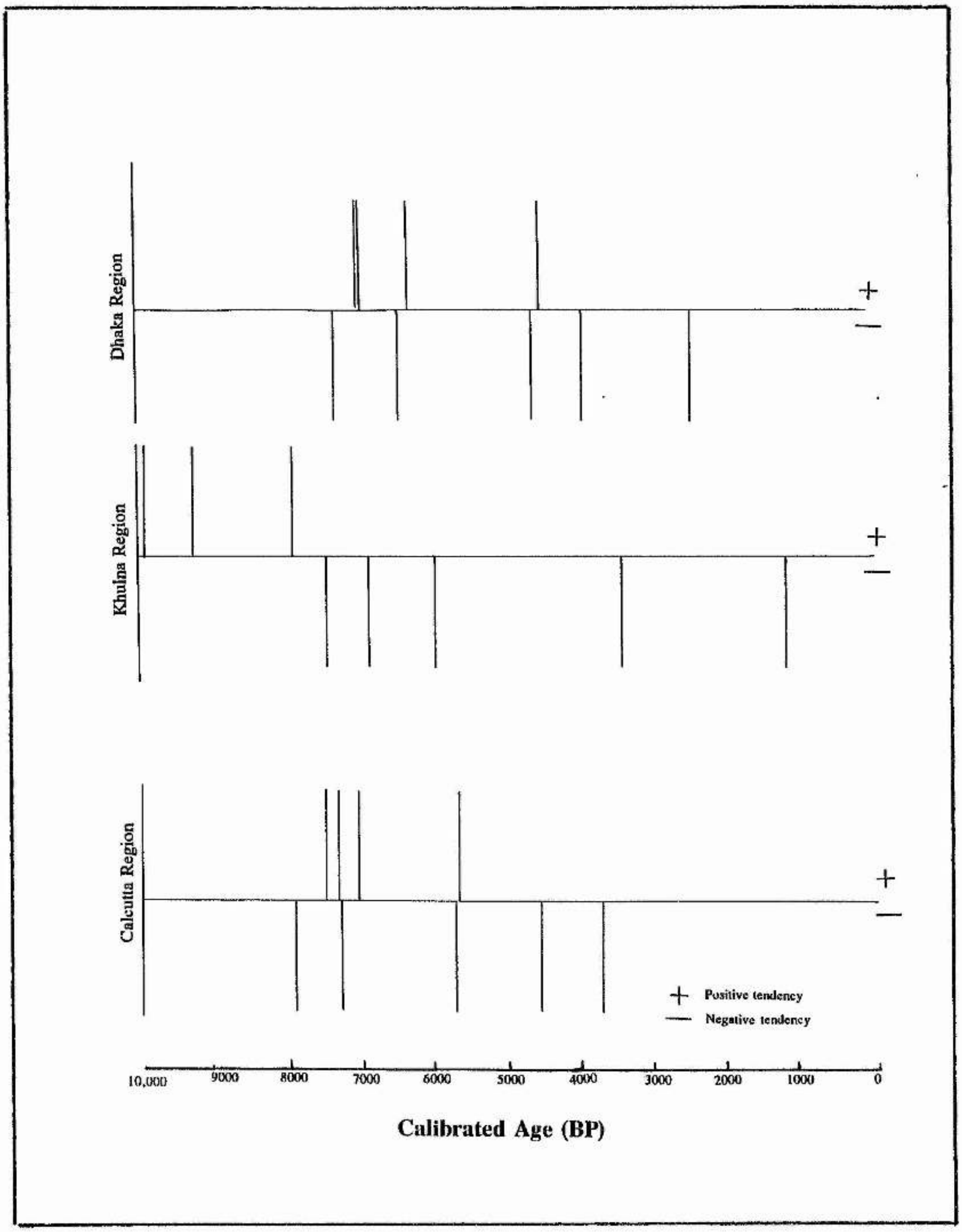

Dhaka Region
Khulna Region
Calcutta Region
+ Positive tendency
— Negative tendency
10,000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Calibrated Age (BP)

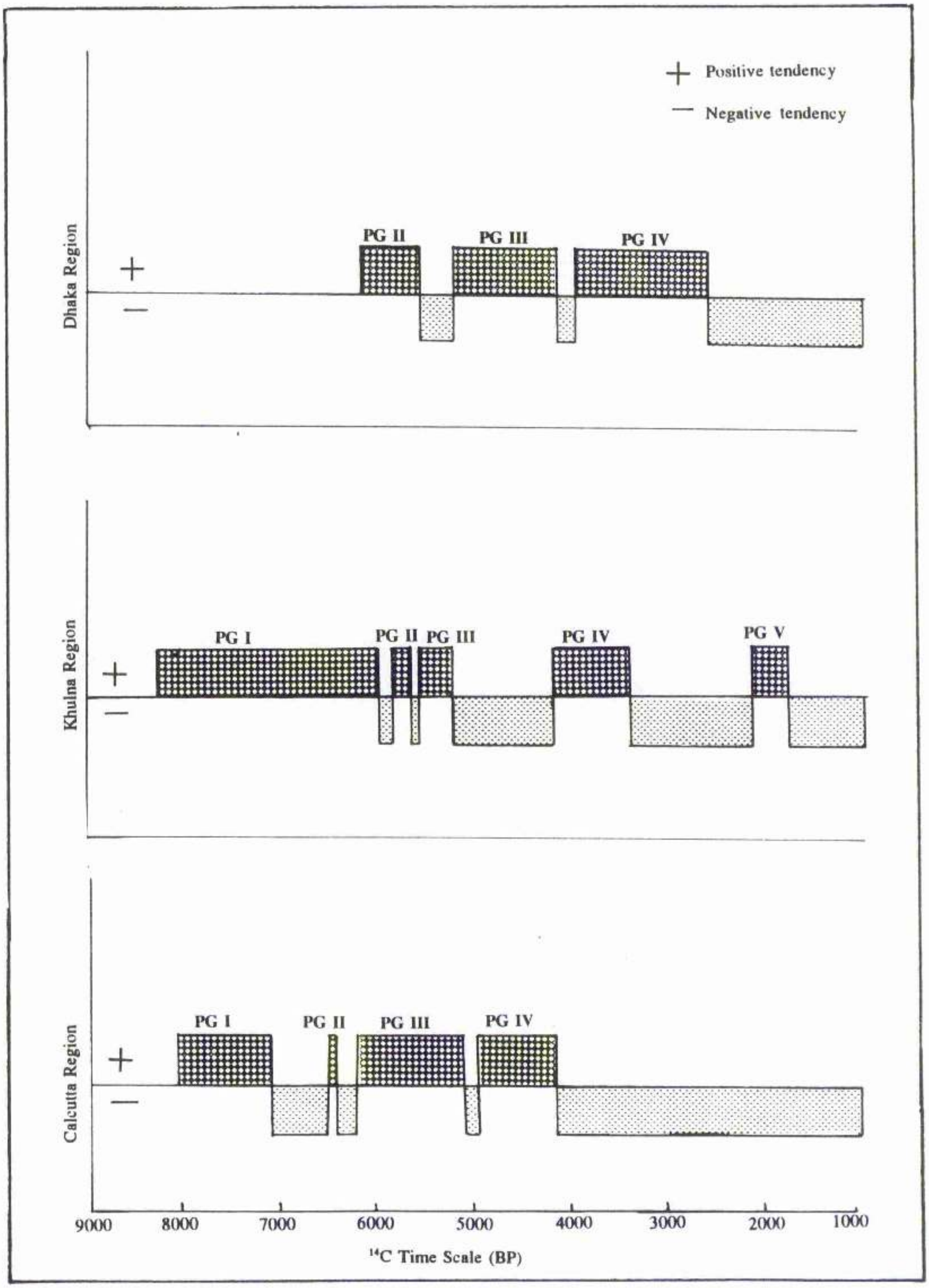
Figure 7.8:

Regional Tendencies of Sea-level Movement- ^{14}C Time Scale

Uppermost: Tendencies at Dhaka Region

Middle: Tendencies at Khulna Region

Lowermost: Tendencies at Calcutta Region



Positive tendency
Negative tendency
Dhaka Region
PG II
PG III
PG IV
Khulna Region
PG I
PG II
PG III
PG IV
PG V
Calcutta Region
PG I
PG II
PG III
PG IV
9000
8000
7000
6000
5000
4000
3000
2000
1000
^{14}C Time Scale (BP)

Figure 7.9:

Regional Tendencies of Sea-level Movement- Sidereal Time Scale

Uppermost: Tendencies at Dhaka Region

Middle: Tendencies at Khulna Region

Lowermost: Tendencies at Calcutta Region

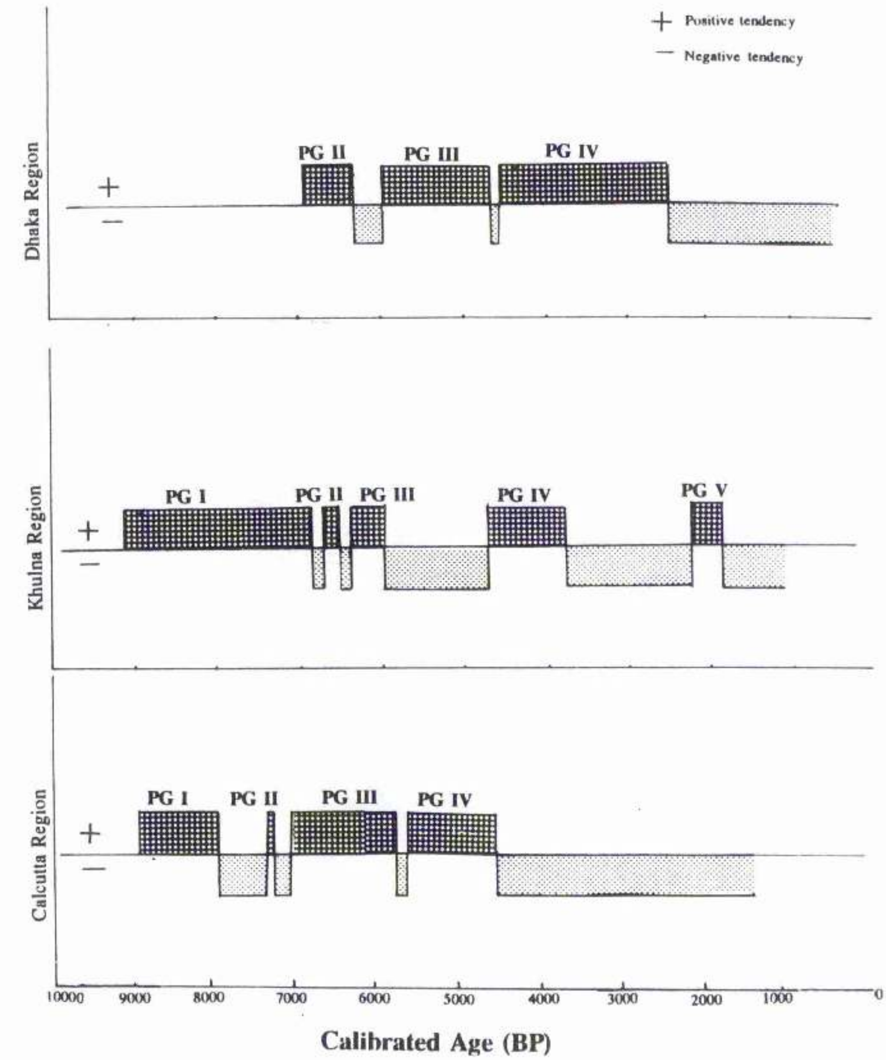
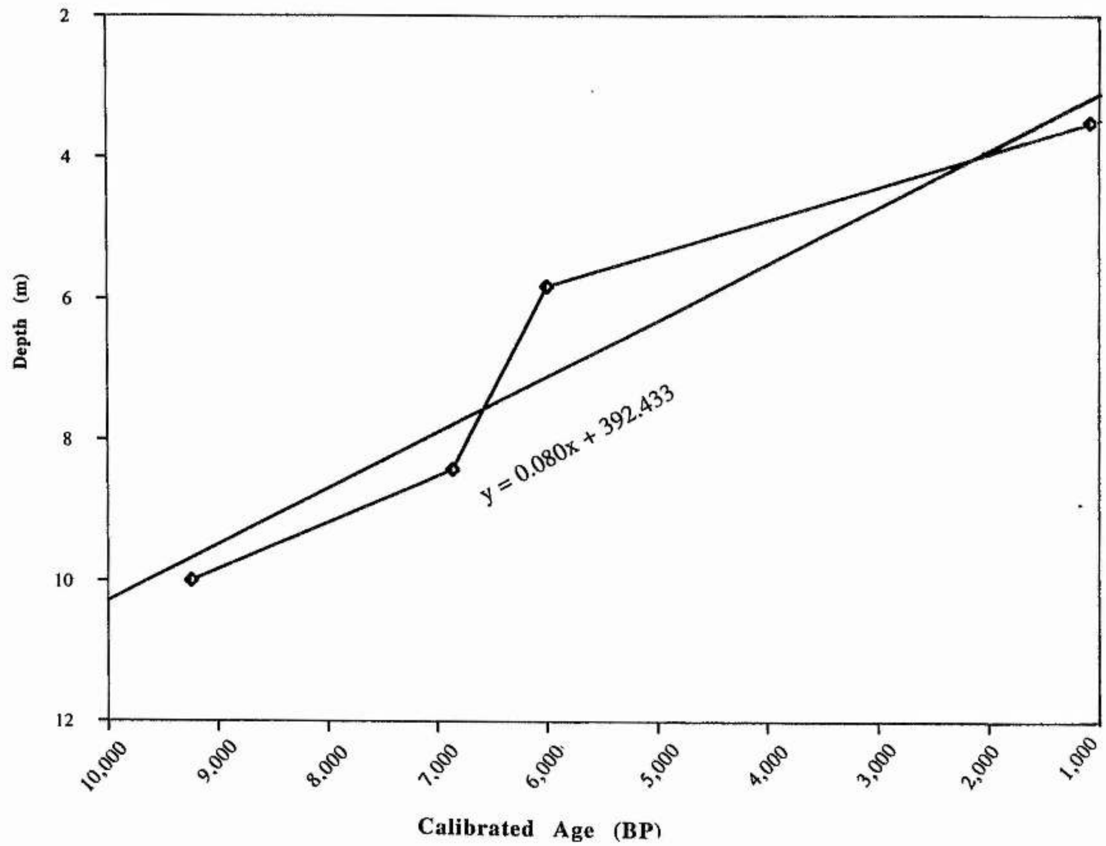

+ Positive tendency
— Negative tendency
Dhaka Region
PG II
PG III
PG IV
Khulna Region
PG I
PG II
PG III
PG IV
PG V
Calcutta Region
PG I
PG II
PG III
PG IV
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Calibrated Age (BP)

Figure 8.1:

Age-depth Graph at Panigati

Sedimentation Rates have been Calculated from Calibrated Radiocarbon Dates on the Basis of Linear Interpolation

Sedimentation Between Two Successive Dates has been Considered as Uniform



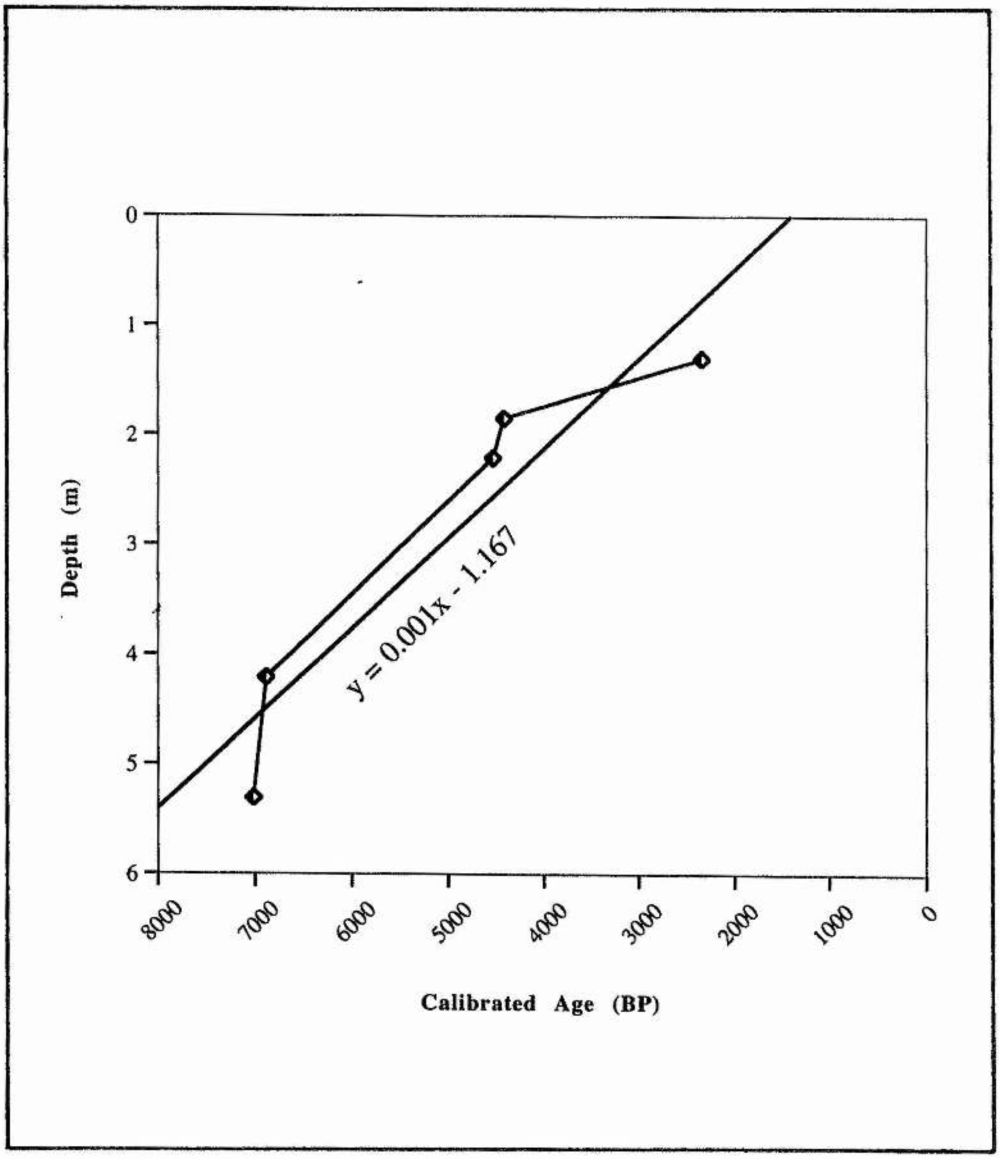
Depth (m)
2
4
6
8
10
12
y = 0.080x + 392.433
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
Calibrated Age (BP)

Figure 8.2:

Age-depth Graph at Matuail

Sedimentation Rates have been Calculated from Calibrated Radiocarbon Dates on the Basis of Linear Interpolation

Sedimentation Between Two Successive Dates has been Considered as Uniform



0
1
2
3
4
5
6
Depth (m)
y = 0.001x - 1.167
8000
7000
6000
5000
4000
3000
2000
1000
0
Calibrated Age (BP)

Figure 8.3:

Subsidence of Each Index Point at Panigati

Each Index Point is Recorded in Relation to the MHWST-level

Angle at Each Index Point Shows Its total Subsidence

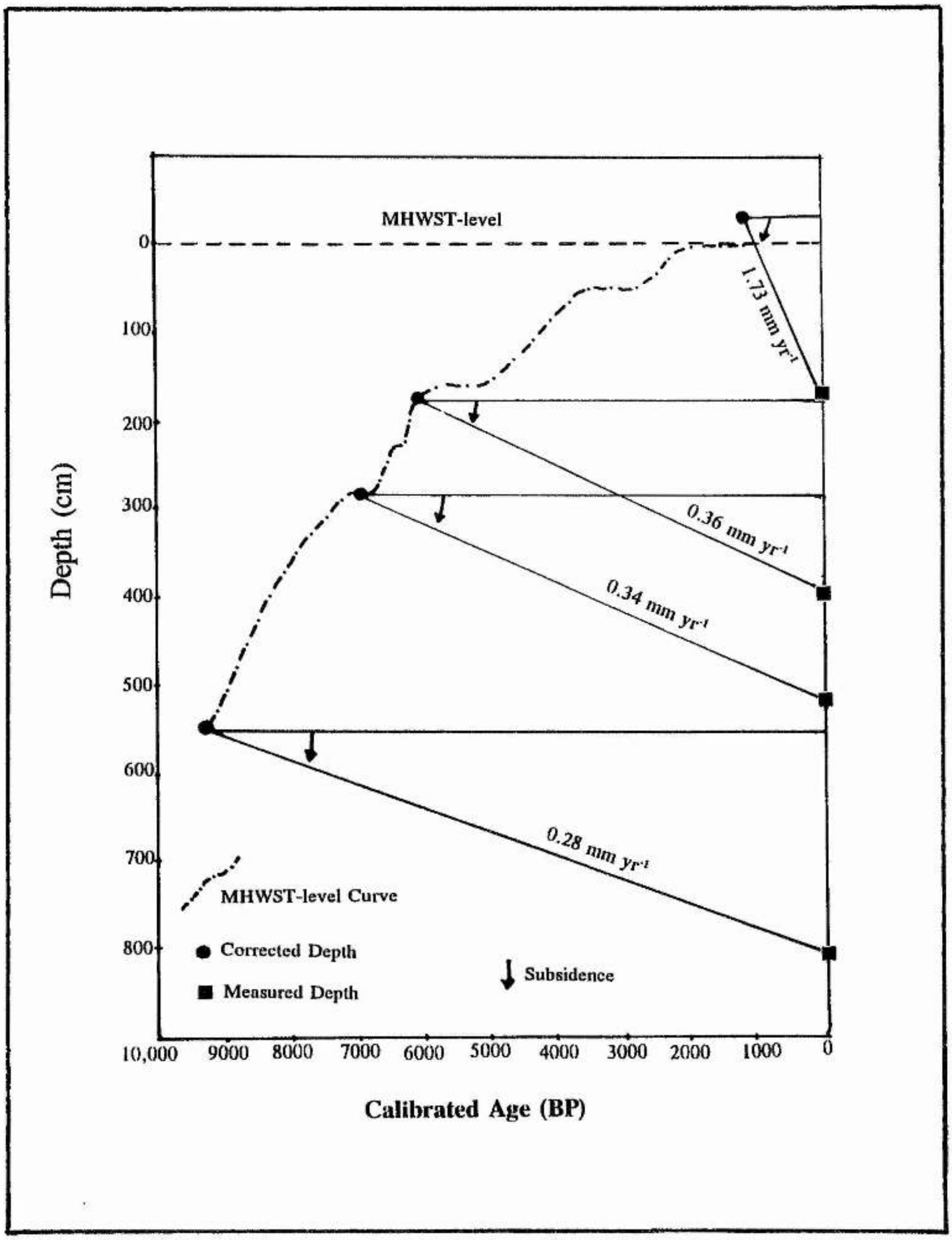

MHWST-level
1.73 mm yr-1
0.36 mm yr-1
0.34 mm yr-1
0.28 mm yr-1
Depth (cm)
0
100
200
300
400
500
600
700
800
10,000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Calibrated Age (BP)
MHWST-level Curve
Corrected Depth
Measured Depth
Subsidence

Figure 8.4:

Uplift of Each Index Point at Matuail

Each Index Point is Recorded in Relation to the MHWST-level

Angle at Each Index Point Shows Its total Uplift

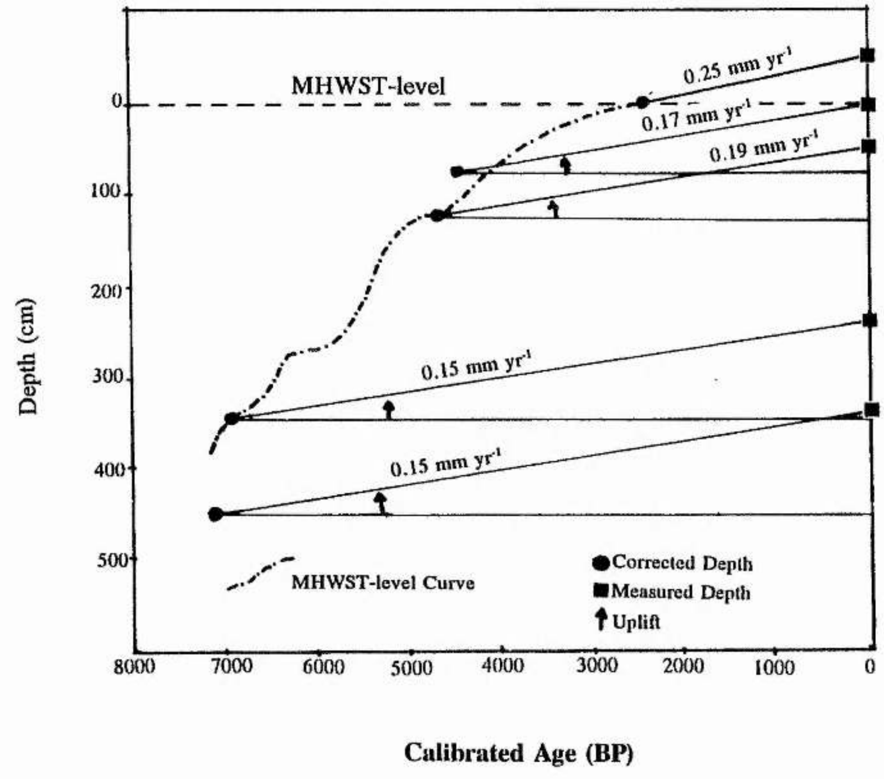

MHWST-level
0.25 mm yr-1
0.17 mm yr-1
0.19 mm yr-1
0.15 mm yr-1
0.15 mm yr-1
Depth (cm)
0
100
200
300
400
500
MHWST-level Curve
Corrected Depth
Measured Depth
Uplift
8000
7000
6000
5000
4000
3000
2000
1000
0
Calibrated Age (BP)

Figure 8.5:

Approximate Holocene Mangal Limits in the Bengal Basin

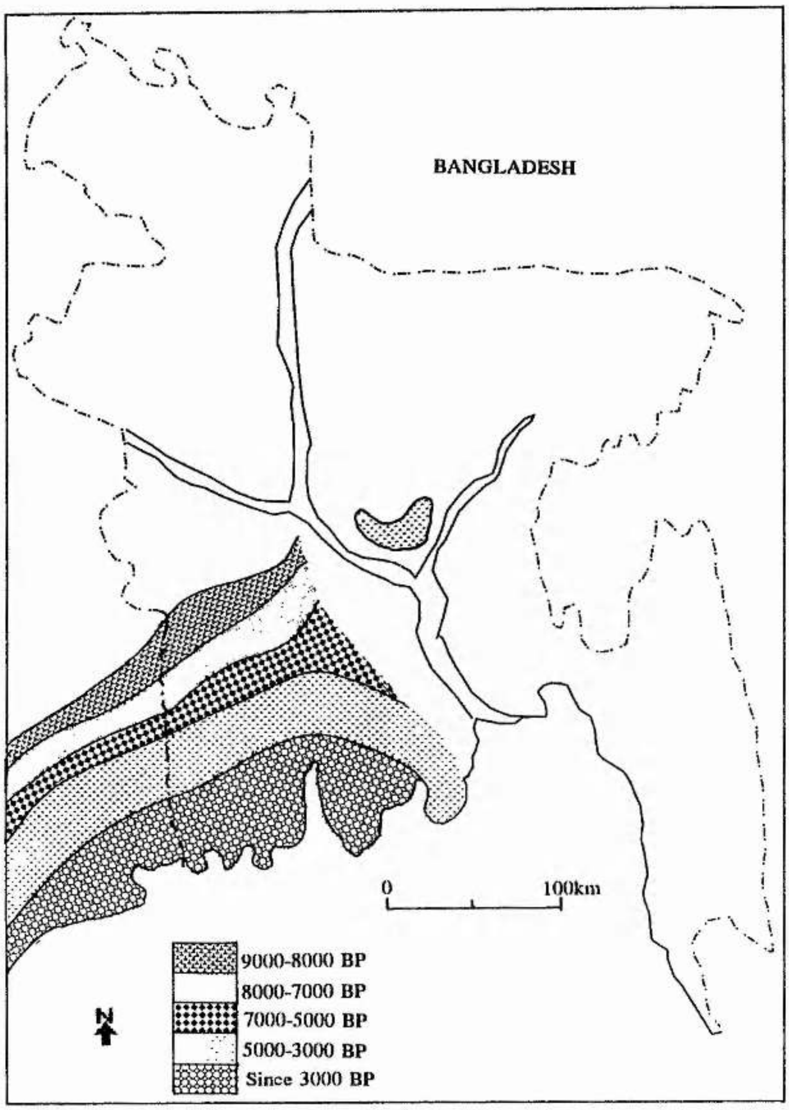
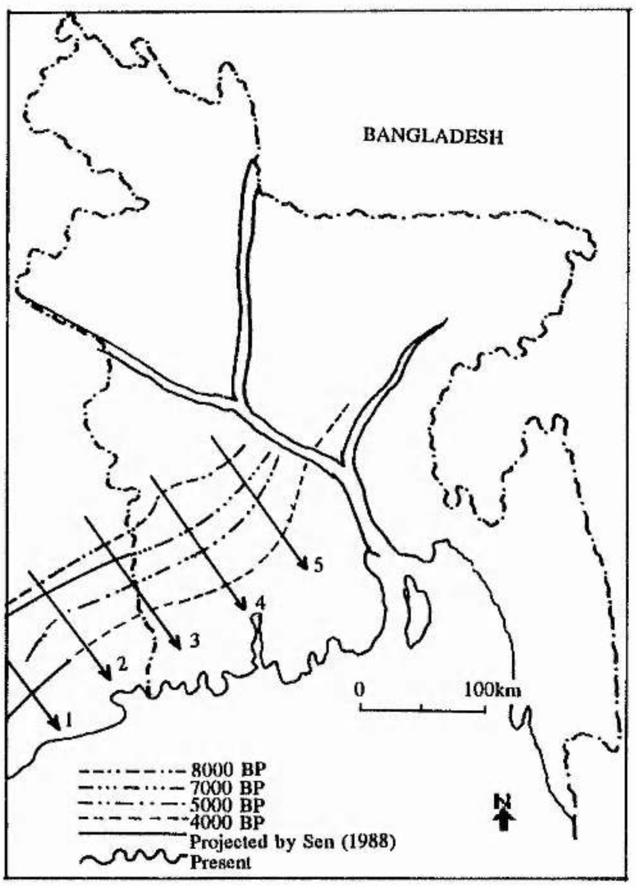

BANGLADESH
0
100km
9000-8000 BP
8000-7000 BP
7000-5000 BP
5000-3000 BP
Since 3000 BP
N

Figure 8.6:

Approximate Holocene Coastline Changes in the Bengal Basin

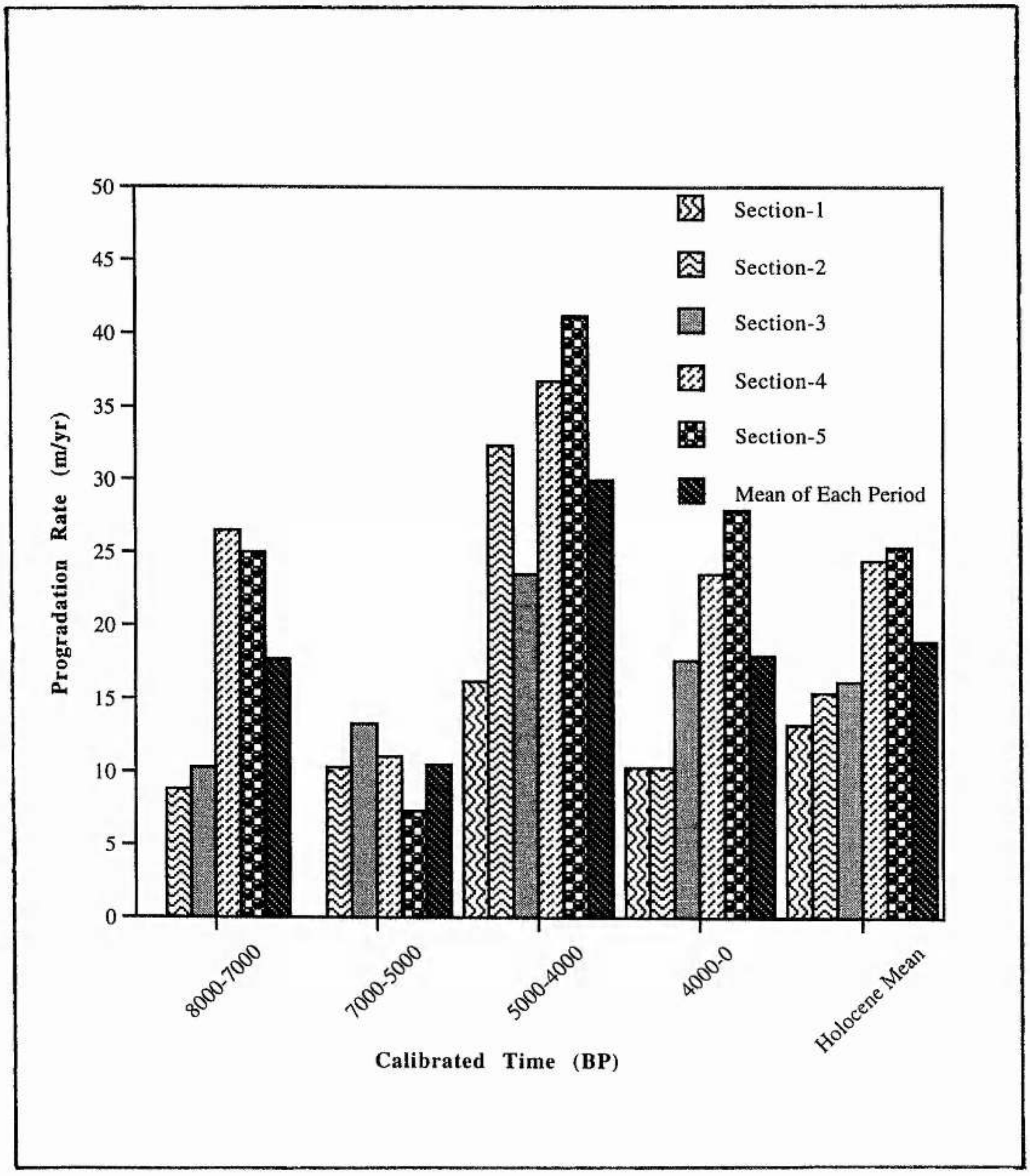


BANGLADESH
5
4
3
2
1
0
100km
8000 BP
7000 BP
5000 BP
4000 BP
Projected by Sen (1988)
Present
N

Figure 8.7:

Holocene Progradation Rates of the Bengal Delta

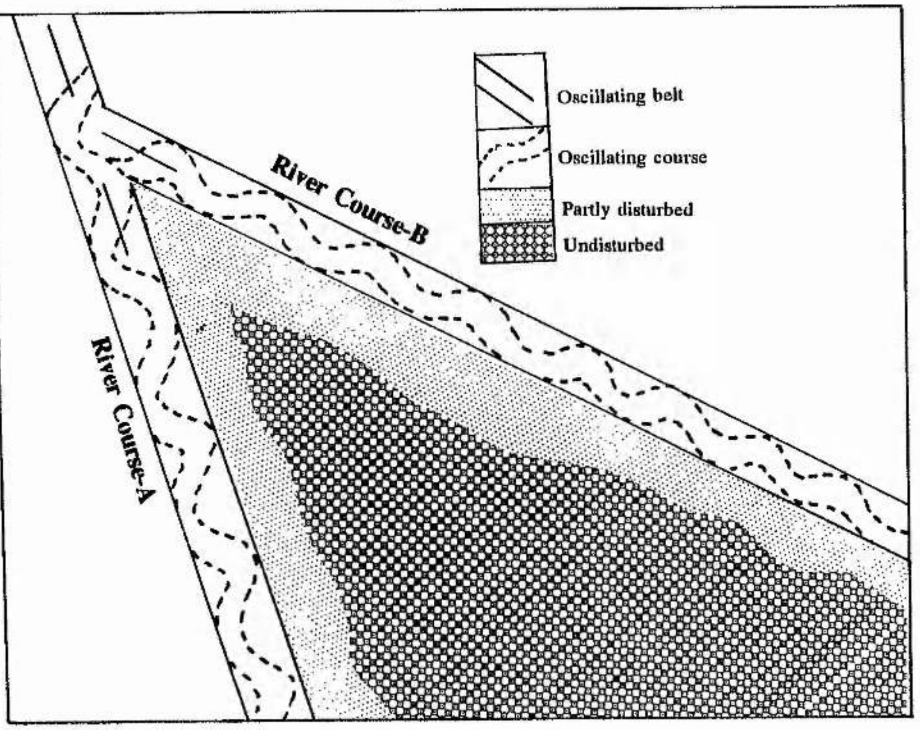
Rates are Calculated from Calibrated Radiocarbon Dates at 5 Different Sections Based on Figure 8.6



Progradation Rate (m/yr)
50
45
40
35
30
25
20
15
10
5
0
Section-1
Section-2
Section-3
Section-4
Section-5
Mean of Each Period
8000-7000
7000-5000
5000-4000
4000-0
Holocene Mean
Calibrated Time (BP)

Figure 8.8:

A Simple Model Showing the Migration of River Courses without Disturbing the Sediments in Between



Oscillating belt
Oscillating course
Partly disturbed
Undisturbed
River Course-B
River Course-A

Appendices

Appendix 1:

Description of Some Mangrove Plants and their Ecology

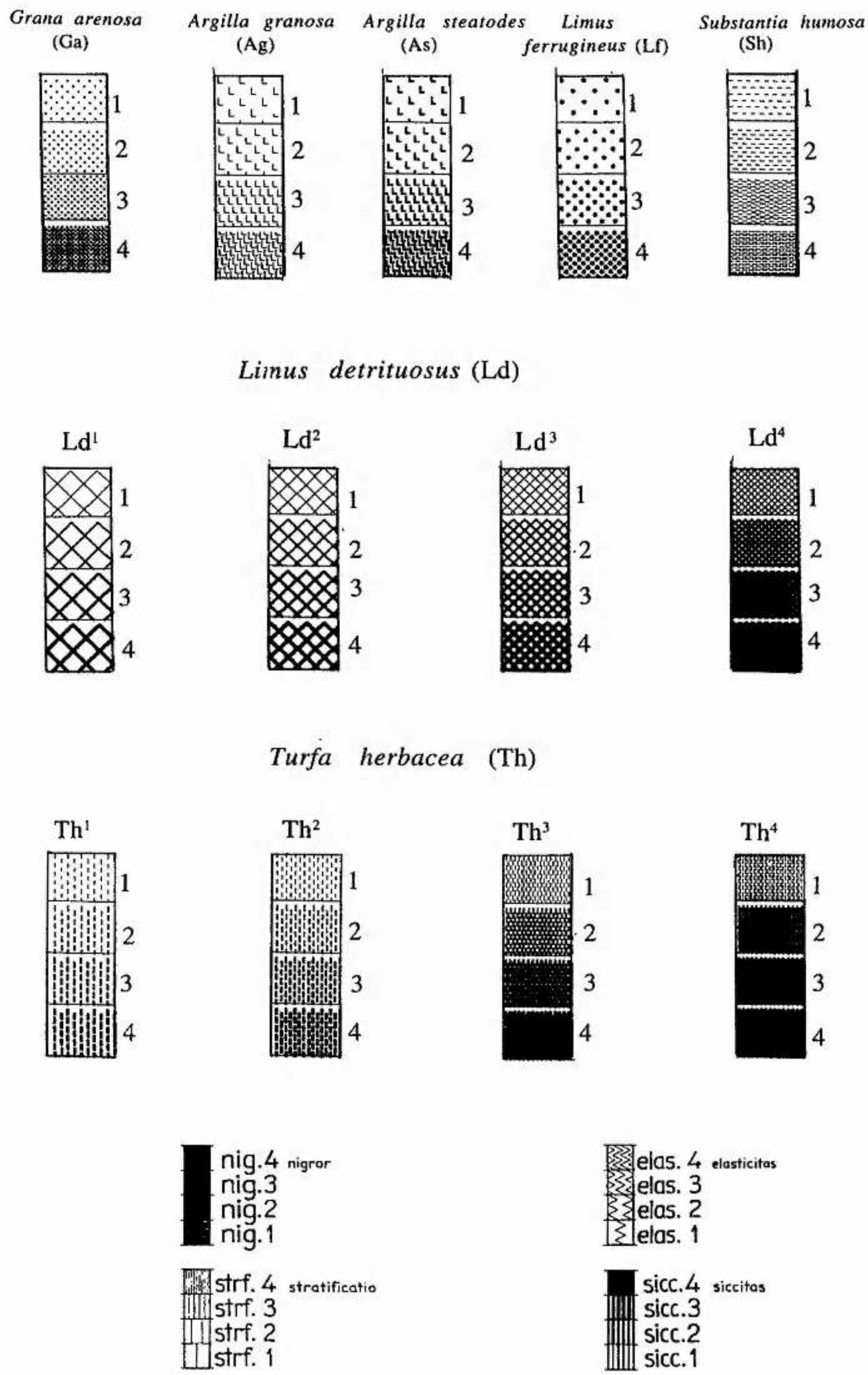
Species (Families)	Description of the Plant	Habitat
Acanthus ilicifolius (Acanthaceae)	An under-shrub; an excellent mud-binding species	Everywhere on river banks and low swampy places within the forest.
Aegiceras corniculatum (Myrsinaceae)	A tree reaching 7 m in height; wood hard, only used as fuel.	Sea coast along the edge of creeks and mud-tidal flat on wet soil inundated with the highest tides.
Amoora cucullata (Meliaceae)	A tree, 10-13 m high; wood hard, apt to split, of red or brown colour; roots with vertical blind suckers.	Commonly grow along the river and creek sides with frequent supply of freshwater from upstream in the transitional area between brackish and freshwater environment.
Avicennia marina (Avicenniaceae)	A large timber tree, 15-20 m high; wood dark-grey, hard; the root send up soft and pith-like blind root-sucker. This is the tallest species of the Sundarbans.	Common on the tidal forest, primary colonists on the sea front including creek channel margin, recently formed mud-flats to sand tidal flats which receive daily inundation.
Bruguiera gymnorhiza (Rhizophoraceae)	A tree 15 m high; wood red-brown and hard.	Along the side of creeks and river bank, grows in less frequently inundated situation towards the land. It makes the final stage of development of the littoral forest and the beginning of the transition of non-littoral forest.
Ceriops decandra (Rhizophoraceae)	A small tree, 4-7 m high, wood brick-red.	Landward areas of the mangrove swamp along tidal creeks or bordering lagoons on well-drained soil within the reach of occasional tide in the inner mangrove forest.
Excoecaria agallocha (Euphorbiaceae)	A tree 10-17 m high; wood white, soft. The breathing organs developed in connection with the roots do not assume the form of vertical blind root-suckers but consists of horizontal thickened segments, richly furnished with lenticels, that produce through the mud.	Common on mangrove forest along channels and river bank, tolerates variable salinity and soil moisture, inundated with only spring high tide.

Heritiera fomes (Sterculiaceae)	A small to medium tree, reaching 13-17 m in height; wood excellent, hard, tough and durable, red in colour. The most common species in present day Sundarbans.	Commonly grow along the river sides, sides of the creeks and landward of the true tidal forest, flooded during the spring tide. Dominated in the transition areas from saline-brackish to brackish-fresh water.
Nypa fruticans (Palmeae)	A soboliferous palm with a very large rootstock.	Everywhere on the banks of the estuaries and tidal rivers and in swampy localities in interior of forests.
Phoenix paludosa (Palmeae)	A gregarious palm, usually 4 m high; the roots send up short blind vertical root-suckers.	On or near bank of tidal rivers; today just north of Sundarbans area.
Rhizophora mucronata (Rhizophoraceae)	A tree 8-12 m high, wood red and hard.	Along the tidal creeks within the reach of daily tidal water within the Sundarbans.
Sonneratia apetala (Sonneratiaceae)	A gregarious tree, 25-20 m high; wood reddish brown, hard. The root send up vertical blind suckers.	Common on the inner estuarine zone, tolerate high salinity condition and regular tidal submergence.

Sources: Prain (1903), Sen and Banerjee (1988), and Karim (1994)

Appendix 2:

Some Commonly Used Symbols in Troels-Smith Scheme (1955)



n^1= 25% decomposed, n^2=50% decomposed, n^3=75% decomposed n^4= 100% decomposed

1=25%, 2=50%, 3=75% and 4=100 of composition

Appendix 3:

Laboratory Procedure for Pollen Analysis

Step 1: Evacuation of Alkali-soluble Organic Components
Take 0.5 cm^3 sediment sample and add *Lycopodium* tablet.

Add Potassium hydroxide.

Heat in boiling water for 30 minutes. Stir occasionally.

Decant through 180 micron sieve. Wash residue.

Centrifuge. Decant and wash until supernatant liquid is unstained.

Step 2: Hydrofluoric Digestion of Siliceous Material
Add hydrofluoric acid. Heat in boiling water until sediment dispenses and stratified sediment appears -1 hour.

Stir, centrifuge, decant.

Add hydrochloric acid (10% soln.). Heat in boiling water for 3 to 5 minutes.

Centrifuge, decant, wash with distilled water. Stir, centrifuge , decant.

Transfer to small tubes.

Step 3: Evacuation of Unaltered Lignin and Cellulose
Add glacial acetic acid. Stir, centrifuge, decant.

Add acetylation mixture (1:9 con. sulphuric acid-acetic anhydride). Stir well.

Heat in boiling water of 1 minute. Top up with glacial acetic acid.

Centrifuge, decant.

Add glacial acid. Stir, centrifuge, decant.

Add distilled water. Stir, centrifuge, decant (twice).

Step 4: Staining
Wash with Ethanol x2 (rinse T/Tube walls) to remove water. Centrifuge, decant.

Add 2 mls Tertiary Alcohol, 2 drop of safranine then transfer into small vials, Centrifuge, decant.

Add silicon fluid, same volume as sample. Stir, plug with cotton wool.

Make slide.

Appendix 4:

Laboratory Procedure for Diatom Analysis

Take about 5 gm sediment sample in a beaker.

Add 50 ml 30% H_2O_2.

Heat gently on a hot plate overnight until organic matter has been removed.

Remove coarse-grained mineral matter by gentle swilling in a beaker followed by decanting the diatoms and finer mineral fractions.

Drop carefully about 0.2 ml of liquid on to a cover slip and leave it on a hot plate at a gentle temperature for few hours until the water evaporates.

Mount the coverslip using Naphrax.

Now ready for counting.

Appendix 5:

Laboratory Procedure for Particle Size Analysis

Take 20 gm air dry sediment sample in a beaker.

Add 150 ml distilled water and 10 ml sodium hexametaphosphate. Stir well.

Transfer carefully in a labelled litre measuring cylinder and top up to volume (1000 ml) with distilled water.

Shake the suspension thoroughly end over end for one minute and then place it on the bench in water bath at 25°C temperature.

Start the stop watch, insert the hydrometer in to the suspension and take first sample of 10 ml at a depth of 10 cm exactly after 4 minutes 5 seconds. Collect the sample in a vial.

Take the second and third sample of similar volume at same depth after 46 minutes, and 6 hours 56 minutes, respectively.

Leave the vials in an oven to evaporate the water and weight the sediment remained.

Calculate the particle size using computer program (available in the Department).

Appendix 6:
Laboratory Procedure for Loss-on-Ignition Measurement

Accurately weight about 10 gm of even dry sediment sample and place in a weighted nickel crucible.

Place the crucible with sample in a muffle furnace pre-heated at 800°C and leave for 30 minutes.

Remove the crucible from the furnace using a handle tong, cool it in a desiccator and re-weight.

Calculate the Loss-on-Ignition in percentage.

Appendix 7:

Lithological Data at Panigati

Borehole No. P-500W

Stratum	Altitude (m)	Depth (cm)	Description
20	+1.90 to +1.27	0 to 63	As3, Ag1, Lf++; nig.2, strf.0, sicc. 3, elas.0, l.s.?. Buff grey silty clay with diffused iron staining; hard and plastic
19	+1.27 to +0.47	63 to 143	As2, Ga1, Ag1, Lf++; nig.2, strf.0, sicc. 2++, elas.0, l.s.0 Buff colour sandy silty clay with diffused iron staining; crumbly
18	+0.47 to +0.13	143 to 177	As2, Ag2, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.0 Buff grey silty clay with diffused iron staining; plastic.
17	+0.13 to -0.10	177 to 200	Ag2, As1, Ga1; nig.2, strf.++, sicc.2, elas.0, l.s.0 Battleship grey silty sandy clay; very coarsely laminated to plastic
16	-0.10 to -0.73	200 to 263	Ga2, Ag2, As+; nig.2, strf.2, sicc.2, elas.0, l.s.+ Battleship grey silty sand with rare clay; laminated.
15	-0.73 to -1.00	263 to 290	Ag2, As1, Ga1; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey sandy clayey silt; plastic.
14	-1.00 to -1.23	290 to 313	As2, Ag2; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey silty clay; plastic
13	-1.23 to -1.40	313 to 330	Ld^{3}2, Sh1, As1, Dh+, anth+; nig.2, strf.1, sicc.2, elas.2, l.s.1 Brown grey organic clay limus with rare charcoal and herbaceous detritus; coarsely laminated
12	-1.40 to -1.88	330 to 378	Ld^{3}4, Dh+, Sh++, anth+; nig.3, strf.2, sicc.2, elas.2, l.s.+ Dark brown limus with herbaceous detritus and charcoal; coarsely laminated
11	-1.88 to -2.19	378 to 409	Ag2, As1, Sh1, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Light brown grey organic clayey silt with rare herbaceous detritus; coarsely laminated
10	-2.19 to -2.66	409 to 456	Ld^{3}4, Dl++, As+, Sh+; nig.3, strf.1, sicc.2, elas.1, l.s.0 Light brown limus with rare clay and woody detritus; coarsely laminated.
09	-2.66 to -3.00	456 to 490	As2, Ag1, Sh1, Dl+, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Brown grey organic silty clay with rare wood and herbaceous detritus; coarsely laminated
08	-3.00 to -4.27	490 to 617	Ld^{3}4, Dh+, Dl+, Th^2++; nig.3, strf.0, sicc.2, elas.2, l.s.1 Dark brown limus with herbaceous and woody detritus, some rootlets; crumbly.
07	-4.27 to -4.47	617 to 637	Ag2, As1, Sh1; nig.2, strf.0, sicc.2, elas.0, l.s.1 Light brown grey organic clay silt; plastic
06	-4.47 to -4.93	637 to 683	Ag2, As1, Ga1, Dh+; nig.2, strf.++, sicc.2, elas.0, l.s.1 Grey colour sandy clayey silt with rare herbaceous detritus; laminated.
05	-4.93 to -5.78	683 to 768	As2, Ag2, Ga++, Dl+; nig.2, strf.++, sicc.2, elas.0, l.s.0 Grey colour sandy silty clay with rare woody detritus; coarsely laminated
04	-5.78 to -6.40	768 to 830	Ag2, As1, Ga1, Sh++; nig.2, strf.++, sicc.2, elas.0, l.s.0 Grey colour organic sandy clay silt; coarsely laminated

03	-6.40 to -6.52	830 to 842	$Ld^3$4, Sh++; nig.3, strf.0, sicc.2, elas.1, l.s.0. Dark brown limus with rare organic matter; crumbly
02	-6.52 to -7.30	842 to 920	As2, Ag2, Ga++, Dl+, Sh+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Light grey silty clay with many woody detritus, rare organic matter and sands; coarsely laminated
01	-7.30 to -8.20	920 to 1010	As2, Ag2, Sh++; nig.2, strf.1, sicc.2, elas.0, l.s.0 Light grey organic silty clay; coarsely laminated

Borehole No. P-400W

Stratum	Altitude (m)	Depth (cm)	Description
21	+1.91 to +1.37	0 to 54	As3, Ag1, Lf++; nig.2, strf.0, sicc.3, elas.0, l.s.? Buff colour silty clay with diffused iron staining; hard
20	+1.37 to +1.03	54 to 88	As2, Ag1, Ga1, Lf++; nig.2, strf.0, sicc.3, elas.0, l.s.0 Buff colour sandy silty clay with diffused iron staining; crumbly
19	+1.03 to +0.46	88 to 145	Ga2, As1, Ag1, Lf++; nig.2, strf.++, sicc.2, elas.0, l.s.0 Buff grey silty clayey sand with diffused iron staining; coarsely laminated
18	+0.46 to +0.17	145 to 174	As2, Ag2, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.0 Buff grey silty clay with diffused iron staining; plastic and hard.
17	+0.17 to -0.09	174 to 200	Ga2, Ag2, Lf++, As+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Buff grey silty sand with rare clay and diffused iron staining; coarsely laminated
16	-0.09 to -0.81	200 to 272	Ga2, Ag2, As+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Battleship grey silty sand with rare clay; coarsely laminated.
15	-0.81 to -0.98	272 to 289	Ag2, As1, Ga1; nig.2, strf.+, sicc.2, elas.0, l.s.0 Battleship grey sandy clayey silt; plastic
14	-0.98 to -1.33	289 to 324	As2+, Ag2, Ga+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey silty clay with rare sand; plastic
13	-1.33 to -1.58	324 to 349	$Ld^3$2, Sh1, As1, anth+; nig.2+, strf.1, sicc.2, elas.1, l.s.2 Brown grey organic clayey limus with rare charcoal; coarsely laminated
12	-1.58 to -2.31	349 to 422	$Ld^3$4, anth++, Dh+,; nig.3, strf.++, sicc.2, elas.2, l.s.0 Dark brown limus with frequent charcoal and rare herbaceous detritus; coarsely laminated.
11	-2.31 to -2.47	422 to 438	Ag2, As1, Sh1; nig.2, strf.0, sicc.2, elas.0, l.s.+ Light brown grey organic clay silt; plastic and sticky
10	-2.47 to -3.16	438 to 507	$Ld^3$4, Dh+, Dl+; nig.2++, strf.0, sicc.2, elas.2, l.s.0 Dark brown limus with rare woody and herbaceous detritus; crumbly.
09	-3.16 to -3.29	507 to 520	As2, Ag1, Sh1; nig.2, strf.0, sicc.2, elas.0, l.s.0 Light brown organic silty clay; plastic
08	-3.29 to -3.83	520 to 574	$Ld^3$4, Dh+; nig.3, strf.1, sicc.2, elas.2, l.s.0 Dark brown limus with rare herbaceous detritus; coarsely laminated
07	-3.83 to -3.99	574 to 590	$Ld^3$2, Sh1, As1; nig.3, strf.0, sicc.2, elas.1, l.s.0 Brown organic clayey limus; spongy and crumbly.
06	-3.99 to -4.59	590 to 650	Ag2, As1, Sh1; nig.2, strf.0, sicc.2, elas.0, l.s.0 Brown grey organic clayey silt; sticky and plastic
05	-4.59 to -4.84	650 to 675	$Ld^3$4, Dl+; nig.2, strf.0, sicc.2, elas.++, l.s.0 Dark brown limus with rare woody detritus; crumbly

04	-4.84 to -5.13	675 to 704	As2, Ag2, Sh++, Ga+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey organic silty clay with rare sand; plastic
03	-5.13 to -6.34	704 to 825	As3, Ag1, Sh+, Ga+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey silty clay with organic deposits and sand; coarsely laminated
02	-6.34 to -6.76	825 to 867	Ld^{3}2, Sh2; nig.2++, strf.0, sicc.1++, elas++, l.s.0 Brown organic limus;partly decomposed forming mud like substance; plastic
01	-6.76 to 7.45	867 to 936	As2, Ag2, Ga+++, Sh+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with frequent sand and rare woody detritus; plastic

Borehole No. P-300W

Stratum	Altitude (m)	Depth (cm)	Description
17	+1.98 to +1.35	0 to 63	As3, Ag1, Lf++, Th^2++; nig.2, strf.0, sicc.3, elas.0, l.s.? Buff grey silty clay with diffused iron staining and rootlets; hard
16	+1.35 to +1.08	63 to 90	As2, Ag1, Ga1, Lf++; nig.2, strf.0, sicc.3, elas.0, l.s.0 Buff colour sandy silty clay with diffused iron staining; crumbly.
15	+1.08 to +0.76	90 to 122	As2, Ag2; nig.2, strf.0, sicc.2, elas.0, l.s.0 Buff grey silty clay with diffused iron staining; plastic and hard
14	+0.76 to +0.55	122 to 143	Ga2, Ag2, Lf++, As+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Buff grey silty sand with rare clay and diffused iron staining; coarsely laminated
13	+0.55 to -0.32	143 to 230	Ga3, Ag1, As+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty sand with rare clay; crumbly
12	-0.32 to -0.52	230 to 250	Ag2, As1, Ga1; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey sandy clayey silt; plastic
11	-0.52 to -0.66	250 to 264	As2, Ag2; nig.2, strf.0, sicc.2, elas.0. l.s.0 Battleship grey silty clay; plastic
10	-0.66 to -0.82	264 to 280	Ld^{3}2, Sh1, As1; nig.2+, strf.1, sicc.2, elas.1, l.s.1 Brawny grey organic clay limus; coarsely laminated
09	-0.82 to -1.27	280 to 325	Ld^{3}4, anth++, Dh+, Dl+; nig.3, strf.++, sicc.2, elas.2, l.s.0 Dark brown limus with frequent charcoal and rare woody and herbaceous detritus; coarsely laminated
08	-1.27 to -1.97	325 to 395	Sh2, As1, Ag1, Dh+, Th^2+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Brown grey organic silty clay with rare herbaceous detritus and rootlets; plastic
07	-1.97 to -2.12	395 to 410	Ld^{3}2, Sh1, As1; nig.2, strf.++, sicc.2, elas.++, l.s.+ Brown grey organic clay limus; coarsely laminated
06	-2.12 to -2.72	410 to 470	As2, Ag1, Sh1, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Brown grey organic silty clay with rare herbaceous detritus; plastic
05	-2.72 to -3.07	470 to 505	Ld^{3}4, Dl+; nig.2++, strf.0, sicc.2, elas.2, l.s.1 Dark brown limus with rare woody detritus; crumbly
04	-3.07 to -3.24	505 to 522	As2, Sh2, anth++; nig.2, strf.1, sicc.2, elas.0, l.s.1 Light brown organic clay with frequent charcoal; coarsely laminated.
03	-3.24 to -3.51	522 to 549	Ld^{3}4, Dh+; nig.2++, strf.1, sicc.2, elas.2, l.s.0 Dark brown limus with rare herbaceous detritus; coarsely laminated
02	-3.51 to -3.70	549 to 568	Ld^{3}2, Sh1, As1; nig.2, strf.0, sicc.2, elas.1, l.s.0 Brown organic clayey limus; crumbly
01	-3.70 to -4.06	568 to 604	Ag2, As1, Sh1, Dh+, Th^2+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Brown organic clayey silt with rare herbaceous detritus and rootlets; plastic

Borehole No. P-208W

Stratum	Altitude (m)	Depth(cm)	Description
21	+1.86 to +1.29	0 to 57	As4, Lf+, Th^0+; nig.2, sicc.3, strf.0, elas.0, l.s.0. Buff-grey clay with living rootlets and diffused iron staining
20	+1.29 to +0.84	57 to 102	As2, Ga1, Lf1; nig.2, sicc.3, strf.+, elas.0, l.s.0. Buff colour sandy clay with diffused iron staining, coarsely laminated
19	+0.84 to +0.48	102 to 138	Ga2, As1, Lf1, Ag++; nig.2, sicc.2, strf.0, elas.0, l.s.0. Buff colour clayey sand with silty clasts, diffused iron staining and crumbly
18	+0.48 to +0.25	138 to 161	Ga3, Lf1; nig.2, sicc.2, strf.0, elas.0. l.s.0. Buff colour sand with diffused iron staining and iron clasts
17	+0.25 to -0.72	161 to 258	Ga4, As++, Ag++; nig.2, sicc.2, strf.+, elas.0, l.s.+. Battleship grey silty clayey fine sand, coarsely laminated
16	-0.72 to -1.09	258 to 295	As2, Ag1, Ga1; nig.2, sicc.2, strf.0, elas.0, l.s.0. Battleship sandy silty clay, coarsely laminated
15	-1.09 to -1.52	295 to 338	As3, Ag1, Ga++; nig.2, sicc.2, strf.0, elas.0, l.s.1. Battleship grey silty clay with rare sand, plastic
14	-1.52 to -1.65	338 to 351	As1, Ag1, Sh1, $Ld^3$1, Sh++, Dh+, Anth++; nig.2, sicc.2, strf.++, elas.++, l.s.1. Brown colour organic silty clay limus with charcoal and rare herbaceous detritus, coarsely laminated
13	-1.65 to -1.99	351 to 385	$Ld^3$4, Anth+; nig.3, sicc.2, strf.1, elas.2, l.s.0. Dark-brown limus with rare charcoal, moderately laminated
12	-1.99 to -2.19	385 to 405	As2, $Ld^2$1, Sh1, Dh+; nig.2, sicc.2, strf.+, elas.++, l.s.0. Light-brown organic clay limus, coarse laminated
11	-2.19 to -2.71	405 to 457	$Ld^2$4, Dh+, Th^3+, Dl+; nig.3, sicc.2, strf.+, elas.2, l.s.+. Brown limus with herbaceous and woody detritus, rare rootlets, coarsely laminated
10	-2.71 to -2.95	457 to 481	$Ld^3$4; nig.3+, sicc.2, strf.0, elas.2, l.s.1. Dark-brown limus, crumbly.
09	-2.95 to -3.41	481 to 527	As2, Ag1, Sh1; nig.2, sicc.2, strf.0, elas.0, l.s.1 Brown-grey organic clay, plastic
08	-3.41 to -3.96	527 to 582	$Ld^3$4, Dh+; nig.3, sicc.2, strf.++, elas.2, l.s.1 Dark-brown limus with herbaceous detritus, coarsely laminated and crumbly.
07	-3.96 to -4.39	582 to 625	As2, Ag1, Sh1, Dh+, Ga+; nig.2, sicc.2, strf.0, elas.0, l.s.0 Brown-grey organic silty clay with herbaceous detritus, rare sand, plastic and sticky
06	-4.39 to -4.62	625 to 648	As3, Ag1, Sh++, Ga+; nig.2, sicc.2, strf+, elas.0, l.s.0 Battleship grey organic silty clay with rare sand, very coarsely laminated and plastic
05	-4.62 to -4.76	648 to 662	$Ld^3$4; nig.3, sicc.2, strf.0, elas.2, l.s.+. Dark-brown limus, crumbly
04	-4.76 to -5.06	662 to 692	As2, Ag1, Sh1; nig.2, sicc.2, strf.0, elas.0, l.s.1 Brown colour organic silty clay, plastic.
03	-5.06 to -5.19	692 to 705	$Ld^3$4; nig.3, sicc.2, strf.0, elas.1, l.s.2 Dark-brown limus, crumbly
02	-5.19 to -5.74	705 to 760	As4, Sh++, Ga+; nig.2, sicc.2, strf.+, elas.0, l.s.1 Battleship grey organic clay with rare sand, coarsely laminated
01	-5.74 to -6.39	760 to 825	As3, Ag1, Sh++, Ga+; nig.2, sicc.2, strf.+, elas.0, l.s.0 Battleship grey organic silty clay with rare sand, coarsely laminated

Borehole No. P-100W

Stratum	Altitude (m)	Depth (cm)	Description
19	+1.67 to +0.93	0 to 74	As3, Ag1, Lf+, Th[1]+; nig.2, strf.0, sicc.3, elas.0, l.s.? Buff grey silty clay with diffused iron staining and rare rootlets; hard
18	+0.93 to +0.69	74 to 98	Ag2, As1, Ga1, Lf++; nig.2, strf.+, sicc.2, elas.0, l.s.0 Buff colour sandy clayey silt with diffused iron staining; coarsely laminated
17	+0.69 to +0.29	98 to 138	As2, Ag2, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.0 Buff grey silty clay with diffused iron staining; rare silty clasts; coarsely laminated
16	+0.29 to -0.43	138 to 210	Ga2, Ag2, As++; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey silty fine sand with few clay; coarsely laminated
15	-0.43 to -0.72	210 to 239	As2, Ag2, Sh+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey silty clay with rare decomposed organic matter; plastic
14	-0.72 to -0.87	239 to 254	Ld[3]2, Sh1, Ag1, Dh+; nig.2, strf.1+, sicc.2, elas.++, l.s.+ Light brown organic clay limus with rare herbaceous detritus; coarsely laminated
13	-0.87 to -1.48	254 to 315	Ld[3]4, anth+++, Dh+, Dl+; nig.3, strf.2, sicc.2, elas.2, l.s.1 Dark brown limus with frequent charcoal; are woody and herbaceous detritus; well laminated
12	-1.48 to -1.59	315 to 326	Ag2, Ld[3]1, Sh1; nig.2, strf.0, sicc.2, elas.+, l.s.0 Brown organic clay limus; moulted
11	-1.59 to -1.87	326 to 354	Ld[3]4, Th[2]++; nig.2, strf.1, sicc.2, elas.2, l.s.0 Brown limus with rootlets; coarsely laminated
10	-1.87 to -1.99	354 to 366	Ag2, Sh1, Ld[3]1, Dh+, Th[2]+; nig.2, strf.+, sicc.2, elas.+, l.s.0 Light brown organic silty limus with rare herbaceous detritus and rootlets; coarsely laminated
09	-1.99 to -2.67	366 to 434	Ld[3]4, Th[2]++, Dh+; nig.3, strf.2, sicc.2, elas.2, l.s.1 Dark brown limus with rootlets and rare herbaceous detritus; coarsely laminated
08	-2.67 to -3.23	434 to 490	As2, Ag2, Sh++, Th[2]++, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey organic silty clay with herbaceous detritus and rootlets; plastic
07	-3.23 to -3.87	490 to 554	Ag2, As1, Sh1, Th[2]++, Dh+; nig.2, strf+, sicc.2, elas.0, l.s.0 Battleship grey organic clayey silt with rare herbaceous detritus and rootlets; sticky and plastic
06	-3.87 to -4.14	554 to 581	Ld[3]3, Sh1, Th[3]++; nig.2, strf.1, sicc.2, elas.2, l.s.1 Brawny organic limus with rootlets; coarsely laminated
05	-4.14 to -4.34	581 to 601	Ag2, Ld[3]1, Sh1, As+; nig.2, strf.+, sicc.2, elas.+, l.s.1 Light brown organic silty limus with rare clay; moulted or coarsely laminated
04	-4.34 to -4.63	601 to 630	As2, Ag2, Sh+, Dh+; nig.2, strf.+, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare decomposed organic matter; rare herbaceous materials; coarsely laminated
03	-4.63 to -5.28	630 to 695	Ag2, As1, Ga1, Sh++, Dh+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Grey organic sandy clayey silt with rare herbaceous and woody detritus; plastic
02	-5.28 to -5.46	695 to 713	Ld[3]2, Sh2, As+; nig.2, strf.++, sicc.1++, elas.++, l.s.0 Brown organic limus with rare clay; partly decomposed forming mud like substance
01	-5.46 to -5.64	713 to 731	Ag2, As2; nig.2, strf.0, sicc.2, elas.0, l.s.++ Battleship grey silty clay; plastic

Borehole No. P-0

Stratum	Altitude (m)	Depth (cm)	Description
11	+1.64 to +0.30	0 to 134	As2, Ag2, Lf++; nig.2, strf.0, sicc.3, elas.0, l.s.? Buff colour silty clay with diffused iron staining; hard
10	+0.30 to -0.86	134 to 250	Ag3, As1, Lf++, Dg+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Buff grey clayey silt with rare organic fragments (eroded peats), plastic
09	-0.86 to -0.97	250 to 261	Sh2, As2, Dh+; nig.2+, strf.2, sicc.2, elas.0, l.s.2 Brown organic clay with rare herbaceous detritus; coarsely laminated
08	-0.97 to -1.57	261 to 321	Ld^{3}4, Th^{2}+, Dl+; nig.3, strf.1, sicc.2, elas.1, l.s.1 Dark brown limus with rare rootlets and woody detritus; coarsely laminated
07	-1.57 to -1.67	321 to 331	As2, Ag2, Th^{2}+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare rootlets; plastic
06	-1.67 to -2.31	331 to 395	Ld^{3}3, Th^{2}1, Dl++; nig.3, strf.2, sicc.2, elas.1, l.s.0 Brown limus with rootlets; some woody detritus; coarsely laminated
05	-2.31 to -2.44	395 to 408	Th^{1}3, Sh1, Ag++; nig.3+, strf.0, sicc.2, elas.2, l.s.1 Brown organic turfa with rare silt; fibrous
04	-2.44 to -2.82	408 to 446	Ld^{2}3, Th^{2}1, Dl++, anth+; nig.2+, strf.1, sicc.2, elas.2, l.s.0 Brown limus with rootlets and rare charcoal and woody detritus; coarsely laminated
03	-2.82 to -3.12	446 to 476	As2, Ag2, Th^{2}+, Sh+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with are rootlets and herbaceous detritus; coarsely laminated
02	-3.12 to -3.38	476 to 502	Ld^{3}4, Th^{2}++, Dl+; nig.2++, strf.2, sicc.2, elas.1, l.s.0 Dark-brown limus with frequent rootlets and rare woody detritus; laminated
01	-3.38 to -3.95	502 to 559	Ag2, As2, Th^{2}+, Dh+, Dl+; nig.2, strf.1, sicc.2, elas.+, l.s.0 Battleship grey clayey silt with rare woody and herbaceous detritus and rootlets; coarsely laminated

Borehole No. P-100E

Stratum	Altitude (m)	Depth (cm)	Description
17	+2.16 to +1.21	0 to 95	As2, Ag2, Lf++; nig.2, strf.0, sicc.3, elas.0, l.s.? Buff colour silty clay with diffused iron staining; hard
16	+1.21 to +0.80	95 to 136	As2, Ag1, Ga1, Lf++; nig.2, strf.+, sicc.2, elas.0, l.s.+ Buff colour sandy silty clay with diffused iron staining; coarsely laminated
15	+0.80 to +0.26	136 to 190	Ag2, As2, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.0 Buff grey clayey silt with diffused iron staining; plastic
14	+0.26 to -0.34	190 to 250	Ga2, As1, Ag1, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.2 Battleship grey silty clayey fine sand with rare herbaceous detritus; coarsely laminated
13	-0.34 to -0.47	250 to 263	As2, Ag1, Ga1, Dh+; nig.2, strf.+, sicc.2, elas.0, l.s.0 Battleship grey silty sandy clay with rare herbaceous detritus; coarsely laminated
12	-0.47 to -0.70	263 to 286	Sh2, Ld^{3}1, As1, anth+, Dh+; nig.2, strf.1, sicc.2, elas.+, l.s.0 Light brown organic clayey limus with rare charcoal and herbaceous detritus; coarsely laminated
11	-0.70 to -1.06	286 to 322	Ld^{3}4, anth++, As+, Dh+; nig.3, strf.0, sicc.2, elas.2, l.s.1 Dark brown limus with rare charcoal, clay and herbaceous detritus; crumbly
10	-1.06 to -1.27	322 to 343	Sh2, As2, Th^{2}++, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Brown organic clay with frequent rootlets and rare herbaceous detritus; plastic

09	-1.27 to -1.42	343 to 358	Ld³4, Th²++, Dh++, Dl+; nig.2++, strf.0, sicc.2, elas.2, l.s.0 Dark brown limus with frequent rootlets and herbaceous detritus and are woody detritus; crumbly
08	-1.42 to -1.61	358 to 377	As2, Ld³1, Sh1, Th²+, Dh+;nig.2, strf.1, sicc.2, elas.+, l.s.0 Brown organic clayey limus with rare rootlets and herbaceous detritus; coarsely laminated
07	-1.61 to -2.06	377 to 422	Ld³4, Th³+, Dh+, Dl+; nig.3, strf.+, sicc.2, elas.2, l.s.0 Dark brown limus with rare rootlets, herbaceous and woody detritus; coarsely laminated
06	-2.06 to -2.23	422 to 439	As2, Sh1, Ld³1, Th³+, Dh+; nig.2, strf.0, sicc.2, elas.1, l.s.0 Light brown organic clay with limus, rare herbaceous detritus and rootlets; plastic
05	-2.23 to -2.82	439 to 498	As2, Ag2, Th²++, Sh+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with frequent rootlets, rare herbaceous detritus and decomposed organic matter; plastic
04	-2.82 to -3.11	498 to 527	Ag2, As1, Ga1, Sh+, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey sandy clayey silt with rare herbaceous detritus; coarsely laminated
03	-3.11 to -3.33	527 to 549	Ld³4; nig.3, strf.0, sicc.2, elas.2, l.s.2 Dark brown limus with silty in-layer at 540 to 543 cm; crumbly
02	-3.33 to -3.52	549 to 568	Sh3, Ld³1, As+; nig.2, strf.0, sicc.2, elas.+, l.s.0 Brown organic limus with rare clay; plastic
01	-3.52 to -4.02	568 to 618	As2, Ag2, Ga+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare sand; coarsely laminated

Borehole No. P-200E

Stratum	Altitude (m)	Depth (cm)	Description
23	+2.27 to +2.07	0 to 20	As2, Ag2, Ga+; nig.2, strf.0, sicc.3, elas.0, l.s.? Battleship grey silty clay with rare sand; hard
22	+2.07 to +1.18	20 to 109	Ga3, Lf1, Th⁰+, Ag+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Buff colour sand with diffused iron staining, silty clasts and living rootlets; crumbly
21	+1.18 to +1.05	109 to 122	Ga2, As2; nig.2, strf.+, sicc.2, elas.0, l.s.0 Battleship grey clay sand; coarsely laminated
20	+1.05 to +0.52	122 to 175	Ga4; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey sand layer; coarsely laminated
19	+0.52 to +0.16	175 to 211	As3, Ag1, Ga+; nig.2, strf.+, sicc.2, elas.0, l.s.0 Battleship grey silty clay with rare sand; plastic
18	+0.16 to -0.13	211 to 240	Ga4; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey sand layer; coarsely laminated
17	-0.13 to -0.19	240 to 246	Ld³2, Sh1, As1, Dh+; nig.2, strf.1, sicc.2, elas.1, l.s.1 Light brown organic clay limus with herbaceous detritus; coarsely laminated
16	-0.19 to -0.71	246 to 298	As2, Ag2, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey silty clay with silty clasts and rare herbaceous detritus; plastic
15	-0.71 to -0.97	298 to 324	Ag2, As1, Sh1; nig.2, strf.0, sicc.2, elas.0, l.s.1 Brown organic clayey silt; moulted
14	-0.97 to -1.51	324 to 378	Ag2, As1, Ga1; nig.2, strf.+, sicc.2, elas.0, l.s.0 Battleship grey sandy clayey silt; coarsely laminated

13	-1.51 to -1.64	378 to 391	Ld^{3}2, Sh1, As1, anth++, nig.2+, strf.1, sicc.2, elas.1, l.s.1 Brown organic clayey limus with frequent charcoal; coarsely laminated
12	-1.64 to -2.02	391 to 429	Ld^{3}4, anth++, Dh+; nig.3, strf.1, sicc.2, elas.2, l.s.1 Dark-brown limus with frequent charcoal rare herbaceous detritus; coarsely laminated
11	-2.02 to -2.14	429 to 441	Ld^{3}2, Sh1, As1, anth+; nig.2, strf.0, sicc.2, elas.+.l.s.1 Brown organic clay limus with charcoal; crumbly
10	-2.14 to -2.74	441 to 501	Ld^{3}4, Dh+; nig.3, strf.1, sicc.2, elas.2, l.s.1 Dark brown limus with rare herbaceous detritus; coarsely laminated
09	-2.74 to -3.00	501 to 527	Ld^{2}4, As++; nig.2+, strf.0, sicc.2, elas.1, l.s.+ Brown clay limus; crumbly
08	-3.00 to -3.24	527 to 551	Sh2, As2, Ag+; nig.2, strf.0, sicc.2, elas.0. l.s.0 Brown organic clay with rare silt; plastic
07	-3.24 to -3.39	551 to 566	Ld^{3}2, Sh1, As1; nig.2, strf.0, sicc.2, elas.++, l.s.0 Brown organic clay limus; crumbly
06	-3.39 to -3.63	566 to 590	Sh2, As2; nig.2, strf.+, sicc.2, elas.+, l.s.1 Brown organic clay; coarsely laminated
05	-3.63 to -4.04	590 to 631	Ld^{3}4, Dh+; nig.3, strf.0, sicc.2, elas.2, l.s.0 Dark-brown limus with rare herbaceous detritus; crumbly
04	-4.04 to -4.20	631 to 647	Ld^{3}2, Sh1, As1; nig.2++, strf.0, sicc.2, elas.1, l.s.1 Brown organic clay limus; crumbly
03	-4.20 to -4.50	647 to 677	Sh2, As2, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Brown organic clay with rare herbaceous detritus; plastic
02	-4.50 to -5.04	677 to 731	As2, Ag2, Dh+; nig.2, strf.+, sicc.2, elas.0, l.s.0 Battleship grey silty clay with rare herbaceous detritus; coarsely laminated
01	-5.04 to -6.00	731 to 827	Ag2, As1, Ga1, Sh+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey silty sandy clay with rare decomposed organic matter; coarsely laminated

Borehole No. P-300E

Stratum	Altitude (M)	Depth (cm)	Description
17	+2.63 to +2.34	0 to 29	As2, Ag2, Ga+; nig.2, strf.0, sicc.3, elas.0, l.s.? Battleship grey silty clay with rare sand; hard
16	+2.34 to +1.40	29 to 123	Ga3, Lf1; nig.2, strf.0, sicc.3, elas.0, l.s.0 Buff colour sandy layer with diffused iron staining; crumbly
15	+1.40 to -0.59	123 to 322	Ga4; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey sandy layer; crumbly
14	-0.59 to -1.00	322 to 363	Ag2, As1, Ga1; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey sandy clayey silt; plastic
13	-1.00 to -1.28	363 to 391	Ag2, As1, Sh1; nig.2, strf.0, sicc.2, elas.0, l.s.1 Brown grey organic clayey silt; plastic
12	-1.28 to -1.50	391 to 413	As2, Ga1, Ag1; nig.2, strf++, sicc.2, elas.0, l.s.0 Battleship grey silty sandy clay; coarsely laminated
11	-1.50 to -1.65	413 to 428	Ld^{3}3, As1; nig.2++, strf.1, sicc.2, elas.++, l.s.1 Brown clay limus; coarsely laminated
10	-1.65 to -2.05	428 to 468	Ld^{3}4; nig.3, strf.0, sicc.2, elas.2, l.s.1 Dark brown limus; crumbly

09	-2.05 to -2.20	468 to 483	Ld^{3}3, As1, anth++, Dh+, Th^2+; nig.2++, strf.1, sicc.2, elas++, l.s.1 Brown clayey limus with frequent charcoal, rare herbaceous detritus and rootlets; coarsely laminated
08	-2.20 to -2.49	483 to 512	Sh2, As2, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Brown organic clay with rare herbaceous detritus; coarsely laminated
07	-2.49 to -2.59	512 to 522	Ld^{3}3, As1, Sh++; nig.2, strf.1, sicc.2, elas.1, l.s.0 Brown organic clay limus; coarsely laminated
06	-2.59 to -3.05	522 to 568	Ld^{3}4, anth+, Dh+, Dl+, Th^2++; nig.3, strf.2, sicc.2, elas.2, l.s.0 Dark brown limus with rootlets and rare charcoal, woody and herbaceous detritus; laminated
05	-3.05 to -3.17	568 to 580	Ld^{3}3, As1, Sh++, Dh+; nig.2, strf.0, sicc.2, elas.++, l.s.+ Brown organic clay limus; coarsely laminated
04	-3.17 to -3.50	580 to 613	As2, Ag1, Sh1, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey silty clay with rare herbaceous detritus; plastic
03	-3.50 to -3.71	613 to 634	Ld^{3}4; nig.3, strf.2, sicc.2, elas.2, l.s.0 Dark brown limus; laminated
02	-3.71 to -3.87	634 to 650	Sh2, As2, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Brown organic clay with rare herbaceous detritus; coarsely laminated
01	-3.87 to -4.53	650 to 716	As3, Ag1, Ga+, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare sand and herbaceous detritus; coarsely laminated

Borehole No. P-400E

Stratum	Altitude (m)	Depth (cm)	Description
18	+3.00 to +2.70	0 to 30	As3, Ga1; nig.2, strf.0, sicc.3, elas.0, l.s.? Battleship grey sandy clay; crumbly
17	+2.70 to +1.46	30 to 154	Ga3, Lf1, As++; nig.2, strf.0, sicc.3, elas.0, l.s.0 Buff colour sandy layer with diffused iron staining and rare clay; crumbly
16	+1.46 to +0.96	154 to 204	Ga4; nig.2, strf.0, sicc.2, elas.0,.l.s.0 Battleship grey sandy layer; crumbly
15	+0.96 to +0.32	204 to 268	As2, Ag1, Ga1; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey sandy silty clay; coarsely laminated
14	+0.32 to -0.04	268 to 304	Ga4; nig.2, strf.0, sicc.2, elas.0, l.s.2 Battleship grey sandy layer; crumbly
13	-0.04 to -0.40	304 to 340	As3, Ag1, Ga+; nig.2, strf++, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare sand; coarsely laminated
12	-0.40 to -0.58	340 to 358	As2, Ag1, Ga1; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey sandy silty clay; coarsely laminated
11	-0.58 to -1.00	358 to 400	As3, Ag1, Ga+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey silty clay with rare sand; plastic
10	-1.00 to -1.20	400 to 420	Ld^{3}4; nig.3, strf.2, sicc.2, elas.2, l.s.0 Dark brown limus; laminated
09	-1.20 to -1.29	420 to 429	Ld^{3}3, As1, Dh+; nig.2, strf.1, sicc.2, elas.1, l.s.0 Brown clay limus with rare herbaceous detritus; coarsely laminated
08	-1.29 to -1.50	429 to 450	Ld^{3}4, Dl+; nig.2, strf.0, sicc.2, elas.2, .l.s.0 Dark brown limus; crumbly

07	-1.50 to -1.82	450 to 482	Sh2, As2, Ga++, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Brown grey organic clay with some sands and rare herbaceous detritus; coarsely laminated
06	-1.82 to -2.04	482 to 504	Ld^{3}4; nig.3, strf.0, sicc.2, elas.2, l.s.1 Dark brown limus; crumbly
05	-2.04 to -3.77	504 to 677	Sh2, As2, Ga++, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.2 Brown grey organic clay with few sand and rare herbaceous detritus; coarsely laminated
04	-3.77 to -3.91	677 to 691	Ld^{3}4, Dh+; nig.3, strf.0, sicc.2, elas.2, l.s.1 Dark brown limus with rare herbaceous detritus; crumbly
03	-3.91 to -4.18	691 to 718	Sh2, As2, Dh+; nig.2, strf.++, sicc.2, elas.0, l.s.0 Brown organic clay with rare herbaceous detritus; very coarsely laminated
02	-3.91 to -4.44	718 to 771	Ld^{3}4, Dh+, Dl+; nig.3, strf.0, sicc.2, elas.2, l.s.+ Dark brown limus with rare woody and herbaceous detritus; crumbly
01	-4.44 to -4.77	771 to 804	As3, Ag1, Sh++; nig.2, strf.+, sicc.2, elas.0, l.s.1 Battleship grey organic silty clay; plastic

Borehole No. P-500E

Stratum	Altitude (m)	Depth (cm)	Description
18	+3.31 to +2.62	0 to 69	Ga2, As2; nig.2, strf.0, sicc.3, elas.0, l.s.? Battleship grey sandy clay; crumbly
17	+2.62 to +1.61	69 to 170	Ga3, Lf1; nig.2, strf.0, sicc.2, elas.0, l.s.0 Buff colour sandy layer with diffused iron staining; crumbly
16	+1.61 to +1.20	170 to 211	Ga2, As1, Ag1, Lf++; nig.2, strf.1, sicc.2, elas.0, l.s.0 Buff colour clayey silty sand with diffused iron staining; coarsely laminated
15	+1.20 to -0.10	211 to 341	Ga4; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey sandy layer; crumbly
14	-0.10 to -0.46	341 to 377	As2, Ag2, Ga+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey silty clay with rare sand; plastic
13	-0.46 to -0.83	377 to 414	Sh2, As2; nig.2, strf.0, sicc.2, elas.0, l.s.+ Brown grey organic clay; plastic
12	-0.83 to -0.96	414 to 427	As3, Ag1; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay; plastic
11	-0.96 to -1.10	427 to 441	Ld^{3}3, As1, Dh+; nig.2+, strf.1, sicc.2, elas.2, l.s.1 Brown clayey limus with herbaceous detritus; coarsely laminated
10	-1.10 to -1.41	441 to 472	Ld^{3}4; nig.3, strf.1, sicc.2, elas.2, l.s.1 Dark brown limus; coarsely laminated
09	-1.41 to -1.67	472 to 498	Sh2, As2, Th^2+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Brown grey organic clay with rare rootlets and herbaceous detritus; plastic
08	-1.67 to -1.78	498 to 509	Ld^{3}4, Sh++; nig.3, strf.0, sicc.2, elas.1+, l.s.1 Dark brown organic limus; crumbly
07	-1.78 to -2.25	509 to 556	Sh2, As2, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Brown organic clay with rare herbaceous detritus; moulted
06	-2.25 to -3.08	556 to 639	Ld^{3}4, Dh+; nig.3, strf++, sicc.2, elas.2, l.s.2 Dark brown limus with rare herbaceous detritus; coarsely laminated

05	-3.08 to -3.22	639 to 653	As2, Sh2, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Brown grey organic clay with rare herbaceous detritus; plastic
04	-3.22 to -3.59	653 to 690	Ld^{3}3, Sh1, Dh+; nig.2, strf.0, sicc.2, elas.2, l.s.0 Brown organic limus; crumbly
03	-3.59 to -3.87	690 to 718	Sh2, As2, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Brown grey organic clay with rare herbaceous detritus; plastic
02	-3.87 to -4.03	718 to 734	Ld^{3}4, Dl+; nig.2++, strf.0, sicc.2, elas.2, l.s.0 Dark brown limus with rare woody detritus; crumbly
01	-4.03 to -4.37	734 to 768	As3, Ga1, Dl+; nig.2, strf.1, sicc.2, elas.0, l.s.2 Battleship grey sandy clay with rare woody detritus; coarsely laminated

Borehole No. P-30N

Stratum	Altitude (m)	Depth (cm)	Description
10	+1.80 to +0.50	0 to 130	As3, Ag1, Lf++, Ga+; nig.2, strf.0, sicc.3, elas.0, l.s.? Buff colour silty clay with diffused iron staining and rare sand; plastic
09	+0.50 to -0.01	130 to 181	As2, Ag2, anth++. Sh+, Dh+; nig.2, strf.+, sicc.2, elas.0, l.s.0 Battleship grey silty clay with frequent charcoal; rare herbaceous detritus; dense and plastic
08	-0.01 to -0.95	181 to 275	Ga2, Ag2, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey silty fine sand with rare herbaceous detritus; mica grains; coarsely laminated
07	-0.95 to -1.20	275 to 300	As3, Ag1, Sh+, Dh+; nig.2, strf.+, sicc.2, elas.0, l.s.0 Battleship grey silty clay with rare decomposed organic matter and herbaceous detritus; plastic
06	-1.20 to -1.49	300 to 329	Ld^{3}3, As1, Dh+, Dl+; nig.2+, strf.1, sicc.2, elas.1, l.s.2 Brown clayey limus with rare woody and herbaceous detritus; coarsely laminated
05	-1.49 to -2.70	329 to 450	Ld^{2}4, Sh++, anth +, Dh+, Dl+; nig.2++, strf.2, sicc.2, elas.1, l.s.+ Dark brown organic limus with rare charcoal, woody and herbaceous detritus; well laminated
04	-2.70 to -2.97	450 to 477	As2, Ag1, Sh1, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey organic silty clay with rare herbaceous detritus; coarsely laminated
03	-2.97 to -3.29	477 to 509	Ld^{3}4, Sh++, Dh+, Dl+; nig.2+, strf.1, sicc.2, elas.1, l.s.0 Dark brown organic limus with rare woody and herbaceous detritus; coarsely laminated
02	-3.29 to -3.42	509 to 522	Ld^{2}2, As1, Sh1, anth++, Dl+; nig.2+, strf.0, sicc.2, elas.0, l.s.1 Grey organic clayey limus with frequent charcoal; rare woody detritus; crumbly
01	-3.42 to -4.88	522 to 668	As3, Ag1, Ga++, Th^{2}+, Dh+; nig.2, strf.1, sicc.2, elas.0,.l.s.2 Battleship grey silty clay with frequent sand; rare herbaceous detritus and rootlets; coarsely laminated

Borehole No. P-100N

Stratum	Altitude (m)	Depth (cm)	Description
17	+2.09 to +1.89	0 to 20	As3, Ag1, Lf+, Ga++; nig.2, strf.0, sicc.3, elas.0, l.s.? Buff colour silty clay with frequent sand and rare diffused iron staining; plastic
16	+1.89 to +1.00	20 to 109	Ga3, Lf1, As+, Ag+; nig.2, strf.0, sicc.3, elas.0, l.s.0 Buff colour sandy layer with diffused iron staining; rare silt and clay; crumbly

15	+1.00 to +0.20	109 to 189	Ga4; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey sandy layer; crumbly
14	+0.20 to -0.59	189 to 268	As3, Ag1, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.+ Battleship grey silty clay with rare herbaceous detritus; plastic
13	-0.59 to -1.77	268 to 386	Ga4; nig.2, strf.+, sicc.2, elas.0, l.s.2 Battleship grey sandy layer; coarsely laminated
12	-1.77 to -1.91	386 to 400	As4, Ag+, Ga+; nig.2, strf.0, sicc.2, elas.0, l.s.+ Battleship grey clay layer with rare silt and sand; plastic
11	-1.91 to -2.12	400 to 421	Ld^{3}3, As1, anth+, Dh+; nig.2, strf.1+, sicc.2, elas.1, l.s.+ Brown clayey limus with rare charcoal and herbaceous detritus; laminated
10	-2.12 to -2.54	421 to 463	Ld^{3}4, Th^2+, anth+, Dh+; nig.3, strf.1, sicc.2, elas.1, l.s.1 Dark brown limus with rare charcoal, rootlets and herbaceous detritus; coarsely laminated
09	-2.54 to -2.63	463 to 472	As3, Sh1; nig.2, strf.0, sicc.2, elas.0, l.s.1 Brown organic clay; plastic
08	-2.63 to -3.45	472 to 554	Ld^{2}4, Th^2+, Dh+, Dl+; nig.3, strf.1, sicc.2, elas.2, l.s.0 Dark brown limus with rare rootlets; woody and herbaceous detritus; laminated
07	-3.45 to -3.63	554 to 572	Ld^{3}4, anth+, Dh+; nig.3+, strf.1, sicc.2, elas.2, l.s.0 Dark brown limus with rare charcoal and herbaceous detritus; well laminated
06	-3.63 to -3.81	572 to 590	As2, Sh1, Ld^{3}1, Dh+; nig.2, strf.1, sicc.2, elas.+. l.s.1 Brown organic clay with limus; rare herbaceous detritus; coarsely laminated
05	-3.81 to -4.27	590 to 636	Ld^{3}4, Dh+; nig.3, strf.0, sicc.2, elas.2, l.s.+ Dark brown limus with rare herbaceous detritus; crumbly
04	-4.27 to -4.38	636 to 647	Ld^{3}3, As1; nig.2++, strf.1, sicc.2, elas.2, l.s.1 Brown clayey limus; coarsely laminated
03	-4.38 to -5.92	647 to 801	As3, Ag1, Ga+, Dl+, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare sand; woody and herbaceous detritus; coarsely laminated
02	-5.92 to -6.13	801 to 822	Sh2, As1, Ld^{3}1, Ag+; nig.2, strf.0, sicc.2, elas.++, l.s.+ Light brown organic clay with limus and rare silt; plastic
01	-6.13 to -7.22	822 to 931	Ga2, As1, Ag1, Th^2+, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.+ Battleship grey silty clayey sand with rare rootlets and herbaceous detritus; coarsely laminated

Borehole No. P-200N

Stratum	Altitude (m)	Depth (cm)	Description
15	+2.07 to +1.75	0 to 32	As3, Ag1, Lf++, Ga++; nig.2, strf.0, sicc.3, elas.0, l.s.? Buff colour silty clay with frequent sand and diffused iron staining; hard
14	+1.75 to +1.00	32 to 107	Ga3, Ag1, Lf++; nig.2, strf.0, sicc.3, elas.0, l.s.0 Battleship grey silty sand with diffused iron staining; crumbly
13	+1.00 to -0.82	107 to 289	Ga4; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey sandy layer; homogeneous and crumbly
12	-0.82 to -1.83	289 to 390	As3, Ag1, Ga++ Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey silty clay with frequent sand and rare herbaceous detritus; plastic
11	-1.83 to -2.02	390 to 409	Ld^{3}2, As2, anth+, Dh+, Dg+; nig.2, strf.1, sicc.2, elas.1, l.s.1 Brown clayey limus with rare charcoal, herbaceous detritus and organic fragments; coarsely laminated

10	-2.02 to -2.43	409 to 450	Ld^{2}4, anth++, Dh+, Dg+; nig.3, strf.0, sicc.2, elas.2, l.s.0 Dark brown limus with frequent charcoal; rare herbaceous detritus and organic fragments; crumbly.
09	-2.43 to -2.61	450 to 468	Ld^{3}3, As1, Dh++, anth+; nig.2+, strf.1+, sicc.2, elas.2, l.s.0 Mid brown clayey limus with frequent herbaceous detritus; rare charcoal; laminated
08	-2.61 to -3.52	468 to 559	Ld^{2}4, Th^{2}+, Dh+, Dl+, Dg+; nig.2+, strf.1+, sicc.2, elas.2, l.s.0 Dark brown limus with rare rootlets, woody and herbaceous detritus; organic fragments; laminated
07	-3.52 to -3.73	559 to 580	Ld^{3}3, As1, Dh++; nig.2, strf.1, sicc.2, elas.1, l.s.1 Mid brown clayey limus with frequent herbaceous detritus; coarsely laminated
06	-3.73 to -4.20	580 to 627	Ld^{3}4, Dl+; nig.3, strf.0, sicc.2, elas.2, l.s.1 Dark brown limus with rare woody detritus; crumbly
05	-4.20 to -4.30	627 to 637	Ld^{3}2, Sh1, As1; nig.2, strf.1, sicc.2, elas.2, l.s.1 Brown organic clayey limus; coarsely laminated
04	-4.30 to -4.40	637 to 647	Ld^{3}4, Dl+; nig.3, strf.0, sicc.2, elas.2, l.s.0 Dark brown limus with rare woody detritus; crumbly
03	-4.40 to -5.39	647 to 746	As2, Ag2, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.2 Battleship grey silty clay with rare herbaceous detritus; coarsely laminated
02	-5.39 to -5.56	746 to 763	Ld^{3}3, As1, Sh++; nig.2, strf.0, sicc.2, elas.1, l.s.0 Light brown organic clayey limus; crumbly
01	-5.56 to -6.29	763 to 836	As3, Ag1, Dh+, Dl+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey silty clay with rare woody and herbaceous detritus; coarsely laminated

Borehole No. P-300N

Stratum	Altitude (m)	Depth (cm)	Description
10	+1.90 to +1.50	0 to 40	As3, Ag1, Lf++, Ga+; nig.2, strf.0, sicc.3, elas.0, l.s.? Buff colour silty clay with diffused iron staining, silty clasts and rare sand; hard
09	+1.50 to +1.04	40 to 86	Ga3, Lf1; nig.2, strf.0, sicc.2, elas.0, l.s.0 Buff colour fine sandy layer with diffused iron staining; crumbly
08	+1.04 to +0.17	86 to 173	As3, Ag1, Lf++, Th^{2}+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey silty clay with diffused iron staining; rare rootlets; plastic
07	+0.17 to -0.05	173 to 195	Ld^{3}3, As1, Sh++, Dh+, Th^{2}+; nig.2, strf.+, sicc.2, elas.1, l.s.1 Brown organic clayey limus with rare herbaceous detritus and rootlets; coarsely laminated
06	-0.05 to -0.37	195 to 227	Ld^{3}4, anth++, Dh+; nig.3, strf.1, sicc.2, elas.2, l.s.1 Dark brown limus with frequent charcoal; rare herbaceous detritus; coarsely laminated
05	-0.37 to -2.55	227 to 445	As2, Ag1, Ga1, Th^{2}+, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey sandy silty clay with frequent herbaceous detritus, rare rootlets; coarsely laminated
04	-2.55 to -3.37	445 to 527	Ga2, As1, Ag1; nig.2, strf.1, sicc.2, elas.0. l.s.0 Battleship grey silty clayey sand; coarsely laminated
03	-3.37 to -3.64	527 to 554	Ld^{3}4, anth++, Dh+; nig.3+, strf.2, sicc.2, elas.2, l.s.2 Dark brown limus with frequent charcoal; rare herbaceous detritus; well laminated
02	-3.64 to -3.90	554 to 580	Ld^{3}3, As1, Sh++, Dh+; nig.2, strf.1, sicc.2, elas.1, l.s.1 Brown organic clayey limus with rare herbaceous detritus; coarsely laminated
01	-3.90 to -4.41	580 to 631	As2, Ag1, Ga1, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.+ Battleship grey sandy silty clay with rare herbaceous detritus; coarsely laminated

Borehole No. P-400N

Stratum	Altitude (m)	Depth (cm)	Description
13	+1.56 to +1.18	0 to 38	As3, Ag1, Sh++, Th^0+; nig.2, strf.0, sicc.3, elas.0, l.s.? Brown organic silty clay with rare living roots; hard and plastic
12	+1.18 to +0.56	38 to 100	Ga3, Ag1, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.0 Buff grey silty sand with diffused iron staining; crumbly
11	+0.56 to +0.13	100 to 143	As3, Ag1, Lf+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare diffused iron staining and iron clasts; rare silty clasts; plastic
10	+0.13 to -0.02	143 to 158	As2, Ag1, $Ld^3$1, Sh+; nig.2, strf.0, sicc.2, elas.1, l.s.1 Grey silty clay with limus; rare decomposed organic matter; heterogenous
09	-0.02 to -0.28	158 to 184	As2, Ag2, Dh+; nig.2, strf.0, sicc.2, elas.0. l.s.1 Battleship grey silty clay with frequent silty clasts; rare herbaceous detritus; plastic
08	-0.28 to -0.67	184 to 223	$Ld^3$3, As1, anth++, Dh+, Dl+; nig.2, strf.2, sicc.2, elas.2, l.s.0 Brown clay limus with frequent charcoal ; rare woody and herbaceous detritus; well laminated
07	-0.67 to -0.88	223 to 244	$Ld^3$4, anth++, Dh++; nig.3, strf.2, sicc.2, elas.2, l.s.0 Dark brown limus with frequent charcoal and herbaceous detritus; laminated
06	-0.88 to -0.99	244 to 255	$Ld^3$2, As1, Ag1, Dh++; nig.2, strf.1, sicc.2, elas.1, l.s.0 Brown silty clayey limus with frequent herbaceous detritus; coarsely laminated
05	-0.99 to -1.34	255 to 290	$Ld^2$3, As1, Dh+, Th^2+; nig.2, strf.2, sicc.2, elas.2, l.s.1 Brown clayey limus with rare rootlets and herbaceous detritus; laminated
04	-1.34 to -1.75	290 to 331	$Ld^3$2, As2, Th^2+, Dh+, Dl+; nig.2, strf.2, sicc.2, elas.1, l.s.0 Brown clayey limus with frequent herbaceous detritus; rare woody detritus and rootlets; laminated
03	-1.75 to -2.67	331 to 423	$Ld^2$4, Dh++, Dg+; nig.2, strf.2, sicc.2, elas.2, l.s.0 Brown limus with frequent herbaceous detritus along the lamination; rare organic fragments; well laminated
02	-2.67 to -3.16	423 to 472	$Ld^2$3, As1, anth++, Dh+, Dl+; nig.2, strf.2, sicc.2, elas.1, l.s.1 Brown clayey limus with frequent charcoal; rare woody and herbaceous detritus; well laminated
01	-3.16 to -4.19	472 to 575	As3, Ag1, Ga++, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Battleship grey silty clay with frequent sand and rare herbaceous detritus; coarsely laminated

Borehole No. P-500N

Stratum	Altitude (m)	Depth (cm)	Description
15	+2.29 to +0.48	0 to 181	As3, Ag1, Lf++, Sh+, Th^0+; nig.2, strf.0, sicc.3, elas.0, l.s.? Buff colour silty clay with diffused iron staining, rare living rootlets and decomposed matter; hard and plastic
14	+0.48 to +0.37	181 to 192	As2, Ag1, $Ld^3$1, Sh++; nig.2, strf.0, sicc.2, elas.++, l.s.0 Light brown organic silty clay with limus; plastic to crumbly
13	+0.37 to +0.20	192 to 209	As2, Ag2, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey silty clay with rare herbaceous detritus; plastic
12	+0.20 to 0.00	209 to 229	$Ld^3$3, As1, Sh++, Ag+, Dh+; nig.2, strf.0, sicc.2, elas.1, l.s.0 Organic brown clayey limus with rare silt and herbaceous detritus; plastic

11	0.00 to -0.37	229 to 266	Ld^{2}4, anth++, Th^{2}+, Dh+; nig.3, strf.2, sicc.2, elas.2, l.s.1 Dark brown limus with frequent charcoal and rare herbaceous detritus and rootlets; well laminated
10	-0.37 to -0.73	266 to 302	Ld^{3}2, As1, Ag1, Th^{2}+; nig.2, strf.0, sicc.2, elas.1. l.s.0 Brown silty clayey limus with rare rootlets; plastic
09	-0.73 to -0.93	302 to 322	Ld^{3}3, As1, Th^{2}+, Dh+, Dl+; nig.2, strf.++, sicc.2, elas.2, l.s.0 Brown clayey limus with rare rootlets; woody and herbaceous detritus; coarsely laminated
08	-0.93 to -1.34	322 to 363	As3, Ag1, Dh++, anth+, Sh+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey silty clay with frequent herbaceous detritus; rare charcoal; coarsely laminated
07	-1.34 to -2.37	363 to 466	Ag2, As2, Sh+, Th^{2}+, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey organic silty clay with rare rootlets and herbaceous detritus; coarsely laminated
06	-2.37 to -2.52	466 to 481	Ld^{3}3, As1, Dh+, Dl+; nig.2, strf.0, sicc.2, elas.1, l.s.2 Mid brown coarsely limus with rare woody and herbaceous detritus; crumbly
05	-2.52 to -2.66	481 to 495	Ag2, As1, Sh1, Dh+, Dl+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Brown organic clayey silt with rare woody and herbaceous detritus; coarsely laminated
04	-2.66 to -3.11	495 to 540	Ld^{3}3, As1, Sh++, Ag+, Dh+; nig.2, strf.1, sicc.2, elas.1, l.s.0 Brown organic clayey limus with rare silt and herbaceous detritus, dicot leaves; coarsely laminated
03	-3.11 to -3.30	540 to 559	Ag3, As1, Sh+, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Battleship grey clayey silt with rare decomposed organic matter and herbaceous detritus; coarsely laminated.
02	-3.30 to -3.39	559 to 568	Ld^{3}4, As+; nig.3, strf.0, sicc.2, elas.2, l.s.1 Dark brown limus with rare clay; crumbly
01	-3.39 to -3.73	568 to 602	As3, Ag1, Dh+, Sh+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare decomposed organic matter and herbaceous detritus; coarsely laminated

Borehole No. P-30S

Stratum	Altitude (m)	Depth (cm)	Description
12 50	+1.81 to +0.91	0 to 90	As3, Ag1, Lf++, Th^{0}+; nig.2, strf.0, sicc.3, elas.0, l.s.? Buff colour silty clay with diffused iron staining, rare living rootlets within upper cm; plastic
11	+0.91 to +0.80	90 to 101	Ag3, Ga1, Lf++, As+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Buff colour sandy silt with rare clay and diffused iron staining; coarsely laminated
10	+0.80 to -0.41	101 to 222	As3, Ag1, Lf+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey silty clay with rare iron clasts; coarsely laminated
09	-0.41 to -0.67	222 to 248	Ld^{3}3, Ag1, anth+; nig.2, strf.0, sicc.2, elas.1, l.s.1 Brown silty limus with rare charcoal; crumbly
08	-0.67 to -1.19	248 to 300	Ld^{2}4, Th^{2}+, anth+, Dh+, Dl+; nig.3, strf.0, sicc.2, elas.1+, l.s.1 Dark brown limus with rare rootlets, charcoal, and woody and herbaceous detritus; crumbly
07	-1.19 to -1.57	300 to 338	As2, Ag1, Sh1, Th^{2}++, Dh+, Dl+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Battleship grey organic silty clay with frequent rootlets; rare woody and herbaceous detritus; coarsely laminated.

06	-1.57 to -2.41	338 to 422	$Ld^{2}3$, $Th^{2}1$, Dl+, Dh+; nig.2++, strf.2, sicc.2, elas.1+, l.s.2 Dark-brown limus with monocot rootlets with rare woody and herbaceous detritus; well laminated
05	-2.41 to -2.73	422 to 454	Ag3, As1, Sh++, Th^{2}+, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.2 Battleship grey organic clayey silt with rare rootlets and herbaceous detritus; coarsely laminated
04	-2.73 to -2.96	454 to 477	$Ld^{3}4$, Th^{3}+, Dh+, Dl+; nig.3, strf.0, sicc.2, elas.2, l.s.0 Dark brown limus with rootlets; woody and herbaceous detritus; crumbly.
03	-2.96 to -3.35	477 to 516	As2, Ag2, Dh+, Sh+; nig.2, strf.1++, sicc.2, elas.0, l.s.2 Brown grey silty clay with rare decomposed organic matter and herbaceous detritus; laminated
02	-3.35 to -3.46	516 to 527	$Ld^{3}3$, Ag1, Th^{3}+, Dh+, Dl+; nig.2, strf.+, sicc.2, elas.1, l.s.2 Brown grey silty limus with rare rootlets and herbaceous detritus; crumbly
01	-3.46 to -4.12	527 to 593	Ag3, As1, Ga++, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.3 Battleship grey sandy clayey silt with rare herbaceous detritus; coarsely laminated

Borehole No. P-100S

Stratum	Altitude (m)	Depth (cm)	Description
17	+1.91 to +1.19	0 to 72	As3, Ag1, Lf++, Sh+; nig.2, strf.0, sicc.3, elas.0, l.s.? Buff colour silty clay with diffused iron staining, rare decomposed organic matter; hard
16	+1.19 to +0.96	72 to 95	Ga3, Lf1, Ag+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Buff colour sandy layer with diffused iron staining and frequent iron clasts; crumbly
15	+0.96 to +0.78	95 to 113	As3, Lf1, Ag++, Ga+; nig.2, strf.+, sicc.2, elas.0, l.s.2 Buff colour clay with diffused iron staining and frequent iron clasts; rare silty clasts and sand; very coarsely laminated
14	+0.78 to +0.16	113 to 175	Ag2, As1, Ga1, nig.2, strf.0, sicc.2, elas.0, l.s.+ Battleship grey sandy clayey silt; crumbly to plastic
13	+0.16 to -0.01	175 to 192	As3, Ag1, Ga+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey silty clay with rare sand; plastic
12	-0.01 to -0.18	192 to 209	As2, Ga2, Ag++; nig.2, strf.++, sicc.2, elas.0, l.s.0 Battleship grey sandy clay with frequent silt; coarsely laminated
11	-0.18 to -0.31	209 to 222	As3 Ag1, Ga+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey silty clay with rare sand; plastic
10	-0.31 to -0.51	222 to 242	$Ld^{3}2$, Sh1, As1, anth+, Dh+; nig.2, strf.1, sicc.2, elas.1, l.s.1 Grey organic clayey limus with rare charcoal and herbaceous detritus; coarsely laminated
09	-0.51 to -1.01	242 to 292	$Ld^{3}4$, Th^{2}+, anth+, Dh+; nig.3, strf.0, sicc.2, elas.2, l.s.1 Dark brown limus with rare rootlets, charcoal and herbaceous detritus; crumbly
08	-1.01 to -1.18	292 to 309	$Ld^{3}2$, $Th^{2}1$, As1, Sh+; nig.2, strf.0, sicc.2, elas.1, l.s.1 Pink grey clay limus with frequent rootlets and rare herbaceous detritus; fibrous to crumbly
07	-1.18 to -2.18	309 to 409	$Ld^{3}4$, Th^{2}++, Dh+, Dl+; nig.3, strf.0, sicc.2, elas.2, l.s.1 Dark brown limus with frequent rootlets; rare woody and herbaceous detritus; crumbly
06	-2.18 to -2.28	409 to 419	$Ld^{3}3$, Ag1, Sh++, Dh+; nig.2, strf.0, sicc.2, elas.1, l.s.1 Grey organic silty limus with rare herbaceous detritus; sticky

05	-2.28 to -2.40	419 to 431	Ld^{3}4, Dh+; nig.3, strf.0, sicc.2, elas.2, l.s.1 Dark brown limus with rare herbaceous detritus; crumbly
04	-240 to -2.66	431 to 457	Ld^{3}2, Sh1, As1, Dh+; nig.2, strf.++, sicc.2, elas.1, l.s.1 Brown organic clayey limus with rare herbaceous detritus; coarsely laminated
03	-2.66 to -2.89	457 to 480	Ld^{3}4, Th^2+, Dh+; nig.3+, strf.1, sicc.2, elas.2, l.s.1 Dark brown limus with rare rootlets and herbaceous detritus; coarsely laminated
02	-2.89 to -3.18	480 to 509	Ld^{2}2, Sh1, As1, Th^2+, Dh+; nig.2, strf.+, sicc.2, elas.+, l.s.1 Brown organic clayey limus with rare rootlets and herbaceous detritus; very coarsely laminated
01	-3.18 to -4.31	509 to 622	Ag2, As1, Ga1, Dl+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Battleship grey sandy clayey silt with rare woody detritus; coarsely laminated

Borehole No. P-200S

Stratum	Altitude (m)	Depth (cm)	Description
11	+1.81 to +0.81	0 to 100	As3, Ag1, Lf++; nig.2, strf.1 sicc.3, elas.0, l.s.? Buff colour silty clay with diffused iron staining; coarsely laminated
10	+0.81 to -0.05	100 to 186	Ag2, As2, Ga+, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Battleship grey clayey silt with rare sand and herbaceous detritus; coarsely laminated
09	-0.05 to -0.19	186 to 200	Ld^{3}2, As1, Ag1, anth++, Dh+; nig.2, strf.1, sicc.2, elas.1, l.s.1 Brown organic silty clayey limus with frequent charcoal and rare herbaceous detritus; coarsely laminated
08	-0.19 to -0.64	200 to 245	Ld^{3}4, Dh++, anth+; nig.3, strf.2, sicc.2, elas.2, l.s.1 Dark brown limus with frequent herbaceous detritus and rare charcoal; well laminated
07	-0.64 to -0.73	245 to 254	As2, Ag1, Sh1, Th^2+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Light brown organic silty clay with rare rootlets and herbaceous detritus; plastic
06	-0.73 to -1.14	254 to 295	Ld^{3}3, As1, Th^2++, Dh++; nig.2, strf.1, sicc.2, elas.1, l.s.0 Brown clayey limus with frequent rootlets and herbaceous detritus; coarsely laminated
05	-1.14 to -1.78	295 to 359	Ld^{3}4, Dh+, Dg+; nig.3, strf.2, sicc.2, elas.2, l.s.1 Dark brown limus with rare herbaceous detritus and organic fragments; well laminated
04	-1.78 to -2.82	359 to 463	As2, Ag2, Sh++, Ga++, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Battleship grey organic silty clay with frequent sands and rare herbaceous detritus; coarsely laminated
03	-2.82 to -2.91	463 to 472	Ld^{3}4, As+; nig.3, strf.0, sicc.2, elas.2, l.s.1 Dark brown limus with rare clay at the lower part of the layer; crumbly
02	-2.91 to -3.09	472 to 490	Ld^{3}2, As2, Sh++, Th^2+, Dh+; nig.2, strf.+, sicc.2, elas.1, l.s.1 Brown organic clayey limus with rare rootlets and herbaceous detritus; very coarsely laminated
01	-3.09 to -3.96	490 to 577	As2, Ag2, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.+ Battleship grey silty clay layer rare herbaceous detritus; coarsely laminated

Borehole No. P-300S

Stratum	Altitude (m)	Depth (cm)	Description
14	+2.23 to +1.51	0 to 72	As3, Ag1, Lf++; nig.2, strf.0 sicc.3, elas.0, l.s.? Buff colour silty clay with diffused iron staining; hard
13	+1.51 to +0.83	72 to 140	As3, Lf1, Ag+; nig.2, strf.0, sicc.3, elas.0, l.s.0 Buff colour clay layer with diffused iron staining and rare silt; hard

12	+0.83 to +0.69	140 to 154	As2, Ga2, Lf+; nig.2, strf.+, sicc.2, elas.0, l.s.0 Battleship grey sandy clay with rare diffused iron staining; very coarsely laminated
11	+0.69 to +0.55	154 to 168	As3, Ag1, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.1 Buff grey silty clay with diffused iron staining and rare iron clasts; hard and plastic
10	+0.55 to +0.05	168 to 218	Ga2, As1, Ag1; nig.2, strf.1, sicc.2, elas.0, l.s.1 Battleship grey silty clayey sand with few silty clasts 175 cm depth; homogeneous
09	+0.05 to -0.49	218 to 272	Ag2, As1, Ga1; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey sandy clayey silt; plastic
08	-0.49 to -0.58	272 to 281	Ld³3, As1, anth++, Dh+; nig.2, strf.2, sicc.2, elas.2, l.s.1 Brown clayey limus with frequent charcoal and rare herbaceous detritus; well laminated
07	-0.58 to -1.90	281 to 413	Ld³4, Th²++, Dh++; nig.3, strf.2, sicc.2, elas.2, l.s.1 Dark brown limus with frequent rootlets and herbaceous detritus; well laminated
06	-1.90 to -2.72	413 to 495	As2, Ag1, Ga1, Sh++, Dh+; nig.2, strf.+, sicc.2, elas.0, l.s.1 Battleship grey organic sandy silty clay with rare herbaceous detritus; very coarsely laminated
05	-2.72 to -2.88	495 to 511	Ld³3, As1, Sh++, Dh+; nig.2, strf.0, sicc.2, elas.1, l.s.0 Brown organic clayey limus with rare herbaceous detritus; moulted
04	-2.88 to -3.15	511 to 538	Ld³4; nig.3, strf.0, sicc.2, elas.2, l.s.1 Dark brown limus; crumbly
03	-3.15 to -3.34	538 to 557	Ld³2, As2, anth+, Dh+; nig.2, strf.1, sicc.2, elas.1+, l.s.1 Brown clayey limus with rare charcoal and herbaceous detritus; coarsely laminated
02	-3.34 to -3.60	557 to 583	As2, Ag1, Sh1, Dh+, Th²+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Grey organic silty clay with rare herbaceous detritus; plastic
01	-3.60 to -4.95	583 to 718	As4, Ag+, Ga+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey clay with rare silt, sand and herbaceous detritus; plastic and sticky

Borehole No. P-400S

Stratum	Altitude (m)	Depth (cm)	Description
13	+2.53 to +1.53	0 to 100	As3, Ag1, Lf++; nig.2, strf.0 sicc.3, elas.0, l.s.? Buff colour silty clay with diffused iron staining; hard
12	+1.53 to +0.67	100 to 186	As3, Lf1, Sh++; nig.2, strf.0, sicc.3, elas.0, l.s.0 Reddish brown clay with diffused iron staining; moulted
11	+0.67 to +0.17	186 to 236	Ga2, As1, Ag1; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey silty clayey sand ; coarsely laminated
10	+0.17 to -0.24	236 to 277	As3, Ag1; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey silty clay; moulted
09	-0.24 to -0.37	277 to 290	Ld³3, As1, anth++, Dh++; nig.2, strf.2, sicc.2, elas.2, l.s.1 Light grey clayey limus with frequent charcoal and herbaceous detritus; well laminated
08	-0.37 to -0.85	290 to 338	Ld³4, anth++, Dh+; nig.3, strf.2, sicc.2, elas.2, l.s.1 Dark brown limus with frequent charcoal and rare herbaceous detritus; well laminated
07	-0.85 to -1.01	338 to 354	As3, Sh1, Th²++, Dh+, Ag+; nig.2, strf.0, sicc.2, elas.+, l.s.0 Grey organic clay with frequent rootlets, and rare silt and herbaceous detritus; plastic
06	-1.01 to -1.56	354 to 409	Ld³2, As2, Th²++, Dh+; nig.2, strf.1, sicc.2, elas.1, l.s.0 Grey clayey limus with frequent rootlets and rare herbaceous detritus; coarsely laminated

05	-1.56 to -2.42	409 to 495	Ld^{3}4, Th^2+, Dh+, Dl+; nig.2, strf.2, sicc.2, elas.2, l.s.+ Dark brown limus with rare rootlets, woody and herbaceous detritus; well laminated
04	-2.42 to -2.77	495 to 530	Ld^{3}2, As2, Sh++, Dh+; nig.2, strf.0, sicc.2, elas.1, l.s.1 Brown organic clay limus with rare herbaceous detritus; plastic
03	-2.77 to -3.01	530 to 554	Ld^{3}4, Th^2+, Dh+; nig.3, strf.1, sicc.2, elas.2, l.s.1 Dark brown limus with rare rootlets and herbaceous detritus; coarsely laminated
02	-3.01 to -3.22	554 to 575	As2, Sh2, anth+; Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Light brown organic clay with rare charcoal and herbaceous detritus; plastic
01	-3.22 to -3.70	575 to 623	As3, Ga1, Th^2+, Dh+, Dl+; nig.2, strf.2, sicc.2, elas.0, l.s.0 Battleship grey fine sandy clay with rare rootlets, and woody and herbaceous detritus; well laminated

Borehole No. P-500S

Stratum	Altitude (m)	Depth (cm)	Description
12	+2.54 to +2.04	0 to 50	As3, Ag1, Lf++; nig.2, strf.0, sicc.3, elas.0, l.s.? Buff colour silty clay with diffused iron staining; hard
11	+2.04 to +0.97	50 to 157	As3, Lf1, Ag+; nig.2, strf.0, sicc.3, elas.0, l.s.0 Reddish brown clay layer with diffused iron staining; plastic
10	+0.97 to +0.68	157 to 186	Ag2, Ga1, Lf1, As+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Buff grey sandy silt with rare clay; coarsely laminated
09	+0.68 to +0.31	186 to 223	Ga3, Ag1, As+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey silty sand with rare clay; coarsely laminated
08	+0.31 to -0.36	223 to 290	As3, Ga1, Ag++; nig.2, strf++, sicc.2, elas.0, l.s.0 Battleship grey sandy clay with frequent silt; coarsely laminated
07	-0.36 to -0.46	290 to 300	Ld^{3}3, As1, anth++, Dh+; nig.2, strf.2, sicc.2, elas.2, l.s.1 Light grey clayey limus with frequent charcoal and rare herbaceous detritus; well laminated
06	-0.46 to -1.14	300 to 368	Ld^{3}4, anth++, Dh+, Dl+; nig.3, strf.2, sicc.2, elas.2, l.s.1 Dark brown limus with frequent charcoal, and rare woody and herbaceous detritus; well laminated
05	-1.14 to -1.68	368 to 422	Ld^{3}3, As1, Th^2++, Dh+; nig.2, strf.2, sicc.2, elas.2, l.s.0 Brown clayey limus with frequent rootlets and rare herbaceous detritus; well laminated
04	-1.68 to -2.23	422 to 477	Ld^{3}4, Th^2++, Dh+; nig.3, strf.2, sicc.2, elas.2, l.s.+ Dark brown limus with frequent rootlets and rare herbaceous detritus; well laminated
03	-2.23 to -2.56	477 to 510	As2, Sh2, Th^2+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.+ Light brown organic clay with rare rootlets and herbaceous detritus; moulted
02	-2.56 to -2.88	510 to 542	Ld^{3}4, Dh+; nig.3, strf.1, sicc.2, elas.2, l.s.1 Dark brown limus with rare herbaceous detritus; coarsely laminated
01	-2.88 to -3.36	542 to 590	As3, Ga1, Th^2+, Dh+, Dl; nig.2, strf.1. sicc.2, elas.0, l.s.0 Battleship grey sandy clay with rare rootlets, and woody and herbaceous detritus; coarsely laminated

Appendix 8:

Lithological Data at Matuail

Borehole No. M-25W

Stratum	Altitude (m)	Depth (cm)	Description
06	+1.64 to +1.44	0 to 20	As4, Ag+, Dl+; nig.2, strf.0, sicc.3, elas.0, l.s.? Battleship grey clay with rare silt and woody detritus; plastic and sticky
05	+1.44 to +.1.34	20 to 30	Ld^{3}4, Dh+, Dl+; nig.3, strf.1, sicc.2, elas.1+, l.s.1 Dark brown limus with rare woody and herbaceous detritus; coarsely laminated
04	+1.34 to +0.81	30 to 83	As3, Ag1, Ga++, Dl+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Battleship grey silty clay rare sand and herbaceous detritus; coarsely laminated
03	+0.81 to -0.46	83 to 210	As2, Ag1, Sh1, Dh+, Dl+; nig.2+, strf.0, sicc.2, elas.0, l.s.+ Grey-brown organic silty clay with rare vivianites, woody and herbaceous detritus; inclusions from layer below; hard and consolidated
02	-0.46 to -0.89	210 to 253	As3, Lf1, Ga++; nig.2, strf.0, sicc.2, elas.0, l.s.0 Buff colour sandy clay with diffused iron staining; hard and plastic
01	-0.89 to -1.46	253 to 310	As2, Ga2, Lf++; nig.2, strf.0, sicc.0, elas.0, l.s.+ Buff grey sandy clay; hard and plastic

Borehole No. M-20W

Stratum	Altitude (m)	Depth (cm)	Description
05	+1.61 to +.1.21	0 to 40	Disturbed
04	+1.21 to +1.05	40 to 56	As3, Ag1, Dl+; nig.2, strf.1, sicc.2, elas.0, l.s.? Battleship grey silty clay with rare herbaceous detritus; coarsely laminated
03	+1.05 to +0.94	56 to 67	As3, Ag1, Sh++, Dh+, Dl+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey organic silty clay with rare herbaceous and woody detritus; coarsely laminated
02	+0.94 to 0.00	67 to 161	As2, Ag1, Sh1, Dg+, Dl+; nig.2+, strf.0, sicc.2, elas.0, l.s.+ Grey-brown organic silty clay with rare vivianites; rare woody detritus and organic fragments; inclusions from layer below; hard and consolidated
01	0.00 to -1.22	161 to 283	As3, Lf1, Ga++; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey Pleistocene clay with frequent sand and diffused iron staining; hard and sticky

Borehole No. M-15W

Stratum	Altitude (m)	Depth (cm)	Description
07	+1.67 to +.1.20	0 to 47	Disturbed
06	+1.20 to +1.00	47 to 67	As3, Ag1, Dl+; nig.2, strf.1, sicc.2, elas.0, l.s.? Battleship grey silty clay with rare woody detritus; coarsely laminated

05	+1.00 to +0.90	67 to 77	As3, Ag1, Sh++, Dh+, Dl+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey organic silty clay with rare herbaceous and woody detritus; coarsely laminated
04	+0.90 to -0.04	77 to 171	As2, Ag1, Sh1, Ga+; nig.2+, strf.0, sicc.2, elas.0, l.s.+ Grey-brown organic silty clay with rare sand and rare vivianites; inclusions from layer below; hard and consolidated
03	-0.04 to -0.73	171 to 240	As3, Ag1, Dh+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare woody and herbaceous detritus; inclusions from the layer above; plastic
02	-0.73 to -1.00	240 to 267	As4, Lf++, Ag+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Light grey Pleistocene clay with diffused iron staining and rare silty and iron inliers; hard and plastic
01	-1.00 to -1.55	267 to 322	As3, Lf1, Ga++, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Light grey Pleistocene clay with frequent sand and rare herbaceous detritus; hard and plastic

Borehole No. M-10W

Stratum	Altitude (m)	Depth (cm)	Description
10	+1.70 to +.1.22	0 to 48	Disturbed
09	+1.22 to +0.91	48 to 79	As3, Ag1, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare herbaceous detritus; coarsely laminated
08	+0.91 to +0.72	79 to 98	As3, Ag1, Sh++, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey organic silty clay with rare herbaceous detritus; coarsely laminated
07	+0.72 to -0.10	98 to 180	As2, Ag1, Sh1, Ga+, Dg+; nig.2+, strf.0, sicc.2, elas.0, l.s.+ Grey-brown organic silty clay with rare sand, and rare vivianites and organic fragments; inclusions from layer below; hard and consolidated
06	-0.10 to -1.00	180 to 270	As3, Ag1, Lf++, Dh+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Buff-grey silty clay with diffused iron staining; rare woody and herbaceous detritus; inclusions from the layer above; plastic
05	-1.00 to -1.92	270 to 362	As2, Ag2, Dl++, Ga+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey silty clay with frequent woody detritus; rare sand; coarsely laminated
04	-1.92 to -2.12	362 to 382	As4, Ga++, Ag+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light grey sandy clay with rare silt; plastic
03	-2.12 to -2.18	382 to 388	Ga3, Sh1, Ag++, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light grey organic silty sand with rare woody detritus; crumbly
02	-2.18 to -2.40	388 to 410	Ga3, Ag1, As+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light grey silty sand with rare clay; crumbly
01	-2.40 to -2.70	410 to 440	Ga3, Ag1, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.0 Buff grey silty sand with diffused iron staining; crumbly

Borehole No. M-5W

Stratum	Altitude (m)	Depth (cm)	Description
10	+1.67 to +.1.30	0 to 37	Disturbed
09	+1.30 to +1.18	37 to 49	Ld³4, As+, Dh+, Dl+; nig.3, strf.1, sicc.2, elas.1, l.s.? Dark brown limus with rare clay, and rare woody and herbaceous detritus; coarsely laminated

08	+1.18 to +1.08	49 to 59	As2, Ag2, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare herbaceous detritus; coarsely laminated
07	+1.08 to +0.75	59 to 92	As2, Ag2, Sh++, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey organic silty clay with rare herbaceous detritus; coarsely laminated
06	+0.75 to -0.03	92 to 170	As2, Ag1, Sh1, Ga+, Dg+; nig.2+, strf.0, sicc.2, elas.0, l.s.+ Grey-brown organic silty clay with rare sand and rare organic fragments; inclusions from layer below; hard and consolidated
05	-0.03 to -1.06	170 to 273	As3, Ag1, Lf+, Dh+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Buff-grey silty clay with diffused iron staining; rare woody and herbaceous detritus; inclusions from the layer above; plastic
04	-1.06 to -1.97	273 to 368	Ag3, As1, Dl++, Ga+; nig.2, strf.++, sicc.2, elas.0, l.s.0 Battleship grey clayey silt with frequent woody detritus; rare sand; coarsely laminated
03	-1.97 to -2.16	368 to 387	Ag2, As1, Sh1, Dg+; nig.2, strf.1, sicc.2, elas.0, l.s.2 Light brown grey organic silt with rare organic fragments; coarsely laminated
02	-2.16 to -2.48	387 to 419	Ga3, Ag1, Lf++, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.3 Light grey silty sand with diffused iron staining; rare herbaceous detritus; crumbly
01	-2.48 to -3.05	419 to 476	Ga4, Sh++, Ag+, Lf+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Light grey organic sand with rare silt and diffused iron staining; crumbly

Borehole No. M-0

Stratum	Altitude (m)	Depth (cm)	Description
16	+1.86 to +.1.21	0 to 65	Disturbed
15	+1.21 to +1.05	65 to 81	As3, Ag1, Ga+, Dl+, Sh+; nig.2, strf.0, sicc.2, elas.0, l.s.? Battleship grey silty clay with rare decomposed organic matter, sand, woody detritus; plastic and sticky
14	+1.05 to +0.78	81 to 108	$Ld^3$4, Dh+, Dl+; nig.3, strf.1, sicc.2, elas.1, l.s.1 Dark brown limus with rare woody and herbaceous detritus; coarsely laminated
13	+0.78 to +0.72	108 to 114	$Ld^3$2, Sh1, As1, Dh+, Th^2+; nig.2, strf.2, sicc.2, elas.2, l.s.0 Brown organic clayey limus with rare herbaceous detritus and rootlets; well laminated
12	+0.72 to +0.65	114 to 121	As2, Ag1, Ga1, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Battleship grey sandy silty clay with rare herbaceous detritus; coarsely laminated
11	+0.65 to +0.57	121 to 129	As2, Ag2, Dl+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey silty clay with rare woody detritus; coarsely laminated
10	+0.57 to +0.35	129 to 151	As2, Ag2, Sh++, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey organic silty clay with rare herbaceous detritus; coarsely laminated
09	+0.35 to -0.05	151 to 191	As2, Ag1, Sh1, Ga+, Dg+; nig.2+, strf.0, sicc.2, elas.0, l.s.+ Grey-brown organic silty clay with rare sand, and rare organic fragments and vivianites; inclusions from layer below; hard and consolidated
08	-0.05 to -1.13	191 to 299	As3, Ag1, Lf+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Buff-grey silty clay with diffused iron staining; rare herbaceous detritus; inclusions from the layer above; plastic
07	-1.13 to -2.10	299 to 396	Ag3, As1, Ga++, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey sandy clayey silt with rare herbaceous detritus; coarsely laminated
06	-2.10 to -2.32	396 to 418	Gg4, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.3 Buff grey mottled coarse sand with iron clasts; crumbly

05	-2.32 to -2.65	418 to 451	Ag2, As1, Sh1, Ga+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Battleship grey organic clayey silt with rare sand and herbaceous detritus; plastic
04	-2.65 to -3.25	451 to 511	Ag2, As1, Sh1, Ga++, Dl+, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey organic sandy clayey silt with rare woody and herbaceous detritus; coarsely laminated
03	-3.25 to -3.33	511 to 519	As3, Ag1, Ga++; nig.2, strf.0, sicc.2, elas,0, l.s.2 Light grey silty clay with rare sand; sticky and plastic
02	-3.33 to -3.36	519 to 522	Gg3, As1, Ag+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Grey coarse sand with clay and rare silt; rare herbaceous detritus and silty clasts; crumbly
01	-3.36 to -3.83	522 to 569	As4, Ga+; nig.2, strf.0, sicc.2+, elas.0, l.s.1 Light grey clay with rare sand; hard and sticky

Borehole No. M-5E

Stratum	Altitude (m)	Depth (cm)	Description
23	+1.97 to +0.98	0 to 99	Disturbed
22	+0.98 to +0.60	99 to 137	As3, Ag1, Sh+; nig.2, strf.0, sicc.2, elas.0, l.s.? Battleship grey silty clay with rare decomposed organic matter, plastic and sticky
21	+0.60 to +0.43	137 to 154	Ld^{3}4, As+, Dh+, Dl+; nig.3, strf.1, sicc.2, elas.1, l.s.1 Dark brown limus with rare clay; rare woody and herbaceous detritus; coarsely laminated
20	+0.43 to +0.35	154 to 162	Ld^{3}2, Sh1, As1, Dh++; nig.2, strf.2, sicc.2, elas.2, l.s.0 Brown organic clayey limus with frequent herbaceous detritus; well laminated
19	+0.35 to +0.28	162 to 169	Ag3, As1, Dh++, Sh+, Ga+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Light grey clayey silt with frequent herbaceous detritus; rare sand and decomposed organic matter; coarsely laminated
18	+0.28 to +0.05	169 to 192	Ag2, As1, Ga1, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.+ Battleship grey sandy clayey silt with rare herbaceous detritus; coarsely laminated
17	+0.05 to -0.08	192 to 205	As2, Ag1, Sh1, Ga+, Dg+; nig.2+, strf.0, sicc.2, elas.0, l.s.+ Grey-brown organic silty clay with rare sand, and rare organic fragments and vivianites; inclusions from layer below; hard and consolidated
16	-0.08 to -1.17	205 to 314	As2, Ag2, Dh+, Dl+, Dg+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare herbaceous and woody detritus; rare organic fragments; inclusions from the layer above; plastic
15	-1.17 to -1.92	314 to 389	Ag3, As1, Dl++, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey clayey silt with frequent woody detritus and rare herbaceous detritus; plastic
14	-1.92 to -2.60	389 to 457	Ag2, As1, Sh1, Dh++, Dl++, Dg+; nig.2, strf.++, sicc.2, elas.0, l.s.+ Light brown-grey organic clayey silt with frequent dicot leaves and herbaceous detritus; rare organic fragments; coarsely laminated
13	-2.60 to -2.73	457 to 470	As3, Ga1, Ag++, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Battleship grey sandy clay with silt and herbaceous detritus; plastic
12	-2.73 to -3.23	470 to 520	As3, Ag1, Sh+++, Ga+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light brown-grey organic silty clay with rare sand and herbaceous detritus; plastic and sticky
11	-3.23 to -3.56	520 to 553	As2, Ag1, Sh1, Ga++, Dl++, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Battleship grey organic silty clay with sand and frequent dicot leaves; rare herbaceous detritus; coarsely laminated

10	-3.56 to -4.13	553 to 610	Ag2, As1, Ga1, Sh++, Dh+; nig.2, strf.++, sicc.2, elas.0, l.s.0 Battleship grey organic sandy clayey silt with rare herbaceous detritus; coarsely laminated
09	-4.13 to -4.21	610 to 618	As3, Ga1, Ag++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Battleship grey sandy clay with frequent silt; moulted
08	-4.21 to -4.45	618 to 642	Ga3, Ag1, Dh+, Dg+; nig.2, strf.1, sicc.2, elas.0, l.s.2 Battleship grey silty sand with rare herbaceous detritus and organic fragments; coarsely laminated
07	-4.45 to -4.51	642 to 648	Gg2, Gg(maj)1, Ag1; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light yellow-grey coarse sand with gravel and clay; crumbly
06	-4.51 to -4.60	648 to 657	Sh2, Ga1, As1, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light brown organic clayey coarse sand with rare herbaceous detritus; moulted
05	-4.60 to -4.66	657 to 663	Ga3, As1; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light grey clay sand; hard
04	-4.66 to -4.80	663 to 677	Ga3, Lf1; nig.2, strf.0, sicc.2, elas.0, l.s.2 Buff grey sandy layer with diffused iron staining and iron clasts; crumbly
03	-4.80 to -4.83	677 to 680	As2, Ag1, Ga1; nig.2, strf.0, sicc.2, elas.0, l.s.2 Battleship grey silty sandy clay; hard
02	-4.83 to -4.88	680 to 685	Ag3, As1, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Light grey clayey silt with rare herbaceous detritus; crumbly
01	-4.88 to -5.10	685 to 707	As3, Lf1, Ga++; nig.2, strf.0, sicc.2, elas.0, l.s.1 Buff grey clay with frequent sand and diffused iron staining; become reddish when oxidized; sticky and hard

Borehole No. M-10.5E

Stratum	Altitude (m)	Depth (cm)	Description
23	+1.88 to +1.33	0 to 55	Disturbed
22	+1.33 to +0.98	55 to 90	As2, Ag2, Ga++, Dh+, Dl+, Sh+; nig.2, sicc.2, strf.0, elas.0, l.s.?. Battleship grey silty clay with rare sand, woody and herbaceous detritus, and dicot leaves; plastic and sticky
21	+0.98 to +0.83	90 to 105	Ld^{3}4, Sh++, As+, Ag+, Ga+, Dl+, Dh+; nig.2, sicc.2, strf.1, elas.1, l.s.+ Dark brown limus with rare clay, sand and silt; herbaceous and woody detritus; coarsely laminated.
20	+0.83 to +0.46	105 to 142	Ag2, As1, Ga1, Dl+, Dh+, Sh+; nig.2, sicc.2, Strf.++, elas.0, l.s.1. Light brown-grey sandy-clayey silt with rare woody and herbaceous detritus; rare vivianite; coarsely laminated
19	+0.46 to +0.23	142 to 165	Ag2, Ga1, As1, Dh+, Dl+; nig.2, sicc.2, strf++, elas.0, l.s.0 Light brown-grey sandy clayey silt with rare woody and herbaceous detritus; coarsely laminated
18	+0.23 to -0.02	165 to 190	As2, Sh1++, Ag1, Ga+, Dg+ Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.+ Grey brown organic silty clay with rare organic fragments, woody detritus and vivianite; some silty clasts; inclusion from the layer below,; very dense and hard.
17	-0.02 to -0.92	190 to 280	As3, Ag1, Ga+, Sh+, Th^{2}+, Dl+, Dh+, Lf+; nig.2+, strf.0, sicc.2, elas.0, l.s.2 Battleship grey silty clay with rare sand, some organic shades, inclusion from layer above, rare diffused iron staining, few silty clasts, rootlets, herbaceous and woody detritus; plastic
16	-0.92 to -1.62	280 to 350	Ag2, As2, Ga++, Sh+, Th^{2}+, Lf+; nig.2, strf.+, sicc.2, elas.0, l.s.0 Battleship grey sandy clayey silt with rare rootlets channels, diffused iron staining along the channels; rare herbaceous detritus; coarsely laminated.

15	-1.62 to -1.82	350 to 370	As2, Ag1, Sh1, Dh+, Dl+; nig.2, strf.1, sicc.2, elas.0, l.s.+ Light brown organic silty clay with rare sand, dicot leaves, herbaceous and woody detritus; coarsely laminated.
14	-1.82 to -2.37	370 to 425	As2, Ag1, Sh1, Ga+, Dh+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Light brown grey organic clayey silt with rare sand, fine broken dicot leaves, rare herbaceous and woody detritus; plastic and sticky.
13	-2.37 to -2.42	425 to 430	Ga3, As1, Ag+, Dl+, Dh+, Sh+; nig.2, strf++, sicc.2, elas.0, l.s.3 Light brown grey clayey sand with rare silt; some blue shades, rare herbaceous and woody detritus; coarsely laminated.
12	-2.42 to -2.77	430 to 465	As2, Ag1, Sh1, Ga++, Dh+, Dl+; nig.2, strf.++, sicc.2, elas.0, l.s.3 Light brown organic silty clay with some sand; rare sandy inliers, herbaceous and woody detritus; some blue shades; plastic.
11	-2.77 to -3.22	465 to 510	Ag2, As1 Sh1, Ga+++, Dl+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Light brown grey organic sandy clayey silt with herbaceous and woody detritus; some blue shades; plastic.
10	-3.22 to -3.37	510 to 525	As2, Ag1, Sh1, Ga++, Dl+; nig.2, strf.++, sicc.2, elas.0, l.s.+ Light brown grey organic sandy silty clay with rare woody detritus; coarsely laminated
09	-3.37 to -3.49	525 to 537	Ag2, As1, Ga1, Dl++, Sh++, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Brown organic sandy clayey silt with frequent woody detritus and rare herbaceous detritus; coarsely laminated.
08	-3.49 to -3.59	537 to 547	Ga4, Sh++, Ga+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Brown grey organic sand, rare gravels; structure less
07	-3.59 to -3.65	547 to 553	Ga2, Ag1, Dl1, Sh++, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.2 Brown organic silty sand with frequent woody detritus; rare herbaceous detritus; crumbly
06	-3.65 to -3.70	553 to 558	Ga3, Sh1, Dh++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light brown organic sand with herbaceous detritus; plastic
05	-3.70 to -3.73	558 to 561	Ga2, Dh1, Sh1; nig.2, strf.0, sicc.2, elas.0, l.s.2 Brown grey organic sand with frequent herbaceous detritus; crumbly
04	-3.73 to -3.79	561 to 567	As3, Ga1; nig.2, strf.0, sicc.2, elas.0, l.s.2 Battleship grey sandy clay; plastic
03	-3.79 to -3.83	567 to 571	Ga4, Lf++: nig.2, strf.0, sicc.2, elas.0, l.s.2 Grey sand with mottled irons, rare gravels; crumbly
02	-3.83 to -3.88	571 to 576	As2, Ag1, Ga1, Sh++; nig.2, strf.0, sicc.2, elas.0, l.s.1 Light brown organic sandy silty clay; plastic
01	-3.88 to -3.96	576 to 584	As4, Ga++, Sh+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Grey organic sandy clay, moulted and plastic.

Borehole No. M-15E

Stratum	Altitude (m)	Depth (cm)	Description
21	+1.98 to +1.02	0 to 96	Disturbed
20	+1.02 to +0.76	96 to 122	As3, Ag1, Sh++, Dh+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.? Battleship grey organic silty clay with rare herbaceous and woody detritus; plastic and sticky
19	+0.76 to +0.60	122 to 138	$Ld^3 4$, Sh++, As+, Dl+, Dh+; nig.3, strf.1, sicc.2, elas.1, l.s.1 Dark brown organic limus with rare clay; rare woody and herbaceous detritus; coarsely laminated

18	+0.60 to +0.55	138 to 143	Ag2, As1, Ga1, Dh+, Dl+; nig.2, strf.1, sicc.2, elas.0. l.s.1 Light brown grey sandy clayey silt with rare woody and herbaceous detritus; rare vivianites; coarsely laminated
17	+0.55 to +0.46	143 to 152	Ag2, Ga2, As++, Dh+, Dl+; nig.2, sicc.2, strf++, elas.0, l.s.0 Light brown-grey silty sand with rare woody and herbaceous detritus; coarsely laminated
16	+0.46 to -0.18	152 to 216	As2, Ag1, Sh1, Ga+, Dg+; nig.2+, strf.0, sicc.2, elas.0, l.s.+ Grey-brown organic silty clay with rare sand, and rare organic fragments and vivianites; inclusions from layer below; hard and consolidated
15	-0.18 to -0.42	216 to 240	As3, Ag1, Dh+, Dl+, Dg+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare herbaceous and woody detritus; rare organic fragments; inclusions from the layer above; plastic
14	-0.42 to -1.03	240 to 301	As2, Ag2, Ga+, Dl+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey silty clay with rare sand; rare woody and herbaceous detritus; plastic
13	-1.03 to -1.27	301 to 325	As2, Ag1, Sh1, Dh+, Dl+, Dg+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Light brown-grey organic silty clay with some dicot leaves, and rare woody and herbaceous detritus; plastic
12	-1.27 to -1.80	325 to 378	As2, Ag1, Sh1++, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.+ Battleship grey organic silty clay with rare woody detritus; plastic
11	-1.80 to -1.87	378 to 385	Ag2, As1, Sh1, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Light brown-grey organic clayey silt with rare woody detritus; plastic and sticky
10	-1.87 to -2.50	385 to 448	As2, Ag1, Sh1, Ga+, Th^2+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey organic silty clay with rare sand, and rare rootlets and woody detritus; moulted
09	-2.50 to -2.53	448 to 451	As2, Ga1, Sh1, Gg(maj)++, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.+ Light yellow grey organic sandy clay with some gravel; rare herbaceous detritus; rough and heterogeneous
08	-2.53 to -2.66	451 to 464	As3, Sh1, Ag++, Ga+, Dl+, Lf+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Brown-grey organic clay with frequent silt and some sand; rare woody detritus and few iron clasts; moulted
07	-2.66 to -2.73	464 to 471	As3, Sh1, Dg++, Dl+, Lf+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Dark grey organic clay with frequent black shaded organic fragments; rare woody detritus and iron clasts; crumbly
06	-2.73 to -2.83	471 to 481	As2, Ga1, Gg(maj)1, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.1 Light yellow-grey sandy clay with gravel and frequent iron clasts; crumbly
05	-2.83 to -2.98	481 to 496	As3, Sh1, Ga+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Light brown-grey organic clay with sand; rare woody detritus; moulted
04	-2.98 to -3.04	496 to 502	As2, Ga2, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light yellow-grey sandy clay with frequent iron clasts; rough and heterogeneous
03	-3.04 to -3.13	502 to 511	As2, Ga1, Sh1, Dl+; nig.2, strf.++ sicc.2, elas.0, l.s.2 Brown-grey organic sandy clay with few dicot leaves and some woody detritus; very coarsely laminated
02	-3.13 to -3.42	511 to 540	As2, Ag2, Ga+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with few sand; plastic and sticky
01	-3.42 to -3.67	540 to 565	As4, Ga+, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.0 Light blue-grey Pleistocene clay with rare sand; diffused iron staining; become reddish when oxidized; hard

Borehole No. M-20E

Stratum	Altitude (m)	Depth (cm)	Description
13	+1.02 to -0.28	0 to 130	Disturbed
12	-0.28 to -0.58	130 to 160	As3, Ag1, Sh+; nig.2, strf.0, sicc.2, elas.0, .l.s.? Battleship grey silty clay with rare decomposed organic matter; sticky and plastic
11	-0.58 to -1.01	160 to 203	As2, Ag2, Sh++, Dl++, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey organic silty clay with frequent woody detritus and rare herbaceous detritus; plastic
10	-1.01 to -1.24	203 to 226	As2, Ag1, Sh1, Dg++, Dh+; nig.2, strf.++, sicc.2, elas.0, l.s.0 Light brown-grey organic silty clay; many organic fragments and rare herbaceous detritus; coarsely laminated
09	-1.24 to -1.78	226 to 280	As2, Ag1, Sh1++, Dh++, Dg+; nig.2, strf.2, sicc.2, elas.0, l.s.0 Mid grey organic silty clay with many herbaceous detritus and few organic fragments; rough and moulted
08	-1.78 to -1.88	280 to 290	Ag2, As1, Sh1, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Light brown-grey organic clayey silt with rare woody detritus; plastic and sticky
07	-1.88 to -2.25	290 to 327	As2, Ag1, Sh1, Ga+, Th^2+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey organic silty clay with rare sand, and rare rootlets and woody detritus; moulted
06	-2.25 to -2.37	327 to 339	As2, Ga1, Sh1, Gg(maj)++, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.+ Light yellow grey organic sandy clay with some gravel; rare herbaceous detritus; rough and heterogeneous
05	-2.37 to -2.41	339 to 343	As2, Ag1, Sh1, Ga+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.+ Brown grey organic silty clay with rare sand and few herbaceous detritus; plastic
04	-2.41 to -2.47	343 to 349	As1, Ag1, Ga1, Sh1, Dg++; nig.2, strf.0, sicc.2, elas.0, l.s.0 Brown grey organic sandy silty clay with many blue shades of organic fragments; rough and moulted
03	-2.47 to -2.51	349 to 353	As2, Ga1, Sh1, Lf++; nig.2, strf.o, sicc.2, elas.0, l.s.2 Brown grey organic sandy clay with sand clasts , diffused iron staining and iron clasts; moulted
02	-2.51 to -2.67	353 to 369	As3, Sh1, Ga++, Dl+; Dg+; nig.2, strf.0, sicc.2. elas.0, l.s.2 Battleship grey organic clay with sand; rare woody detritus and organic fragments; moulted
01	-2.67 to -3.18	369 to 420	As4, Ga+, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.1 Light blue-grey Pleistocene clay with rare sand; diffused iron staining; become reddish when oxidized; hard

Borehole No. M-25E

Stratum	Altitude (m)	Depth (cm)	Description
06	+0.86 to -0.54	0 to 140	Disturbed
05	-0.54 to -0.68	140 to 154	As2, Ag2, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.? Battleship grey silty clay with rare herbaceous detritus; plastic
04	-0.68 to -0.97	154 to 183	Ag2, As1, Sh1, Dh+, Dg+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Light brown-grey silty clay with rare herbaceous detritus and few organic fragments; sticky and plastic
03	-0.97 to -1.49	183 to 235	Ag2, As1, Sh1+, Dg+, Dh+, Dl+; nig.2, strf.0, sicc.2 elas.0, l.s.0 Brown grey organic clayey silt with rare woody and herbaceous detritus; few organic fragments; plastic

02	-1.49 to --1.60	235 to 246	Ag2, Ga1, Sh1, Dl+; nig.2, strf.0, sicc.2. elas.0, l.s.0 Battleship grey organic sandy silt with rare woody detritus; moulted
01	-1.60 to -1.94	246 to 280	As4, Ga+, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.1 Light blue-grey Pleistocene clay with rare sand; diffused iron staining; become reddish when oxidized; hard

Borehole No. M-35E

Stratum	Altitude (m)	Depth (cm)	Description
03	+0.87 to -0.45	0 to 132	Disturbed
02	-0.45 to -0.58	132 to 145	As4, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.? Light blue grey Pleistocene clay with diffused iron staining; hard
01	-0.58 to -0.68	145 to 155	As3, Lf1; nig.2, strf.0, sicc.2, elas.0, l.s.+ Light buff grey Pleistocene clay with diffused iron staining; very hard

Borehole No. M-15N

Stratum	Altitude (m)	Depth (cm)	Description
17	+1.80 to +1.34	0 to 46	Disturbed
16	+1.34 to +1.24	46 to 56	As3, Ag1, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.? Battleship grey silty clay with diffused iron staining; plastic and sticky
15	+1.24 to +1.12	56 to 68	$Ld^3$4, As++, Sh++, Dl+, Dh+; nig.3, strf.1, sicc.2, elas.1, l.s.1 Dark brown organic limus with clay; rare woody and herbaceous detritus; coarsely laminated
14	+1.12 to +0.93	68 to 87	Ga2, Ag1, As1, Dh+, Dl+; nig.2, strf.1, sicc.2, elas.0. l.s.1 Light brown grey silty clayey sand with rare woody and herbaceous detritus; coarsely laminated
13	+0.93 to +0.70	87 to 110	Ag2, Ga1, As1, Dh+, Dl+; nig.2, sicc.2, strf++, elas.0, l.s.0 Light brown-grey sandy clayey silt with rare woody and herbaceous detritus; coarsely laminated
12	+0.70 to +0.12	110 to 168	As2, Ag1, Sh1, Ga+, Dg+; nig.2+, strf.0, sicc.2, elas.0, l.s.+ Grey-brown organic silty clay with rare sand, and rare organic fragments and vivianites; inclusions from layer below; hard and consolidated
11	+0.12 to -0.34	168 to 214	As3, Ag1, Dh+, Lf+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare herbaceous detritus; rare iron clasts; plastic
10	-0.34 to -1.10	214 to 290	As2, Ag2, Dh+, Dl++; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey silty clay with frequent woody detritus; rare herbaceous detritus; plastic
09	-1.10 to -2.28	290 to 408	As3, Ag1, Dl++, Dh+, Dg+; nig.2, strf.+, sicc.2, elas.0, l.s.0 Battleship grey silty clay with some dicot leaves, some big wood pieces (*Heritiera fomes*) and few light black shaded organic fragments; very coarsely laminated
08	-2.28 to -2.32	408 to 412	As2, Ag1, Lf1; nig.2, strf.0, sicc.2, elas.0, l.s.2 Buff grey silty clay with diffused iron staining and many iron clasts; rough
07	-2.32 to -2.38	412 to 418	As2, Ag1, Sh1, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Brown grey organic silty clay with rare herbaceous detritus; plastic
06	-2.38 to -2.44	418 to 424	As3, Ag1, Sh++ Ga+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light brown-grey organic silty clay with rare sand and woody detritus; plastic
05	-2.44 to -2.82	424 to 462	As3, Sh1, Ag++, Ga+, Dh+, Dl+; nig.2, strf.++, sicc.2, elas.0, l.s.1 Light brown grey organic silty clay with rare sand, and rare herbaceous and woody detritus; coarsely laminated

04	-2.82 to -3.12	462 to 492	As2, Ga1, Sh1, Dh+; nig.2, strf.1+, sicc.2, elas.0, l.s.0 Light brown grey organic sandy clay with sandy inliers along the lamination; rare herbaceous detritus; laminated
03	-3.12 to -3.19	492 to 499	As3, Sh1, Ag++, Ga+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Brown-grey organic clay with frequent silt and some sand; rare woody detritus; moulted
02	-3.19 to -3.29	499 to 509	As3, Sh1++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Dark grey organic clay; plastic
01	-3.29 to -3.60	509 to 540	As4, Ga+, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light blue-grey Pleistocene clay with rare sand; diffused iron staining; become reddish when oxidized; hard

Borehole No. M-10N

Stratum	Altitude (m)	Depth (cm)	Description
13	+1.81 to +1.28	0 to 53	Disturbed
12	+1.28 to +1.15	53 to 66	As3, Ag1, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.? Battleship grey silty clay with diffused iron staining; plastic and sticky
11	+1.15 to +1.01	66 to 80	$Ld^3$4, As++, Sh++, Dl++, Dh+; nig.3, strf.1, sicc.2, elas.1, l.s.1 Dark brown organic limus with clay; frequent woody detritus and rare herbaceous detritus; coarsely laminated
10	+1.01 to +0.74	80 to 107	Ga2, Ag1, As1, Dh+; nig.2, strf.1, sicc.2, elas.0. l.s.1 Light brown grey silty clayey sand with rare herbaceous detritus; coarsely laminated
09	+0.74 to +0.52	107 to 129	Ag2, Ga1+, As1, Dh+, Dl+; nig.2, sicc.2, strf++, elas.0, l.s.0 Light brown-grey sandy clayey silt with rare woody and herbaceous detritus; coarsely laminated
08	+0.52 to -0.01	129 to 180	As2, Ag1, Sh1, Ga+; nig.2+, strf.0, sicc.2, elas.0, l.s.+ Grey-brown organic silty clay with rare sand and frequent vivianites; inclusions from layer below; hard and consolidated
07	-0.01 to -0.51	180 to 232	As3, Ag1, Th^2+, Dh+, Lf+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare rootlets and herbaceous detritus; rare iron clasts; plastic
06	-0.51 to -1.36	232 to 317	As3, Ag1, Dh+, Sh+; nig.2, strf.+, sicc.2, elas.0, l.s.0 Battleship grey silty clay with rare herbaceous detritus and few decomposed organic matter; very coarsely laminated to plastic
05	-1.36 to -2.25	317 to 406	As3, Sh1, Ag++, Dh+, Dl+, Dg+; nig.2, strf.++, sicc.2, elas.0, l.s.0 Light brown grey organic silty clay with rare woody and herbaceous detritus; few organic fragments; coarsely laminated
04	-2.25 to -2.75	406 to 456	As2, Ga1, Sh1, Dh++; nig.2, strf.1, sicc.2, elas.0, l.s.0 Light brown grey organic sandy clay with sandy inliers along the lamination; frequent herbaceous detritus; coarsely laminated
03	-2.75 to -3.21	456 to 502	As3, Sh1, Ga++, Dh++; nig.2, strf.1, sicc.2, elas.0, l.s.0 Brown-grey organic sandy clay with frequent herbaceous detritus; coarsely laminated
02	-3.21 to -3.34	502 to 515	As3, Sh1++, Dh+; nig.2, strf.++, sicc.2, elas.0, l.s.2 Dark grey organic clay with rare herbaceous detritus; coarsely laminated
01	-3.34 to -3.61	515 to 542	As4, Ga+, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light blue-grey Pleistocene clay with rare sand; diffused iron staining; become reddish when oxidized; hard

Borehole No. M-5N

Stratum	Altitude (m)	Depth (cm)	Description
18	+1.77 to +1.12	0 to 65	Disturbed
17	+1.12 to +1.00	65 to 77	As4, Ag++, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.? Battleship grey silty clay with diffused iron staining; plastic and sticky
16	+1.00 to +0.92	77 to 85	Ld^{3}3, As1, Dl+, Dh+; nig.3, strf.1, sicc.2, elas.1, l.s.1 Dark brown limus with clay; rare woody and herbaceous detritus; coarsely laminated
15	+0.92 to +0.78	85 to 99	Ga2, Ag1, As1, Dh+; nig.2, strf.1, sicc.2, elas.0. l.s.1 Light brown grey silty clayey sand with rare herbaceous detritus; coarsely laminated
14	+0.78 to +0.70	99 to 107	Ag2, Ga1+, As1, Dh+, nig.2, sicc.2, strf++, elas.0, l.s.0 Light brown-grey sandy clayey silt with rare herbaceous detritus; coarsely laminated
13	+0.70 to 0.00	107 to 177	As2, Ag1, Sh1+; nig.2+, strf.0, sicc.2, elas.0, l.s.+ Grey-brown organic silty clay with rare vivianites; inclusions from layer below; hard and consolidated
12	0.00 to -0.56	177 to 233	As3, Ag1, Ga+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare herbaceous detritus; plastic
11	-0.56 to -0.93	233 to 270	As2, Ag2, Dh+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey silty clay with rare woody and herbaceous detritus; plastic
10	-0.93 to -1.17	270 to 294	As3, Sh1, Dh+, Dl+; nig.2, strf.++, sicc.2, elas.0, l.s.0 Light brown grey organic clay with rare woody and herbaceous detritus; coarsely laminated
09	-1.17 to -1.23	294 to 300	As2, Ga2, Sh++, Dh++; nig.2, strf.0, sicc.2, elas.0, l.s.1 Light brown grey organic sandy clay with frequent herbaceous detritus; crumbly
08	-1.23 to -1.88	300 to 365	As3, Sh1, Dh+, Lf+; nig.2, strf.++, sicc.2, elas.0, l.s.2 Brown-grey organic clay with rare herbaceous detritus; few iron clasts; coarsely laminated
07	-1.88 to -2.86	365 to 463	As3, Sh1+, Ga++, Dh+, Dg+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Brown-grey organic clay with sand; rare herbaceous detritus and few organic fragments; coarsely laminated
06	-2.86 to -2.90	463 to 467	As1, Ag1, Ga1, Sh1, Dg++; nig.2, strf.0, sicc.2, elas.0, l.s.1 Brown grey organic sandy silty clay layer with frequent organic fragments; crumbly
05	-2.90 to -3.02	467 to 479	As2, Ag1, Sh1, Ga++, Dh+, Dg+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Brown grey organic sandy silty clay with few blue shades of organic fragments; plastic
04	-3.02 to -3.10	479 to 487	As3, Sh1, Dh+; nig.2, strf.++, sicc.2, elas.0, .l.s.2 Brown-grey organic clay with rare herbaceous detritus; coarsely laminated
03	-3.10 to -3.30	487 to 507	As3, Sh1, Ga++, Lf+, Dh+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Brown grey organic sandy clay with rare woody and herbaceous detritus; few iron clasts; hard and crumbly
02	-3.30 to -3.34	507 to 511	As2, Sh1, Dg1, Ga+, Dh+, Lf+; nig.3, strf.0, sicc.2, elas.0, l.s.2 Light blue black organic clay with many organic fragments; few sand and rare herbaceous detritus; few iron clasts; crumbly
01	-3.34 to -3.61	511 to 542	As4, Ga+, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light blue-grey Pleistocene clay with rare sand; diffused iron staining; become reddish when oxidized; hard

Borehole No. M-5S

Stratum	Altitude (m)	Depth (cm)	Description
22	+1.92 to +0.95	0 to 97	Disturbed
21	+0.95 to +0.80	97 to 112	As4, Ag++, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.? Battleship grey silty clay with diffused iron staining; plastic and sticky
20	+0.80 to +0.75	112 to 117	$Ld^3$4, As++, Dh+; nig.3, strf.1, sicc.2, elas.1, l.s.1 Dark brown limus with clay; rare herbaceous detritus; coarsely laminated
19	+0.75 to +0.68	117 to 124	Ga2, Ag1, As1, Dh+, Dl+; nig.2, strf.1, sicc.2, elas.0. l.s.1 Light brown grey silty clayey sand with rare woody and herbaceous detritus; coarsely laminated
18	+0.68 to +0.55	124 to 137	Ag2, Ga1+, As1, Dh+, Lf+; nig.2, sicc.2, strf++, elas.0, l.s.0 Light brown-grey sandy clayey silt with rare herbaceous detritus and few diffused iron staining; coarsely laminated
17	+0.55 to +0.07	137 to 185	As2, Ag1, Sh1+, Dh+; nig.2+, strf.0, sicc.2, elas.0, l.s.+ Grey-brown organic silty clay with rare herbaceous detritus and few vivianites; inclusions from layer below; hard and consolidated
16	+0.07 to -0.46	185 to 238	As3, Ag1, Ga+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare herbaceous detritus; plastic
15	-0.46 to -0.73	238 to 265	As3, Ag1; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey silty clay; plastic
14	-0.73 to -1.03	265 to 295	Ag2, As1, Sh1, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Light grey organic silty clay with rare herbaceous detritus; plastic and sticky
13	-1.03 to -1.07	295 to 299	Ga2, As1, Sh1, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Light brown grey organic clayey sand with rare herbaceous detritus; crumbly
12	-1.07 to -1.19	299 to 311	Ag3, As1, Sh++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Battleship grey organic clayey silt; plastic and sticky
11	-1.19 to -1.83	311 to 375	As2, Ag1, Sh1, Dh+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Light brown-grey organic silty clay with rare woody and herbaceous detritus; plastic
10	-1.83 to -1.95	375 to 387	As2, Ag1, Sh1, Ga++, Dh+; nig.2, strf.++ sicc.2, elas.0, l.s.0 Brown grey organic sandy silty clay with rare herbaceous detritus; coarsely laminated
09	-1.95 to -2.02	387 to 394	As2, Ag1, Ga1, Sh++, Dg++; nig.2, strf.0, sicc.2, elas.0, .l.s.2 Light brown grey organic silty clay with sand and many organic fragments; moulted
08	-2.02 to -2.35	394 to 427	As3, Sh1+, Ga+, Dh+, Dl+, Dg+; nig.2, strf.++, sicc.2, elas.0, l.s.2 Brown-grey organic clay with rare sand; rare woody and herbaceous detritus and few organic fragments; coarsely laminated
07	-2.35 to -2.42	427 to 434	As2, Ga1, Sh1, Dg+; nig.2, strf.1, sicc.2, elas.0, l.s.2 Brown grey organic sandy clay with rare organic fragments; coarsely laminated
06	-2.42 to -2.80	434 to 472	As2, Ag1, Sh1, Dh++, Dg+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Brown grey organic silty clay with many herbaceous detritus and few organic fragments; plastic
05	-2.80 to -3.25	472 to 517	As2, Ag1, Sh1, Ga++, Dg++; nig.2, strf.++, sicc.2, elas.0, l.s.+ Brown grey organic sandy silty clay with many organic fragments; very coarsely laminated
04	-3.25 to -3.48	517 to 540	As1, Ag1, Ga1, Sh1, Dg++; nig.2, strf.+, sicc.2, elas.0, l.s.2 Brown grey organic sandy silty clay layer with frequent organic fragments; very coarsely laminated

03	-3.48 to -3.74	540 to 566	As2, Sh2, Dh+; nig.2+, strf.0, sicc.2, elas.0, l.s.2 Dark brown grey organic clay with few herbaceous detritus; plastic
02	-3.74 to -3.90	566 to 582	As2, Sh2, Dh+, Dl+, Dg+; nig.2, strf.1, sicc.2, elas.0, l.s.2 Brown grey organic clay with rare woody and herbaceous detritus; few organic fragments; coarsely laminated
01	-3.90 to -4.08	582 to 600	As4, Ga+, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light blue-grey Pleistocene clay with rare sand; diffused iron staining; become reddish when oxidized; hard

Borehole No. M-10S

Stratum	Altitude (m)	Depth (cm)	Description
24	+1.80 to +1.28	0 to 52	Disturbed
23	+1.28 to +0.98	52 to 82	As3, Ag1, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.? Battleship grey silty clay with diffused iron staining; plastic and sticky
22	+0.98 to +0.87	82 to 93	Ld^{3}4, As++, Dh+, Dl+; nig.3, strf.1, sicc.2, elas.1, l.s.1 Dark brown limus with clay; rare woody and herbaceous detritus; coarsely laminated
21	+0.87 to +0.74	93 to 106	Ag2, As1, Ga1, Dh+, Dl+; nig.2, strf.1, sicc.2, elas.0. l.s.1 Light brown grey sandy clayey silt with rare woody and herbaceous detritus; coarsely laminated
20	+0.74 to +0.54	106 to 126	Ag2, As1, Ga1, Dh+, Lf+; nig.2, sicc.2, strf++, elas.0, l.s.0 Light brown-grey sandy clayey silt with rare herbaceous detritus and few diffused iron staining; coarsely laminated
19	+0.54 to +0.04	126 to 176	As2, Ag1, Sh1+, Dh+, Dl++; nig.2+, strf.0, sicc.2, elas.0, l.s.+ Grey-brown organic silty clay with rare woody, herbaceous detritus and few vivianites; inclusions from layer below; hard and consolidated
18	+0.04 to -0.42	176 to 222	As3, Ag1, Ga+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare herbaceous detritus; plastic
17	-0.42 to -1.03	222 to 283	As2, Ag2, Ga+; nig.2, strf.+, sicc.2, elas.0, l.s.0 Battleship grey silty clay; plastic to very coarsely laminated
16	-1.03 to -1.10	283 to 290	As2, Ag1, Sh1, Ga+; nig.2, strf.0, sicc.2, elas.0, l.s.+ Light grey organic silty clay with rare sandy inliers; plastic and sticky
15	-1.10 to -1.21	290 to 301	Ag3, As1; nig.2, strf.0, sicc.2, elas.0, l.s.+ Battleship grey clayey silt ; plastic and sticky
14	-1.21 to -1.30	301 to 310	As2, Ag1, Sh1, Ga+; nig.2, strf.0, sicc.2, elas.0, l.s.+ Light grey organic silty clay with rare sandy inliers; plastic and sticky
13	-1.30 to -1.41	310 to 321	Ag3, As1, Sh++; nig.2, strf.0, sicc.2,elas.0, l.s.+ Battleship grey organic clayey silt; plastic and sticky
12	-1.41 to -1.48	321 to 328	Ag2, As1, Sh1, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.+ Light grey organic clay silt with rare herbaceous detritus; plastic and sticky
11	-1.48 to -1.58	328 to 338	Ag3, As1, Sh++; nig.2, strf.0, sicc.2, elas.0, l.s.1 Brown grey organic clayey silt; plastic
10	-1.58 to -1.93	338 to 373	As2, Ag1, Sh1, Dh+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Light brown-grey organic silty clay with rare woody and herbaceous detritus; plastic
09	-1.93 to -3.65	373 to 545	As2, Ag1, Sh1++, Ga+, Dl+, Dh+, nig.2, strf.++, sicc.2, elas.0, l.s.0 Brown grey organic silty clay with few sandy inliers ; rare woody and herbaceous detritus; coarsely laminated
08	-3.65 to -3.80	545 to 560	As2, Ag1, Sh1, Dg++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Brown grey organic silty clay with frequent organic fragments; rough and crumbly

07	-3.80 to -3.83	560 to 563	Ga2, As1, Sh1; nig.2, strf.0, sicc.2, elas.0, l.s.2 Dark brown organic clayey sand; crumbly
06	-3.83 to -3.96	563 to 576	As1, Ag1, Ga1, Sh1, Dh+; nig.2, strf.++, sicc.2, elas.0, l.s.2 Brown grey organic sandy silty clay layer with rare herbaceous detritus; coarsely laminated
05	-3.96 to -4.06	576 to 586	Ga2, As1, Sh1; nig.2, strf.1+, sicc.2, elas.0, l.s.2 Dark brown organic clayey sand; frequent sandy inliers;laminated
04	-4.06 to -4.21	584 to 599	As2, Sh2, Ag+, Dh+, Dl+; nig.2+, strf.1+, sicc.2, elas.0, l.s.2 Dark brown grey organic clay with rare silt clasts; few woody and herbaceous detritus; laminated
03	-4.21 to -4.40	599 to 620	Ga2, Ag1, Sh1, As+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light brown grey organic silty sand with rare clay; crumbly
02	-4.40 to -4.52	620 to 632	As2, Ld^{2}1, Sh1, Ga+, Dh+; nig.2, strf.0, sicc.2, elas++, l.s.2 Brown grey organic clay with limus and rare sand; few herbaceous detritus; crumbly
01	-4.52 to -4.70	632 to 650	As4, Ga+, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light blue-grey Pleistocene clay with rare sand; diffused iron staining; become reddish when oxidized; hard

Borehole No. M-15S

Stratum	Altitude (m)	Depth (cm)	Description
23	+1.82 to +1.22	0 to 60	Disturbed
22	+1.22 to +1.04	60 to 78	As3, Ag1, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.? Battleship grey silty clay with diffused iron staining; plastic and sticky
21	+1.04 to +0.92	78 to 90	Ld^{3}4, As++, Dh+, Dl+; nig.3, strf.1, sicc.2, elas.1, l.s.1 Dark brown limus with clay; rare woody and herbaceous detritus; coarsely laminated
20	+0.92 to +0.83	90 to 99	Ag2, As1, Ga1, Dh+, Dl+; nig.2, strf.1, sicc.2, elas.0. l.s.1 Light brown grey sandy clayey silt with rare woody and herbaceous detritus; coarsely laminated
19	+0.83 to +0.76	99 to 106	Ag2, As1, Ga1, Dh+; nig.2, sicc.2, strf++, elas.0, l.s.0 Light brown-grey sandy clayey silt with rare herbaceous detritus; coarsely laminated
18	+0.76 to +0.44	106 to 138	As2, Ag1, Sh1+, Dh+, Dl+; nig.2+, strf.0, sicc.2, elas.0, l.s.+ Grey-brown organic silty clay with rare woody and herbaceous detritus; inclusions from layer below; hard and consolidated
17	+0.44 to 0.00	138 to 182	As3, Ag1, Ga+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare herbaceous detritus; plastic
16	0.00 to -0.12	182 to 194	As2, Ag1, Ga1, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light grey silty sandy clay with rare herbaceous detritus; few crumbly sandy inliers; crumbly
15	-0.12 to -0.50	194 to 232	As3, Ag1, Ga++, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Battleship grey sandy silty clay with rare herbaceous detritus; plastic
14	-0.50 to -0.79	232 to 261	As2, Ag2, Ga+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey silty clay; plastic
13	-0.79 to -0.88	261 to 270	As2, Ag1, Sh1, Ga+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Light grey organic silty clay with rare sandy inliers; plastic and sticky
12	-0.88 to -0.99	270 to 281	Ag2+, As2, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey clayey silt with rare herbaceous detritus; plastic and sticky

11	-0.99 to -1.16	281 to 298	As2, Ag1, Sh1, Ga+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Light grey organic silty clay with rare sandy inliers; few herbaceous detritus;plastic and sticky
10	-1.16 to -1.21	298 to 303	Ag3, As1, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey clayey silt with rare herbaceous detritus; plastic and sticky
09	-1.21 to -1.28	303 to 310	Ag2, As1, Sh1, Ga+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Light grey organic clay silt with rare sand; few herbaceous detritus; plastic and sticky
08	-1.28 to -1.52	310 to 334	As2, Ag1, Sh1+, Dh++, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Brown grey organic silty clay with frequent herbaceous detritus; rare woody detritus; plastic
07	-1.52 to -1.76	334 to 358	As2, Sh2, Dh+; nig.2+, strf.0, sicc.2, elas.0, l.s.1 Dark brown-grey organic clay with rare herbaceous detritus; plastic
06	-1.76 to -2.84	358 to 466	As2, Ag1, Sh1++, Ga+, Dl+, Dh+, nig.2, strf.1, sicc.2, elas.0, l.s.0 Brown grey organic silty clay with few sandy inliers ; rare woody and herbaceous detritus; coarsely laminated
05	-2.84 to -3.05	466 to 487	As2, Ag1, Sh1, Ga++, Dh+, Dg+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Brown grey organic sandy silty clay with rare herbaceous detritus and few organic fragments; coarsely laminated
04	--3.05 to -3.11	487 to 493	As2, Ga1, Sh1, Dh+, Lf+; nig.2, strf.++, sicc.2, elas.0, l.s.2 Light brown grey organic sandy clay with few iron clasts; rare herbaceous detritus; coarsely laminated
03	-3.11 to -3.17	493 to 499	As2, Ga1, Sh1, Dg++, Dh+; nig.2, strf.++, sicc.2, elas.0, l.s.2 Brown grey organic sandy clay with frequent black shaded organic fragments; rare herbaceous detritus; rough surface; coarsely laminated
02	-3.17 to -3.28	499 to 510	As2, Sh1, Lf1, Ga+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Buff grey organic clayey with rare sand and diffused iron staining; many iron clasts; some black colour small stones; rare herbaceous detritus; crumbly
01	-3.28 to -3.64	510 to 546	As4, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light blue-grey Pleistocene clay with diffused iron staining; become reddish when oxidized; hard

Borehole No. M-20S

Stratum	Altitude (m)	Depth (cm)	Description
22	+1.87 to +1.21	0 to 66	Disturbed
21	+1.21 to +1.02	66 to 85	As3, Ag1, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.? Battleship grey silty clay with diffused iron staining; plastic and sticky
20	+1.02 to +0.90	85 to 97	$Ld^3 4$, As++, Dh+; nig.3, strf.1, sicc.2, elas.1, l.s.1 Dark brown limus with clay; rare herbaceous detritus; coarsely laminated
19	+0.90 to +0.81	97 to 106	Ag2, As1, Ga1; nig.2, strf.1, sicc.2, elas.0. l.s.1 Light brown grey sandy clayey silt; coarsely laminated
18	+0.81 to +0.70	106 to 117	Ag2, As1, Ga1, Dh+; nig.2, sicc.2, strf++, elas.0, l.s.0 Light brown-grey sandy clayey silt with rare herbaceous detritus; coarsely laminated
17	+0.70 to +0.44	117 to 143	As2, Ag1, Sh1+, Dh+, Dl+; nig.2+, strf.0, sicc.2, elas.0, l.s.+ Grey-brown organic silty clay with rare woody and herbaceous detritus; few vivianites; inclusions from layer below; hard
16	+0.44 to -0.36	143 to 223	As3, Ag1, Ga+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare sand; plastic

15	-0.36 to -0.51	223 to 238	As2, Ag2, Ga++; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey sandy silty clay; plastic
14	-0.51 to -0.59	238 to 246	As3, Ag1, Sh++; nig.2, strf.0, sicc.2, elas.0, l.s.+ Light brown grey organic silty clay; moulted
13	-0.59 to -0.83	246 to 270	As2, Ag2, Ga++; nig.2, strf.0, sicc.2, elas.0, l.s.+ Battleship grey sandy silty clay; plastic
12	-0.83 to -1.33	270 to 320	As2, Ag1, Sh1; Ga+, Dh+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Light grown grey organic silty clay with rare sand; few dicot leaves; rare woody and herbaceous detritus; plastic
11	-1.33 to -1.41	320 to 328	Ag2, As1, Sh1+; nig.2, strf.0, sicc.2, elas.0, l.s.+ Light grey organic clay silt; plastic and sticky
10	-1.41 to -1.79	328 to 366	As2, Ag1, Sh1+, Dh+, Dl++; nig.2, strf.0, sicc.2, elas.0, l.s.0 Brown grey organic silty clay with frequent woody detritus; rare herbaceous detritus; plastic
09	-1.79 to -1.93	366 to 380	As2, Ag1, Sh1, Th^3++, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Brown grey organic silty clay with frequent rootlets; few herbaceous detritus; plastic
08	-1.93 to -2.35	380 to 422	As2, Ag1, Sh1++, Th^3+, Dh++, nig.2, strf.0, sicc.2, elas.0, l.s.0 Brown grey organic silty clay with frequent herbaceous detritus; few rootlets, plastic
07	-2.35 to -2.54	422 to 441	As3, Sh1, Ag++, Dh+, Dg+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Dark Brown grey organic silty clay with rare herbaceous detritus and few organic fragments; plastic
06	-2.54 to -2.93	441 to 480	As2, Ag1, Sh1, Dh++, Dl+; nig.2, strf.1. sicc.2, elas.0, l.s.0 Brown grey organic silty clay with frequent herbaceous detritus; rare woody detritus; coarsely laminated
05	-2.93 to -2.99	480 to 486	As2, Ag1, Sh1, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Buff grey organic silty clay with frequent iron clasts and diffused iron staining; crumbly
04	-2.99 to -3.11	486 to 498	As2, Ag1, Sh1, Dh++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light brown grey organic silty clay with frequent herbaceous detritus; moulted
03	-3.11 to -3.25	498 to 512	As2, Ga2, Lf++, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light grey sandy clay with many iron clasts and diffused iron staining; rare herbaceous detritus; crumbly
02	-3.25 to -3.29	512 to 516	Ga3, As1, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light brown grey clayey sand with few woody detritus; crumbly
01	-3.29 to -3.53	516 to 540	As4, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light blue-grey Pleistocene clay with diffused iron staining; become reddish when oxidized; hard

Borehole No. M-25S

Stratum	Altitude (m)	Depth (cm)	Description
30	+2.11 to +1.25	0 to 86	Disturbed
29	+1.25 to +1.12	86 to 99	As2, Ag2, Lf+; nig.2, strf.0, sicc.2, elas.0, l.s.? Battleship grey silty clay with diffused iron staining; plastic and sticky
28	+1.12 to +1.00	99 to 111	$Ld^3$4, As++, Dh+, Dl+; nig.3, strf.1, sicc.2, elas.1, l.s.1 Dark brown limus with clay; rare woody and herbaceous detritus; coarsely laminated
27	+1.00 to +0.90	111 to 121	Ag2, As1, Ga1, Dh+, Dl+; nig.2, strf.1, sicc.2, elas.0. l.s.1 Light brown grey sandy clayey silt with rare woody and herbaceous detritus; coarsely laminated

26	+0.90 to +0.77	121 to 134	Ag2, As1, Ga1, Dh+; nig.2, sicc.2, strf.1, elas.0, 1.s.0 Light brown-grey sandy clayey silt with rare herbaceous detritus; coarsely laminated
25	+0.77 to +0.57	134 to 154	As2, Ag1, Sh1+, Dh+, Dl+; nig.2+, strf.0, sicc.2, elas.0, 1.s.+ Grey-brown organic silty clay with rare woody and herbaceous detritus and few vivianites; hard
24	+0.57 to -0.05	154 to 216	As3, Ag1, Ga+, Dh+, Th^2+; nig.2, strf.1, sicc.2, elas.0, 1.s.1 Battleship grey silty clay with rare sand; few herbaceous detritus and rootlets; coarsely laminated
23	-0.05 to -0.51	216 to 262	As2, Ag2, Ga++; nig.2, strf.0, sicc.2, elas.0, 1.s.0 Battleship grey sandy silty clay; plastic
22	-0.52 to -0.60	262 to 271	Ag2, As2, Sh++, Ga+; nig.2, strf.0, sicc.2, elas.0, 1.s.+ Light grey organic clayey silt with few sand; sticky and plastic
21	-0.60 to -0.70	271 to 281	As2, Ag2, Ga+; nig.2, strf.0, sicc.2, elas.0, 1.s.+ Battleship grey silty clay with rare sand; plastic
20	-0.70 to -0.82	281 to 293	As2, Ag1, Sh1, Dh+; nig.2, strf.0, sicc.2, elas.0, 1.s.0 Light grey organic silty clay with rare herbaceous detritus; moulted
19	-0.82 to -0.88	293 to 299	As2, Ag1, Sh1, Ga++, Dh+; nig.2, strf.++, sicc.2, elas.0, 1.s.+ Light brown grey organic sandy silty clay with rare herbaceous detritus; coarsely laminated
18	-0.88 to -1.46	299 to 357	As2, Ag1, Sh1; Ga+, Dh++; nig.2, strf.++, sicc.2, elas.0, 1.s.0 Light grown grey organic silty clay with rare sand; many herbaceous detritus; coarsely laminated
17	-1.46 to -1.66	357 to 377	As2, Sh2, Ga++, Dh++; nig.2+ strf.1+, sicc.2, elas.0, 1.s.+ Dark brown grey organic sandy clay with many herbaceous detritus; laminated
16	-1.66 to -2.28	377 to 439	As2, Sh2, Ga++, Dh+, Dl+; nig.2, strf.++, sicc.2, elas.0, 1.s.0 Brown grey organic sandy clay with rare woody and herbaceous detritus; coarsely laminated
15	-2.28 to -2.33	439 to 444	As3, Ag1; Sh+; nig.2, strf.0, sicc.2, elas.0, 1.s.+ Battleship grey silty clay with some decomposed organic matter; sticky and plastic
14	-2.33 to -2.48	444 to 459	As2, Ag1, Sh1++, Dh+; nig.2, strf.0, sicc.2, elas.0, 1.s.+ Brown grey organic silty clay with rare herbaceous detritus; plastic
13	-2.48 to -2.51	459 to 462	As2, Sh2; nig.2, strf.0, sicc.2, elas.0, 1.s.+ Dark Brown grey organic clay; plastic
12	-2.51 to -2.77	462 to 488	Sh2, As1, Ag1, Dg+; nig.2, strf.0, sicc.2, elas.0, 1.s.+ Brown grey organic silty clay with rare organic fragments; plastic
11	-2.77 to -2.82	488 to 493	As2, Ga1, Sh1, Dh+; nig.2, strf.++, sicc.2, elas.0, 1.s.2 Light brown grey organic sandy clay with sandy inliers along the lamination; rare herbaceous detritus; coarsely laminated
10	-2.82 to -3.06	493 to 517	As2, Ag1, Sh1, Dg+; nig.2, strf.0, sicc.2, elas.0, 1.s.2 Brown grey organic silty clay with few organic fragments; moulted
09	-3.06 to -3.10	517 to 521	As2, Ag1, Sh1, Lf++, Dh+, Dl+; nig.2, strf.0, sicc.2, elas.0, 1.s.+ Light blue grey organic silty clay with diffused iron staining and mottled iron clasts; rare woody and herbaceous detritus; crumbly
08	-3.10 to -3.23	521 to 534	As2, Ag1, Sh1+, Dg+; nig.2, strf.0, sicc.2, elas.0, 1.s.0 Brown grey organic silty clay with few organic fragments; moulted
07	-3.23 to -3.73	534 to 584	As2, Ag1, Sh1, Ga+, Dh+, Dg+; nig.2, strf.0, sicc.2, elas.0, 1.s.0 Brown grey organic silty clay with rare sand, rare herbaceous detritus and few organic fragments; moulted

06	-3.73 to -3.80	584 to 591	As2, Ag1, Sh1, Dh++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Brown grey organic silty clay with many herbaceous detritus; few mottled iron clasts; crumbly
05	-3.80 to -3.87	591 to 598	As2, Sh2, Dh+; nig.2+, strf.0, sicc.2, elas.0, l.s.2 Dark brown organic clay with rare herbaceous detritus; plastic
04	-3.87 to -3.93	598 to 604	As2, Sh2, Dg+; nig.2+, strf.0, sicc.2, elas.0, l.s.2 Dark brown grey organic clay with rare organic fragments; plastic
03	-3.93 to -4.10	604 to 621	As2, Sh2, Dh++, Dg+; nig.2+, strf.0, sicc.2, elas.0, l.s.2 Brown grey organic clay with frequent herbaceous detritus and few organic fragments; plastic
02	-4.10 to -4.24	621 to 635	As2, Ag1, Sh1, Lf++, Dg+; nig.2, strf.0, sicc.2, elas.0. l.s.2 Brown grey organic silty clay with blue inliers of few organic fragments; some mottled iron clasts; crumbly
01	-4.24 to -4.50	635 to 661	As4, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light blue-grey Pleistocene clay with diffused iron staining; become reddish when oxidized; hard

Borehole No. M-30S

Stratum	Altitude (m)	Depth (cm)	Description
20	+2.00 to +1.27	0 to 73	Disturbed
19	+1.27 to +1.10	73 to 90	As3, Ag1, Lf++, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.? Battleship grey silty clay with diffused iron staining; rare herbaceous detritus; plastic and sticky
18	+1.10 to +1.02	90 to 98	Ld^{3}3, As1, Dh+, Dl+; nig.3, strf.1, sicc.2, elas.1, l.s.1 Dark brown limus with clay; rare woody and herbaceous detritus; coarsely laminated
17	+1.02 to +0.94	98 to 106	Ag2, As1, Ga1, Dh+, Dl+; nig.2, strf.1, sicc.2, elas.0. l.s.1 Light brown grey sandy clayey silt with rare woody and herbaceous detritus; coarsely laminated
16	+0.94 to +0.78	106 to 122	Ag2, As1, Ga1, Dh+; nig.2, sicc.2, strf.1, elas.0, l.s.0 Light brown-grey sandy clayey silt with rare herbaceous detritus; coarsely laminated
15	+0.78 to +0.64	122 to 136	As2, Ag1+, Sh1, Dh+, Dl+; nig.2+, strf.0, sicc.2, elas.0, l.s.+ Grey-brown organic silty clay with rare woody and herbaceous detritus; hard
14	+0.64 to +0.30	136 to 170	As3, Ag1, Dh+; nig.2, strf.1, sicc.2, elas.0, l.s.1 Battleship grey silty clay with few herbaceous detritus; coarsely laminated
13	+0.30 to -0.40	170 to 240	Ag2, As2, Sh+, Dh+; nig.2, strf.++, sicc.2, elas.0, l.s.0 Battleship grey organic silty clay with few herbaceous detritus; coarsely laminated
12	-0.40 to -0.52	240 to 252	As2, Ag2, Sh++; nig.2, strf.0, sicc.2, elas.0, l.s.+ Battleship grey organic silty clay; plastic
11	-0.52 to -0.86	252 to 286	As2, Ag2, Ga+; Dh+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.+ Battleship grey silty clay with rare sand; plastic
10	-0.86 to -1.45	286 to 345	As2, Ag1, Sh1+, Dh++, Dl+; nig.2, strf.++, sicc.2, elas.0, l.s.0 Light brown grey organic silty clay with frequent herbaceous detritus; and few woody detritus; coarsely laminated
09	-1.45 to -1.52	345 to 352	As2, Sh2, Dh+; nig.2+ strf.0, sicc.2, elas.0, l.s.+ Dark brown grey organic clay with few herbaceous detritus; plastic
08	-1.52 to -2.60	352 to 460	As2, Sh2, Dh+, Dl+; Dg+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Brown grey organic clay with rare woody and herbaceous detritus; few organic fragments; plastic

07	-2.60 to -2.66	460 to 466	Ga2, As1, Sh1; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light grey organic clayey sand; crumbly
06	-2.66 to -2.75	466 to 475	As2, Sh2, Ga++, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Dark grey organic sandy clay with rare herbaceous detritus; plastic
05	-2.75 to -2.86	475 to 486	Ga2, As1, Sh1; Dh++, Dg++; nig.2, strf.1+, sicc.2, elas.0, l.s.2 Light grey organic clayey sand with frequent herbaceous detritus and many organic fragments; laminated
04	-2.86 to -2.95	486 to 495	As2, Ag1, Ga1, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Buff grey sandy silty clay layer with frequent mottled iron clasts; crumbly
03	-2.95 to -3.03	495 to 503	Ga2, As1, Dl1, Lf+; nig.2, strf.1+, sicc.2, elas.0, l.s.2 Brown grey clayey sand with many black shaded woody detritus; few mottled iron clasts; laminated
02	-3.03 to -3.13	503 to 513	As3, Ga1, Lf+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light blue grey sandy clay with few iron clasts; plastic
01	-3.13 to -3.53	513 to 553	As4, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light blue-grey Pleistocene clay with diffused iron staining; become reddish when oxidized; hard

Borehole No. M-35S

Stratum	Altitude (m)	Depth (cm)	Description
18	+1.84 to +1.24	0 to 60	Disturbed
17	+1.24 to +1.04	60 to 80	As3, Ag1, Lf++, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.? Battleship grey silty clay with diffused iron staining; rare herbaceous detritus; plastic and sticky
16	+1.04 to +0.98	80 to 86	Ld³3, As1 Dh+; nig.3, strf.1, sicc.2, elas.1, l.s.1 Dark brown limus with clay; rare herbaceous detritus; coarsely laminated
15	+0.98 to +0.84	86 to 100	Ag2, Ga2, Dh+, Dl+; nig.2, strf.1, sicc.2, elas.0. l.s.1 Light brown grey sandy silt with rare woody and herbaceous detritus; coarsely laminated
14	+0.84 to +0.70	100 to 114	Ag2, Ga2+, Dh+; nig.2, sicc.2, strf.1, elas.0, l.s.0 Light brown-grey sandy silt with rare herbaceous detritus; coarsely laminated
13	+0.70 to +0.44	114 to 140	As2, Ag1, Sh1, Dh+, Dl+; nig.2+, strf.0, sicc.2, elas.0, l.s.+ Grey-brown organic silty clay with rare woody and herbaceous detritus; hard
12	+0.44 to -0.06	140 to 190	As3, Ag1, Ga+, Dh+; nig.2, strf.+, sicc.2, elas.0, l.s.1 Battleship grey silty clay with rare sand; few herbaceous detritus; very coarsely laminated
11	-0.06 to -0.66	190 to 250	As2, Ag2, Ga+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey silty clay with few sand; rare herbaceous detritus; coarsely laminated
10	-0.66 to -0.74	250 to 258	As3, Ag1, Sh++, Dh+, Dg+; nig.2, strf.0, sicc.2, elas.0, l.s.+ Battleship grey organic silty clay; rare herbaceous detritus; few organic fragments; plastic
09	-0.74 to -0.99	258 to 283	As2, Ag2, Ga+, Dh+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.+ Battleship grey silty clay with rare sand; plastic
08	-0.99 to -1.52	283 to 336	As2, Ag1, Sh1+, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Light brown grey organic silty clay with rare herbaceous detritus; and few woody detritus; plastic

07	-1.52 to -1.62	336 to 346	As2, Sh2, Dg++, Dh+, Dl+; nig.2+ strf.++, sicc.2, elas.0, l.s.+ Dark brown grey organic clay with frequent organic fragments; few herbaceous and woody detritus; coarsely laminated
06	-1.62 to -2.92	346 to 476	As2, Sh2, Dh+, Dl+, Dg+; nig.2, strf.++, sicc.2, elas.0, l.s.0 Brown grey organic clay with rare woody and herbaceous detritus; few organic fragments; coarsely laminated
05	-2.92 to -2.99	476 to 483	Ga2, As1, Sh1, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light grey organic clayey sand; rare woody detritus; crumbly
04	-2.99 to -3.14	483 to 498	As2, Sh2, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Dark grey organic clay with rare herbaceous detritus; plastic
03	-3.14 to -3.31	498 to 515	As2, Sh1, Ld^{3}1, Ga++, Dh++; nig.2, strf.1, sicc.2, elas.++, l.s.2 Brown grey organic sandy clay with limus; frequent herbaceous detritus; coarsely laminated.
02	-3.31 to -3.61	515 to 545	As2, Ag1, Sh1, Ga+, Dh+, Th^{3}+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Brown grey organic silty clay with rare sand, herbaceous detritus and rootlets; plastic
01	-3.61 to -4.09	545 to 593	As4, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light blue-grey Pleistocene clay with diffused iron staining; become reddish when oxidized; hard

Borehole No. M-40S

Stratum	Altitude (m)	Depth (cm)	Description
13	+1.76 to +0.70	0 to 106	Disturbed
12	+0.70 to +0.29	106 to 147	Ag2, Ga2+, Sh++, Dh+; nig.2, sicc.2, strf.1, elas.0, l.s.? Light brown-grey organic sandy silt with rare herbaceous detritus; coarsely laminated
11	+0.29 to 0.00	147 to 176	As2, Ag1, Sh1, Dg++, Dl+; nig.2+, strf.0, sicc.2, elas.0, l.s.+ Grey-brown organic silty clay with frequent organic fragments, rare woody detritus; hard
10	0.00 to -0.34	176 to 210	As3, Ag1, Dh++; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with frequent herbaceous detritus; plastic
09	-0.34 to -1.34	210 to 310	As2, Ag2, Sh++, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey organic silty clay with few herbaceous detritus; plastic
08	-1.34 to -1.79	310 to 355	As3, Ag1, Sh1, Dh+, Dl+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey organic silty clay; rare herbaceous and woody detritus; plastic
07	-1.79 to -1.86	355 to 362	As2, Sh2, Dh+; nig.2+ strf.0, sicc.2, elas.0, l.s.+ Dark brown grey organic clay with few herbaceous detritus; plastic
06	-1.86 to -2.37	362 to 413	As2, Ag1, Sh1, Dh++; nig.2, strf.0, sicc.2, elas.0, l.s.+ Light brown grey organic clay with frequent herbaceous detritus; plastic
05	-2.37 to -3.14	413 to 490	As2, Sh2, Dh++, Dl+; nig.2, strf.1, sicc.2, elas.0, l.s.0 Brown grey organic clay with frequent herbaceous detritus; rare woody detritus; coarsely laminated
04	-3.14 to -3.20	490 to 496	As2, Sh2++, Dh+; nig.3, strf.0, sicc.2, elas.0, l.s.2 Dark brown organic clay with rare herbaceous detritus; plastic
03	-3.20 to -3.30	496 to 506	As2, Sh1, Ld^{3}1, Dh+; nig.2, strf.0, sicc.2, elas.++, l.s.2 Brown grey organic clay with some limus; rare herbaceous detritus; sticky and plastic
02	-3.30 to -3.34	506 to 510	Ga2, As1, Sh1, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Buff grey organic clayey sand with frequent mottled iron clasts; rough and crumbly

01	-3.34 to -3.94	510 to 570	As4, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light blue-grey Pleistocene clay with diffused iron staining; become reddish when oxidized; hard

Borehole No. M-45S

Stratum	Altitude (m)	Depth (cm)	Description
15	+1.73 to +0.73	0 to 100	Disturbed
14	+0.73 to +0.25	100 to 148	Ga2+, As1, Ag1, Sh++, Dh+; nig.2, sicc.2, strf.1, elas.0, l.s.? Light brown-grey organic silty clayey sand with rare herbaceous detritus; coarsely laminated
13	+0.25 to -0.17	148 to 190	As2, Ag1, Sh1, Ga+, Dg+, Dl+; nig.2+, strf.0, sicc.2, elas.0, l.s.+ Grey-brown organic silty clay with rare sand; few organic fragments, rare woody detritus; hard
12	-0.17 to -0.85	190 to 258	As3, Ag1, Dh++; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with frequent herbaceous detritus; plastic
11	-0.85 to -1.77	258 to 350	As2, Ag1, Sh1, Dh+, Dl+, Dg+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Battleship grey organic silty clay with few woody and herbaceous detritus; rare organic fragments; plastic
10	-1.77 to -1.83	350 to 356	As2, Sh2, Ga+, Dh+; nig.2+ strf.0, sicc.2, elas.0, l.s.+ Dark brown grey organic clay with few sand; few herbaceous detritus; plastic
09	-1.83 to -2.73	356 to 446	As2, Ag1, Sh1+, Dh+, Dg+; nig.2, strf.0, sicc.2, elas.0, l.s.+ Light brown grey organic silty clay with rare herbaceous detritus; few organic fragments; plastic
08	-2.73 to -3.20	446 to 493	As2, Sh2, Dg++; nig.2, strf.++, sicc.2, elas.0, l.s.0 Brown grey organic clay with frequent organic fragments; coarsely laminated
07	-3.20 to -3.27	493 to 500	As2, Ag1, Sh1+, Ga+, Lf+; nig.2, strf.0, sicc.2, elas.0, l.s.0 Brown grey organic silty clay with rare sand; few mottled iron clasts; rough and crumbly
06	-3.27 to -3.34	500 to 507	As2, Sh1, $Ld^3$1, Ga++; nig.2, strf.0, sicc.2, elas.++, l.s.2 Brown grey organic sandy clay with some limus; plastic
05	-3.34 to -3.40	507 to 513	Ga2, As1, Sh1, Dg+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Brown grey organic clayey sand with few organic fragments; crumbly
04	-3.40 to -3.52	513 to 525	As2, Sh2, Dh+; nig.2+, strf.0, sicc.2, elas.0, l.s.2 Dark brown organic clay with rare herbaceous detritus; plastic
03	-3.52 to -3.59	525 to 532	As2, Ga2, Lf++; nig.2, strf.0, sicc.2, elas.0. l.s.2 Buff grey sandy clay with frequent iron clasts; plastic
02	-3.59 to -3.69	532 to 542	As2, Ga1, Sh1, Dh+; nig.2, strf.0, sicc.2, elas.0, l.s.2 Brown grey organic sandy clay with rare herbaceous detritus; plastic
01	-3.69 to -410	542 to 583	As4, Lf++; nig.2, strf.0, sicc.2, elas.0, l.s.2 Light blue-grey Pleistocene clay with diffused iron staining; become reddish when oxidized; hard

Monolith Core

Stratum	Altitude (m)	Depth (cm)	Description
07	+1.88 to +0.84	0 to 104	Not collected in monolith
06	+0.84 to +0.73	104 to 115	$Ld^3$4, Dh+, Dl+, Dg+, Ag+; nig.3, strf.1, sicc.2, elas.1+, l.s.1 Dark-brown limus with rare woody and herbaceous detritus and few organic fragments and silty clasts; laminated

05	+0.73 to +0.57	115 to 131	Ld^{2}3, As1, Dh++, Th^2+, Dl+; nig.2, strf.2, sicc. 2, elas.2, l.s.0 Brown clayey limus with frequent herbaceous detritus, and rare rootlets and woody detritus; well laminated
04	+0.57 to +0.40	131 to 148	Ag3, As1, Ga++, Dh++, Dl, Lf+; nig.2, strf.1, sicc.2, elas.0, l.s.+ Light grey clayey silt with frequent sand and herbaceous detritus,rare woody detritus and diffused iron staining; coarsely laminated
03	+0.40 to +0.06	148 to 182	Ga2, Ag1, As1, Sh++, Dg+, Dl+; nig.2, strf.1, sicc.2, elas.0, l.s.+ Ash-grey organic silty clayey sand with rare organic fragments and woody detritus; rare vivianite; coarsely laminated
02	+0.06 to -0.34	182 to 222	As2, Ag1, Sh1, Dg+, Ga+, Dl+, f.o.+; nig.2+, strf.0. sicc.2, elas.0. l.s.0 Grey-brown organic silty clay with; rare sandy clasts, discrete woody fragments and vivianites crystals; a vertebrate at the top of the layer; inclusions from the layer below very hard and consolidated
01	-0.34 to -0.52	222 to 240	As2, Ag2, Th^2+, Dh+, Dl+, Ga+; nig.2, strf.0, sicc.2, elas.0, l.s.1 Battleship grey silty clay with some woody and herbaceous detritus; discrete woody inclusions; inclusions from the layer above; plastic

Appendix 9:

Particle Size data for Panigati

Depth (m)	Coarse sand	Medium sand	Fine sand	Coarse silt	Medium silt	Fine silt	Clay	Stratum Number	Field Analysis
P-208W									
170	0.1	0.2	21.2	65.4	7.0	2.1	4.0	17	Ga4,As++,Ag++
220	0.2	0.2	20.5	65.9	6.5	2.2	4.5	17	*do.*
280	0.0	0.1	18.6	67.7	7.4	2.1	4.2	16	As2,Ag1,Ga1
300	0.0	0.1	0.1	14.7	45.4	17.3	22.5	15	As3,Ag1,Ga++
320	0.0	0.0	0.0	11.5	43.4	19.4	25.7	15	*do.*
330	0.0	0.0	0.0	7.6	42.9	22.5	27.0	15	*do.*
345	0.0	0.0	0.0	31.0	16.2	12.5	40.3	14	As2,Ag1,Ld^{3}1,Sh++??
390	0.0	0.0	0.0	28.7	27.3	24.7	19.1	12	As2, Ld^{2}1,Sh1,Dh+
400	0.0	0.0	0.0	27.8	24.7	26.7	20.7	12	*do.*
500	0.3	0.3	0.6	5.4	14.5	32.8	46.2	9	As2,Ag1,Sh1
520	0.0	0.0	0.0	7.4	30.3	37.5	24.8	9	*do.*
590	0.0	1.9	2.7	13.8	30.8	25.1	25.7	7	As2,Ag1,Sh1,Dh+,Ga+
610	0.8	1.6	2.6	17.5	34.1	25.4	17.9	7	*do.*
640	0.4	0.5	0.3	8.0	41.7	26.6	22.5	6	As3,Ag1,Sh++,Ga+
665	0.0	0.0	0.0	1.5	92.4	2.9	3.2	4	As2,Ag1,Sh1
685	0.0	0.0	0.1	11.7	41.0	21.1	26.1	4	*do.*
710	0.0	0.0	0.2	18.2	47.6	16.7	17.3	2	As4,Sh++
730	0.1	0.1	0.3	17.2	44.8	17.4	20.2	2	*do.*
750	0.2	0.1	0.3	17.7	43.0	16.8	22.0	2	*do.*
780	0.3	0.1	0.6	18.0	36.0	22.1	22.8	1	As3,Ag1,Sh++
820	0.0	0.1	0.3	13.1	27.6	30.5	28.3	1	*do.*
P-500W									
850	0.1	0.3	0.3	21.5	47.6	13.0	17.1	2	As2,Ag2,Ga++,Dl+,Sh+
870	0.1	0.4	0.4	22.3	48.3	13.2	15.3	2	*do.*
910	0.0	0.2	0.2	12.2	50.4	19.4	17.6	2	*do.*
930	0.0	0.2	0.3	10.0	44.9	22.7	21.9	1	As2,Ag2,Sh++
950	0.0	0.1	0.3	7.7	37.0	27.1	27.9	1	*do.*
980	0.0	0.0	0.1	8.3	35.1	27.3	29.3	1	*do.*
1000	0.0	0.0	0.2	6.7	34.1	26.9	32.1	1	*do.*

Appendix 10:

Particle Size Data of Umitsu's Core

Depth (m)	Coarse sand	Medium sand	Fine sand	Coarse silt	Medium silt	Fine silt	Clay
25	0.2	0.3	1.1	21.7	37.8	16.5	22.4
26	0.0	0.1	0.9	22.4	38.1	16.8	21.7
27	0.0	0.0	0.2	8.8	44.5	23.5	22.9
28	0.0	0.1	0.7	20.2	38.0	18.9	22.1
31	0.1	0.3	0.9	23.7	38.0	15.6	21.4
32	0.3	0.6	29.0	36.9	16.3	9.5	7.4
33	0.2	0.4	15.0	38.6	21.5	10.2	14.2
34	0.4	2.0	9.1	22.5	21.5	9.8	34.5
35	0.3	2.0	9.1	25.2	23.9	10.2	29.1
37	1.3	2.0	8.6	21.8	18.0	8.7	39.8
38	0.3	2.1	10.3	21.5	16.5	7.0	42.3
39	0.0	5.8	11.1	21.0	14.3	16.1	40.8
40	0.3	1.4	11.9	22.4	14.8	7.1	42.1
41	0.3	3.3	11.1	19.6	16.7	7.6	41.4
42	0.0	0.5	2.0	6.8	25.7	21.7	43.3
43	0.0	0.7	2.4	8.5	30.4	20.4	37.6
44	0.0	1.2	26.9	19.5	15.7	10.4	26.3
45	0.0	2.9	68.6	28.6	0.0	0.0	0.0
46	0.0	2.0	66.3	31.7	0.0	0.0	0.0
47	2.0	44.1	34.3	19.6	0.0	0.0	0.0
48	2.0	39.2	34.3	24.5	0.0	0.0	0.0
49	3.8	48.1	28.8	19.2	0.0	0.0	0.0
50	1.0	46.6	31.1	21.4	0.0	0.0	0.0
51	1.0	51.5	27.7	19.8	0.0	0.0	0.0
52	1.0	43.1	35.3	20.6	0.0	0.0	0.0
53	1.0	35.9	39.8	23.3	0.0	0.0	0.0
54	2.9	51.0	34.3	11.8	0.0	0.0	0.0
55	1.9	51.5	32.0	14.6	0.0	0.0	0.0
56	5.9	53.9	30.4	9.8	0.0	0.0	0.0
57	5.0	54.5	29.7	10.9	0.0	0.0	0.0
58	7.1	25.5	31.6	35.7	0.0	0.0	0.0
59	7.3	26.0	38.5	28.1	0.0	0.0	0.0
60	9.8	38.2	29.4	22.5	0.0	0.0	0.0
61	12.7	49.0	28.4	9.8	0.0	0.0	0.0
62	9.9	48.5	29.7	11.9	0.0	0.0	0.0
63	8.8	58.8	17.6	14.7	0.0	0.0	0.0
64	5.0	49.5	29.7	15.8	0.0	0.0	0.0
65	6.9	49.0	29.4	14.7	0.0	0.0	0.0
66	4.9	53.9	21.6	19.6	0.0	0.0	0.0
67	18.6	53.9	16.7	10.8	0.0	0.0	0.0
68	19.8	44.6	20.8	14.9	0.0	0.0	0.0
69	12.9	54.5	17.8	14.9	0.0	0.0	0.0
70	33.7	34.8	19.6	12.0	0.0	0.0	0.0

Appendix 11:

Particle Size Data for Matuail

Depth (m)	Coarse sand	Medium sand	Fine sand	Coarse silt	Medium silt	Fine silt	Clay	Stratum Number	Field Analysis
M-Monolith									
135	0.0	0.0	10.1	30.6	38.6	9.0	11.7	4	Ag3,As1,Ga++,Dh++,Dl+,
145	0.0	0.0	12.6	29.5	37.1	8.8	12.0	4	do
160	0.7	1.1	17.5	45.7	21.9	4.8	8.3	3	Ga2,Ag1,As1,Sh++,Dg+,Dl+
180	1.0	2.6	23.6	46.7	19.2	2.2	4.7	3	do
200	0.0	0.9	2.8	26.4	34.0	14.2	21.7	2	As2,Ag1,Sh1,Dg+,Ga+,Dl+
220	0.0	1.1	3.5	28.7	33.9	13.9	19.1	2	do
240	0.0	0.1	0.9	21.1	25.8	17.2	34.8	1	As2,Ag2,Th^2+,Dh+,Dl+Ga+
M-10.5E									
210	0.0	0.0	0.5	10.5	36.1	22.8	30.1	17	As3,Ag1,Ga+,Sh+,Th^2+Dh+
240	0.0	0.2	3.3	22.6	21.0	16.4	36.4	17	do
260	0.0	0.3	3.4	25.1	28.6	11.9	30.8	17	do
310	0.1	0.3	6.6	26.4	25.3	12.1	29.2	16	Ag2,As2,Ga++,Sh+,Th^2+
340	0.0	0.2	5.7	26.5	25.8	13.1	28.7	16	do
360	0.2	0.7	7.0	28.4	24.7	13.4	25.6	15	As2,Ag1,Sh1,Dh+,Dl+
390	0.3	2.6	9.7	30.5	28.5	11.8	16.6	14	As2,Ag1,Sh1,Ga+,Dh+,Dl+
425	5.2	21.6	46.6	10.4	5.4	5.7	5.2	13	Ga3,As1,Sh+,Ag+,Dh+,Dl+
450	0.0	0.8	4.7	30.5	12.5	9.5	42.0	12	As2,Ag1,Sh1,Ga++,Dh+,Dl+
480	0.2	1.1	15.0	35.1	13.5	9.3	25.8	11	Ag2,As1,Sh1,Ga+++,Dh+
500	0.0	1.0	15.1	35.1	13.2	9.1	26.4	11	do
520	2.0	2.0	8.1	21.1	22.8	9.2	34.8	10	As2,Ag1,Sh1,Ga++,Dl+
530	0.0	1.1	21.0	20.8	21.5	8.5	27.1	9	Ag2,Ga1,As1,Dl++,Sh++

Appendix 12:

Total Pollen Count at Each Level: P-208W

Species	Depth (cm) → 340	350	360	370	380	390	400	410	420	430	440	450	460	470	480	490	500
Tree																	
Aegi. Corniculatum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Amoora cucullata	0	0	0	0	1	3	0	0	0	0	2	4	0	0	0	0	0
Avicennia marina	0	0	0	0	6	7	10	5	0	0	0	5	9	0	0	12	10
Barringtonia racemosa	0	0	0	0	0	2	8	0	22	0	12	0	0	0	10	0	10
Bruguiera gymnorhiza	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	6	10
Ceriops decandra	0	0	0	0	0	3	16	0	0	0	4	4	0	0	20	0	0
Excoecaria agallocha	3	0	24	8	28	85	100	45	60	32	250	200	205	4	10	6	155
Heritiera fomes	4	6	0	0	2	16	26	9	11	0	130	56	38	0	10	0	5
Rhiz. mucronata	0	0	0	0	0	1	20	5	0	0	6	2	0	0	10	7	2
Sonneratia apetala	0	0	0	0	0	0	2	0	0	0	24	11	22	7	0	0	0
Xylocarpus sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Shrubs																	
Anacardium sp.	0	0	2	4	2	2	2	5	0	0	6	9	17	0	0	0	0
Nypa fruticans	0	0	0	0	1	0	0	5	0	0	20	0	0	0	0	0	0
Phoenix paludosa	0	6	2	2	1	2	0	0	0	0	13	0	4	0	0	0	0
Terminalia sp.	0	0	0	0	0	0	4	0	0	0	0	0	6	0	0	0	0
Umbelliferae	0	0	0	0	1	0	0	0	3	0	0	0	0	0	0	0	0
Herbs																	
Astir type	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cheno-amaranthaceae	1	7	0	0	0	0	18	0	0	0	0	0	0	3	0	0	0
Compositae	2	3	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Cucumis trigonus	20	27	30	10	17	25	44	37	39	72	0	8	9	8	10	54	0
Cyperaceae	9	9	4	10	6	1	6	13	0	40	0	1	0	0	11	12	0
Gramineae (small)	35	33	14	24	27	5	2	41	0	16	0	2	8	50	10	6	0
Gramineae (large)	80	96	104	100	140	37	26	0	33	20	0	15	35	80	75	72	0
Suaeda sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aquatic																	
Potamogeton	2	6	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
Typha angustata	8	9	0	0	0	0	2	3	143	8	40	3	56	5	11	0	0
Acacia arabica	2	3	0	0	0	0	0	0	22	0	0	0	4	4	0	0	0
Plantago sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	4	10	0	0
Spores																	
Acrostichum aureum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	8	60
Monolete verrucate	30	39	112	200	72	54	26	70	200	250	30	50	100	30	30	140	12
Monolete psilate	20	0	15	44	5	3	4	28	48	50	15	10	16	14	6	14	16
Trilete verrucate	12	0	0	0	0	0	0	0	12	2	2	2	0	20	12	8	8
Trilete psilate	2	0	0	0	0	0	0	0	6	0	0	0	0	0	2	8	60
Ceratopteris	0	6	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0

Specie Depth (cm) →	510	520	530	540	550	560	570	580	590	600	610	620	630	640	650	660	670
Tree																	
Aegi. corniculatum	0	0	0	0	0	0	0	0	2	4	3	2	2	0	3	2	5
Amoora cucullata	0	0	0	0	0	0	0	0	0	0	1	0	6	8	3	3	0
Avicennia marina	3	0	0	0	0	0	0	0	0	0	6	6	10	15	1	2	12
Barringtonia racemosa	0	0	0	0	0	0	0	0	2	4	3	0	2	7	0	1	2
Bruguiera gymnorhiza	0	0	0	0	0	0	0	0	0	0	3	6	8	8	4	6	5
Ceriops decandra	6	0	0	0	0	0	0	0	0	0	2	5	7	8	6	4	5
Excoecaria agallocha	42	32	30	24	22	14	4	34	30	32	30	30	45	55	30	60	35
Heritiera fomes	6	0	3	4	0	4	0	18	10	12	18	15	21	30	25	45	18
Rhiz. mucronata	0	0	9	0	0	0	0	0	0	0	7	8	7	8	18	7	5
Sonneratia apetala	6	0	3	0	0	0	0	0	5	8	13	14	15	20	17	14	35
Xylocarpus sp.	0	0	0	0	0	0	0	0	0	0	10	15	0	0	1	2	5
Shrubs																	
Anacardium sp.	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	2
Nypa fruticans	0	0	0	0	0	0	0	0	2	0	1	0	1	2	1	2	0
Phoenix paludosa	0	0	0	0	0	0	0	0	1	0	2	4	0	0	2	1	6
Terminalia sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Umbelliferae	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	4
Herbs																	
Aster type	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	2	4
Cheno-amaranthaceae	0	0	0	0	0	0	0	0	0	0	1	0	0	5	1	2	2
Compositae	0	0	3	0	0	0	0	2	2	0	0	0	0	2	0	1	0
Cucumis trigonus	30	0	60	40	32	30	56	150	66	28	22	20	12	10	20	10	18
Cyperaceae	6	0	3	4	4	10	0	12	5	4	6	2	3	0	5	7	0
Gramineae (small)	0	0	15	16	0	20	20	8	8	4	6	8	8	10	40	20	15
Gramineae (large)	54	64	51	80	120	80	88	120	80	80	70	18	10	10	10	5	2
Suaeda sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Aquatic																	
Potamogeton	0	0	0	0	0	0	0	0	2	4	2	0	0	0	0	2	6
Typha angustata	0	96	3	0	0	0	0	0	0	0	2	0	2	0	10	12	8
Acacia arabica	0	0	0	0	0	0	0	8	8	0	0	0	0	0	0	0	0
Plantago sp	0	0	3	0	0	0	0	0	0	0	2	0	1	0	1	2	0
Spores																	
Acrostichum aureum	50	0	2	0	0	0	0	0	2	2	1	0	1	0	1	1	0
Monolete verrucate	2	20	26	40	36	36	48	180	40	60	10	7	6	8	6	5	6
Monolete psilate	20	60	16	34	60	80	100	90	20	5	10	4	5	7	8	13	13
Trilete verrucate	0	0	20	46	12	20	12	4	7	5	7	2	7	3	9	10	5
Trilete psilate	34	4	14	10	0	10	10	4	3	5	3	0	9	1	3	5	3
Ceratopteris	0	0	0	0	0	0	0	36	2	0	1	0	0	0	0	0	0

Species Depth (cm) →	680	690	695	705	710	720	730	750	770	790	810
Tree											
Aegi. corniculatum	0	0	2	1	0	0	0	0	1	1	0
Amoora cucullata	0	0	4	2	0	1	4	0	2	0	0
Avicennia marina	1	0	2	2	5	4	3	1	0	2	1
Barringtonia racemosa	0	0	0	0	0	1	0	0	1	0	0
Bruguiera gymnorhiza	1	1	3	5	7	5	2	2	1	2	2
Ceriops decandra	0	2	6	5	14	13	3	1	3	2	1
Excoecaria agallocha	8	10	40	80	50	40	8	7	3	8	2
Heritiera fomes	8	8	30	50	40	25	5	3	5	4	2
Rhiz. mucronata	3	1	9	4	3	2	2	0	2	1	4
Sonneratia apetala	2	3	18	7	12	10	4	2	0	4	1
Xylocarpus sp.	0	1	0	3	1	0	1	0	0	1	2
Shrubs											
Anacardium sp.	0	2	0	0	0	0	0	0	0	1	0
Nypa fruticans	2	0	0	4	4	2	1	0	0	0	1
Phoenix paludosa	0	0	2	0	0	0	0	0	0	0	0
Terminalia sp.	0	0	0	0	0	0	0	1	0	0	1
Umbelliferae	0	0	0	0	0	1	1	0	0	1	0
Herbs											
Aster type	0	0	0	0	0	0	2	1	0	2	0
Cheno-amaranthaceae	1	2	2	0	2	0	2	1	2	1	0
Compositae	0	0	0	0	0	0	0	0	0	0	0
Cucumis trigonus	0	0	33	4	4	2	2	2	5	7	1
Cyperaceae	0	0	10	2	0	0	0	1	2	3	5
Gramineae (small)	0	8	50	30	8	4	8	8	7	3	5
Gramineae (large)	4	0	20	6	2	2	2	3	4	2	1
Suaeda sp.	0	2	2	3	0	0	2	1	0	1	0
Aquatic											
Potamogeton	1	0	5	0	0	0	0	1	0	0	0
Typha angustata	3	6	13	14	14	1	3	1	0	2	1
Acacia arabica	0	0	9	0	0	0	0	0	0	0	0
Plantago sp	0	2	0	0	0	0	0	0	0	0	0
Spores											
Acrostichum aureum	0	0	0	1	0	0	0	0	0	0	0
Monolete verrucate	5	8	26	60	6	7	8	8	4	7	5
Monolete psilate	4	13	27	38	4	5	2	3	2	9	3
Trilete verrucate	7	3	0	3	0	3	3	4	7	3	5
Trilete psilate	2	2	0	5	0	2	0	0	1	3	9
Ceratopteris	0	0	0	1	0	0	0	0	0	1	0

Appendix 13:

Total Pollen Count at Each Level in Core P-500W (830-1000 cm): Panigati

Species Depth (cm) →	830	840	850	860	870	880	900	920	940	960	980	990	1000
Tree													
Aegiceras corniculatum	2	0	0	0	0	0	1	1	0	1	0	2	2
Amoora cucullata	4	3	0	4	3	0	0	0	0	2	2	0	6
Avicennia marina	2	2	5	3	5	1	2	2	0	0	0	5	9
Barringtonia racemosa	0	1	0	0	0	0	1	0	2	2	2	0	2
Bruguiera gymnorhiza	2	4	6	2	0	1	1	2	0	0	1	5	8
Ceriops decandra	4	6	11	3	2	2	3	2	2	1	4	4	6
Excoecaria agallocha	45	70	44	8	8	8	3	8	1	3	5	25	40
Heritiera fomes	34	60	45	5	3	6	6	4	2	3	3	16	22
Rhizophora mucronata	12	5	7	3	4	1	2	1	2	2	3	8	7
Sonneratia apetala	9	9	9	5	2	2	0	4	1	0	2	11	12
Xylocarpus sp.	0	4	2	2	3	0	0	1	2	1	0	12	10
Shrubs													
Anacardium sp.	0	0	0	0	1	0	1	1	0	0	2	1	0
Nypa fruticans	0	4	5	1	0	0	0	0	1	0	0	0	1
Phoenix paludosa	2	6	0	1	1	0	2	0	0	1	0	5	4
Terminalia sp.	0	0	0	0	0	1	4	0	1	0	0	0	0
Umbelliferae	0	0	0	1	1	0	0	1	0	0	1	0	0
Herbs													
Aster type	1	0	0	2	2	1	0	2	0	0	2	0	0
Cheno-amaranthaceae	1	7	2	1	0	1	1	1	0	2	0	2	0
Compositae	0	3	0	2	3	0	0	0	0	0	0	0	0
Cucumis trigonus	20	7	4	2	7	2	4	7	3	7	4	19	12
Cyperaceae	10	9	1	1	5	1	3	3	5	2	3	2	3
Gramineae (small)	25	33	7	9	2	5	7	4	5	6	2	7	8
Gramineae (large)	20	16	4	3	4	7	6	0	1	3	0	15	12
Suaeda sp.	4	2	0	2	0	1	0	1	0	0	0	2	0
Aquatic													
Potamogeton	2	0	0	0	0	1	0	0	0	0	1	0	0
Typha angustata	8	9	10	3	2	1	2	3	1	0	4	0	3
Acacia arabica	7	0	0	0	0	0	0	0	2	0	0	0	0
Plantago sp	0	2	0	0	0	0	0	0	0	0	0	1	1
Spores													
Acrostichum aureum	0	0	0	0	0	0	0	0	0	0	0	0	0
Monolete verrucate	30	39	12	7	2	8	6	7	2	3	3	5	6
Monolete psilate	20	20	5	4	5	3	4	8	4	0	5	4	6
Trilete verrucate	12	7	0	0	0	4	0	2	2	2	2	2	7
Trilete psilate	2	5	3	0	0	0	3	2	6	0	0	0	6
Ceratopteris	0	0	0	0	0	0	0	1	0	0	0	1	0

Appendix 14:

Total Pollen Count at Each Level: M-10.5E

Species	Depth (cm)→200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350	360	370
Tree																		
Aegi. corniculatum	1	2	0	0	0	0	2	1	0	0	2	0	1	0	0	1	0	2
Amoora cucullata	5	12	3	0	1	1	0	0	0	0	2	0	0	0	0	1	0	1
Avicennia marina	7	3	1	0	1	0	0	1	2	1	0	0	0	0	0	0	1	0
Barr. racemosa	0	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	1
Brug. gymnorhiza	6	5	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2	1
Ceriops decandra	4	5	0	0	1	0	1	0	1	2	1	1	1	0	0	0	0	1
Excoecaria agallocha	15	10	9	2	5	3	3	3	2	4	4	2	3	0	0	2	3	5
Heritiera fomes	12	11	3	1	3	1	4	1	3	2	3	2	1	0	0	2	2	2
Rhiz. mucronata	10	8	6	4	1	0	0	1	0	0	1	1	2	0	0	1	0	2
Sonneratia apetala	11	12	0	5	1	0	1	0	1	2	1	1	1	0	0	2	2	1
Xylocarpus sp.	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Shrubs																		
Acanthus ilicifolius	1	5	0	0	3	1	0	1	0	2	1	0	0	0	0	0	0	0
Nypa fruticans	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	1
Phoenix paludosa	1	1	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Herbs																		
Aster type	0	2	0	0	0	1	0	1	1	0	0	1	0	0	0	0	0	0
Che.-amaranthaceae	2	1	1	0	0	0	0	1	2	0	0	1	0	0	0	0	0	0
Cyperaceae	0	0	0	0	1	0	2	0	2	1	0	2	0	0	0	2	1	2
Gramineae	6	5	3	4	10	3	4	4	3	3	4	3	10	7	10	8	7	10
Suaeda sp.	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Aquatic																		
Potamogeton	4	1	0	0	0	0	0	1	0	0	0	0	3	0	2	0	2	0
Typha sp.	2	1	0	0	0	1	0	0	0	02	0	1	2	0	0	0	2	0
Unknown Type																		
Type A	0	0	0	1	2	1	1	0	0	1	0	2	3	1	0	1	0	0
Type B	1	0	1	1	1	0	1	0	1	1	2	1	2	0	2	1	1	0
Type C	1	1	0	0	0	1	0	1	1	2	0	0	1	1	0	0	0	1
Type D	1	0	0	1	1	0	1	0	0	1	1	0	2	0	1	0	0	0
Spores																		
Acrostichum aureum	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
Monolete verrucate	4	10	9	16	13	8	20	23	10	7	2	12	10	2	5	7	2	9
Monolete psilate	3	5	6	6	3	6	4	9	2	4	14	10	8	2	1	2	2	3
Trilete verrucate	4	3	0	2	0	1	0	0	0	2	0	2	2	2	1	2	2	2
Trilete psilate	2	1	2	2	1	2	1	1	0	1	0	1	2	2	1	2	2	2
Ceratopteris	0	1	0	0	0	0	0	0	0	0	0	2	2	1	0	0	2	0
Exotic Pollen	1(p), 1(b)	1(p)	1(c)	0	0	0	0	1(p)	0	1(p)	0	3(p)	0	0	0	1(c)	0	0

Species Depth (cm)→	380	390	400	410	420	430	440	450	560	470	480	490	500	510	520	530
Tree																
Aegi. corniculatum	0	0	0	0	0	0	2	1	0	0	0	0	1	0	0	0
Amoora cucullata	0	0	2	0	1	1	0	0	0	0	1	0	0	0	1	1
Avicennia marina	1	1	0	0	3	0	0	1	1	1	0	1	0	0	0	0
Barr. racemosa	0	0	1	0	0	1	0	0	0	0	1	0	1	1	0	0
Brug. gymnorhiza	2	1	0	1	1	0	1	0	1	0	0	0	0	0	0	1
Ceriops decandra	1	2	0	0	1	0	1	0	2	3	1	1	2	1	2	0
Excoecaria agallocha	5	7	7	2	6	3	5	3	2	2	4	2	3	1	1	2
Heritiera fomes	2	5	4	3	4	2	4	2	3	2	3	2	1	0	1	0
Rhiz. mucronata	0	1	2	1	1	0	0	1	0	0	0	0	2	0	0	1
Sonneratia apetala	0	0	0	5	1	0	1	0	1	2	1	1	0	1	0	0
Xylocarpus sp.	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Shrubs																
Acanthus ilicifolius	0	1	1	0	3	1	0	1	0	2	1	1	0	0	0	0
Nypa fruticans	1	0	0	1	0	0	1	0	2	1	0	0	1	0	0	0
Phoenix paludosa	1	1	0	0	0	0	0	0	1	0	0	0	0	0	2	1
Herbs																
Aster type	0	0	0	0	0	1	0	0	1	0	0	1	0	1	1	0
Che.-amaranthaceae	2	0	1	0	0	0	0	1	2	0	1	0	0	0	0	0
Cyperaceae	0	1	0	0	1	0	2	0	0	1	0	2	0	0	0	2
Gramineae	2	4	3	4	10	3	3	2	1	0	4	3	7	7	7	7
Suaeda sp.	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aquatic																
Potamogeton	3	1	0	0	0	0	1	1	0	0	0	0	3	0	2	0
Typha sp.	2	0	0	0	1	1	0	0	0	2	0	1	1	1	0	0
Unknown Type																
Type A	0	1	0	1	2	0	1	0	0	1	0	2	3	1	0	1
Type B	1	0	1	1	1	0	0	0	1	1	2	1	3	0	2	0
Type C	2	1	0	0	0	1	0	1	1	0	1	0	1	1	0	0
Type D	1	0	0	1	1	0	1	0	0	1	1	0	2	0	1	0
Spores																
Acrostichum aureum	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Monolete verrucate	4	5	7	6	13	11	17	12	7	2	10	8	1	5	7	5
Monolete psilate	3	5	5	6	3	6	4	9	2	5	4	10	12	2	1	1
Trilete verrucate	4	1	0	2	0	1	0	0	0	7	0	2	2	2	0	1
Trilete psilate	2	1	2	2	1	1	1	1	0	1	0	1	2	2	1	1
Ceratopteris	0	0	0	0	0	0	0	0	0	0	2	0	1	1	0	0
Exotic Pollen[1]	0	0	0	1(p)	0	0	0	1(p)	0	0	0	3(p), 1(c)	0	0	0	1(p)

[1]p=Pinus, b=Betula, c=Corylus

Appendix 15:

Total Pollen Count at Each Level: M-Monolith

Species Depth (cm) →	105	110	120	130	140	150	160	170	180	185	190	200	210	220	230	240
Tree																
Aegiceras corniculatum	0	0	1	4	1	0	1	0	2	2	1	0	4	7	1	2
Amoora cucullata	0	1	1	9	2	1	0	4	8	10	5	10	20	15	8	6
Avicennia marina	0	0	0	3	1	1	1	8	8	7	8	6	7	6	12	10
Barringtonia racemosa	7	8	15	9	3	1	2	0	2	2	0	11	0	0	0	0
Bruguiera gymnorhiza	0	0	1	2	1	0	1	0	3	5	9	6	9	5	12	11
Ceriops decandra	0	0	0	0	0	1	2	6	5	5	3	5	5	4	6	7
Excoecaria agallocha	1	2	2	9	2	3	3	24	62	40	34	20	26	25	24	21
Heritiera fomes	1	3	4	7	2	2	1	18	38	35	35	51	25	43	19	18
Rhizophora mucronata	0	2	1	1	1	0	2	6	5	4	3	18	7	6	18	17
Sonneratia apetala	0	0	0	1	0	2	0	4	3	4	8	10	7	19	18	19
Xylocarpus sp.	0	0	0	0	1	1	1	4	3	3	4	5	7	7	2	3
Shrubs																
Acanthus ilicifolius	0	1	1	2	1	0	1	0	6	4	2	3	1	4	1	2
Nypa fruticans	0	0	0	0	0	0	0	0	0	1	2	2	1	4	0	1
Phoenix paludosa	4	3	6	2	0	0	1	0	2	0	0	0	0	0	0	0
Herbs																
Aster type	1	5	2	3	1	1	0	0	0	0	0	1	0	0	0	0
Cheno-amaranthaceae		0	0	0	0	1	1	2	0	0	1	5	0	4	4	43
Cyperaceae	17	13	18	10	2	0	0	0	3	2	30	7	20	0	0	0
Gramineae	58	57	55	45	6	4	5	18	28	35	49	40	60	12	10	9
Suaeda sp.	1	2	2	1	0	1	1	2	5	4	16	5	3	4	1	2
Aquatic																
Potamogeton	0	0	0	0	0	1	3	0	3	2	1	22	1	2	7	8
Typha sp.	13	13	10	11	4	4	2	12	8	6	4	35	0	1	2	3
Unknown Type																
Type A	17	11	5	11	3	3	4	14	0	0	1	0	1	1	0	0
Type B	16	5	18	3	5	4	3	4	3	2	0	1	0	0	1	0
Type C	12	15	1	17	4	2	2	4	2	1	0	1	0	1	0	2
Type D	19	11	16	2	3	1	3	8	0	0	2	0	1	0	1	0
Spores																
Acrostichum aureum	0	0	1	0	0	0	0	4	2	3	17	4	5	5	2	4
Monolete verrucate	8	10	10	18	1	2	3	12	18	18	25	18	12	6	5	6
Monolete psilate	10	12	12	15	2	2	4	12	12	12	5	2	2	8	5	3
Trilete verrucate	13	9	14	11	1	1	4	12	6	8	11	1	2	6	8	7
Trilete psilate	17	12	16	10	1	2	7	0	11	10	13	45	40	13	6	5
Ceratopteris	0	1	2	2	0	0	0	0	0	1	2	2	4	0	1	0
Exotic pollen	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix 16:

Total Diatom Count at Each Level: M-10.5E

Species Depth (cm)-»	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350	360
Polyhalobous																	
Actinocyclus divisus	4	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coscinodiscus africanas	2	3	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0
Cos. apiculatus	27	26	26	16	18	4	4	0	0	0	0	0	0	0	0	0	1
Cos. centralis	4	6	4	11	6	9	3	4	2	2	1	0	0	0	0	0	3
Cos. excentricus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Cos. marginatus	35	32	27	23	18	24	17	16	17	8	6	2	4	0	0	0	5
Cos. radiatus	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cos. spp.	25	26	26	18	16	24	14	6	4	11	4	3	3	0	0	0	5
Diploneis smithii	0	0	0	0	4	4	2	2	0	0	0	0	0	0	0	0	0
Dip. weissflogii	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Opephora pacifica	10	5	7	8	11	18	8	5	2	1	3	2	0	0	0	0	3
Paralia sulcata	2	11	7	6	13	6	3	2	0	0	0	0	0	0	0	0	1
Thalassionema nitzschiodes	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mesohalobous																	
Cyclotella striata	37	84	89	69	65	80	80	78	72	66	52	69	73	64	68	50	36
Diploneis didyma	0	0	0	0	0	0	0	2	5	8	12	19	19	18	16	15	13
Navicula pygmea	0	0	0	4	4	0	0	6	4	8	6	12	13	10	8	6	5
Synedra tabulata	29	23	28	26	30	10	4	12	13	11	6	8	10	13	8	11	6
Oligohalobous-halophilous																	
Nitzschia frustulum	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nit. tryblionella	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oligohalobous-indifferent																	
Cymbella ventricosa	0	0	3	2	2	0	2	2	2	0	0	0	0	0	0	0	0
Eunotia pectinalis	0	0	0	0	0	0	0	1	2	6	12	5	4	3	3	3	3
Gomphonema angustatum	0	0	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0
Melosira granulata	14	0	0	0	0	1	3	2	2	5	6	5	3	4	3	6	5
Pinnularia microstauron	0	2	0	2	1	2	3	2	3	6	9	8	6	7	6	3	2
Synedra ulna	0	0	0	15	11	0	1	2	2	7	11	12	7	4	8	6	6
Halophobous																	
Eunotia parallela	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E. spp.	6	0	0	6	0	4	0	4	6	5	12	5	3	3	3	4	4
Pinnularia acrosphaeria	0	0	0	0	0	0	0	2	4	5	10	2	3	1	2	2	2

Species Depth (cm)-»	370	380	390	400	410	420	430	450	470	490	510	530	550
Polyhalobous													
Actinocyclus divisus	0	0	0	0	0	0	0	0	0	0	0	0	0
Coscinodiscus africanas	0	0	0	0	0	0	0	0	0	0	0	0	0
Cos. apiculatus	1	0	0	5	0	0	0	0	0	1	0	0	2
Cos. centralis	3	0	0	4	0	0	0	2	0	0	1	0	0
Cos. excentricus	2	0	0	0	0	0	0	0	0	0	2	0	1
Cos. marginatus	6	0	0	0	0	0	0	0	0	0	0	0	0
Cos. radiatus	0	0	0	0	0	0	0	0	2	0	0	3	0
Cos. spp.	5	0	0	0	0	0	0	1	0	0	0	0	0
Diploneis smithii	0	1	0	0	0	0	0	0	0	0	0	0	0
Dip. weissflogii	0	0	0	0	1	0	0	0	0	0	0	0	0
Opephora pacifica	3	0	0	0	0	0	0	0	0	0	1	0	0
Paralia sulcata	1	0	0	0	0	0	0	0	0	0	0	0	0
Thalassionema nitzschiodes	0	0	1	0	0	0	0	0	0	0	0	0	0
Mesohalobous													
Cyclotella striata	30	35	26	18	14	18	0	1	0	2	0	0	4
Diploneis didyma	10	12	7	4	3	4	0	0	0	0	0	0	0
Navicula pygmea	3	5	3	3	2	3	0	0	0	0	0	0	0
Synedra tabulata	7	10	6	5	4	3	0	1	0	0	2	0	0
Oligohalobous-halophilous													
Nitzschia frustulum	0	0	1	0	0	0	0	0	0	0	0	0	0
Nit. tryblionella	1	0	0	0	0	0	0	0	0	1	0	0	0
Oligohalobous-indifferent													
Cymbella ventricosa	0	1	0	0	0	0	0	0	0	0	0	0	0
Eunotia pectinalis	1	1	4	7	4	5	0	0	1	1	0	0	1
Gomphonema angustatum	0	0	1	0	0	0	0	0	0	0	0	0	0
Melosira granulata	5	5	8	9	11	3	0	0	1	0	0	2	0
Pinnularia microstauron	3	2	4	4	5	3	0	0	0	0	1	0	0
Synedra ulna	5	3	7	7	9	2	0	0	0	0	0	0	0
Halophobous													
Eunotia parallela	0	1	0	0	1	0	0	0	0	0	0	0	0
E. spp.	5	5	5	6	5	6	0	0	1	0	0	0	0
Pinnularia acrosphaeria	3	2	4	2	1	2	0	0	0	0	1	0	0

Appendix 17:

Total Diatom Count at Each Level: M-Monolith

Species Depth (cm) -»	105	110	120	130	135	140	150	160	170	180	185	190	200	210	220	230	240
Polyhalobous																	
Actinocyclus divisus	0	0	0	0	0	6	1	2	2	1	2	0	0	0	0	0	0
Coscinodiscus africanas	0	0	3	0	15	0	32	35	0	19	2	0	3	1	0	0	0
Cos. apiculatus	0	0	3	0	8	27	0	0	9	4	7	7	0	0	5	24	21
Cos. excentricus	0	0	0	0	0	0	0	9	2	7	1	0	0	2	0	0	0
Cos. marginatus	0	0	0	0	5	16	0	0	15	5	2	3	2	2	6	34	24
Cos. radiatus	0	0	0	0	17	8	14	19	3	9	0	0	2	1	0	0	0
Cos. stellaris	0	0	0	0	0	0	3	0	2	0	1	0	0	0	0	0	0
Cos. spp.	0	0	20	3	8	27	23	28	23	15	18	21	4	0	6	22	22
Diploneis smithii	0	0	0	3	2	5	3	0	0	2	0	0	0	0	0	0	0
Dip. weissflogii	0	0	7	0	0	3	1	0	0	0	0	0	1	0	0	0	0
Navicula pennata	0	0	0	0	0	0	0	0	0	0	2	3	0	0	0	0	0
Opephora pacifica	0	0	0	0	6	0	0	2	3	4	0	0	1	0	1	4	4
Paralia sulcata	0	0	3	0	2	13	0	5	2	9	1	2	2	1	2	0	10
Thalassionema nitzschiodes	4	0	0	0	0	0	0	0	2	0	1	6	0	0	0	6	0
Mesohalobous																	
Achnantes linkei	12	0	0	8	0	0	0	0	0	0	5	0	0	0	0	0	0
Cyclotella striata	10	4	25	0	26	24	59	35	18	22	30	23	10	11	8	27	65
Navicula cruciculoides	0	0	0	0	0	0	0	2	2	4	4	0	4	1	0	0	0
N. halophila	0	2	0	0	3	3	0	2	3	5	7	0	0	0	0	0	5
Nitzschia filiformis	0	4	0	0	0	6	3	5	3	4	6	0	2	5	3	5	0
N. linkei	0	0	0	1	0	0	0	0	3	4	7	7	2	2	4	0	3
N. obtusa	2	0	0	0	0	0	0	5	5	2	12	8	1	3	5	0	0
Synedra tabulata	0	10	20	3	12	19	5	5	3	14	17	0	1	3	6	65	20
Oligohalobous-halophilous																	
Navicula cuspidata	0	0	0	3	0	0	0	0	0	0	1	3	0	0	0	0	0
Nitzschia frustulum	0	0	0	2	0	0	5	0	3	0	0	1	0	0	2	2	0
Nit. tryblionella	0	0	0	0	0	0	0	0	0	0	1	2	2	0	0	0	1

Oligohalobous-indifferent																	
Achnantes lanceolata	0	0	0	0	0	0	0	0	12	0	7	9	2	0	0	0	0
Cymbella tumida	0	0	0	0	0	0	3	0	0	5	0	2	10	5	4	1	0
C. turgida	9	15	0	8	3	0	4	0	2	7	2	1	17	6	0	1	2
C. ventricosa	16	18	0	27	0	0	1	6	3	0	6	9	4	0	20	3	2
Eunotia pectinalis	0	28	0	0	11	0	3	0	0	12	7	13	17	59	8	0	0
Gomphonema angustatum	9	10	0	15	2	0	0	5	3	0	0	8	4	12	18	2	1
G. longiceps	14	6	0	9	2	0	0	0	0	0	2	7	4	3	8	0	0
G. parvulum	2	4	0	0	0	0	0	0	2	0	1	0	0	10	0	0	0
Melosira granulata	9	38	72	22	58	47	48	41	36	42	12	24	39	12	23	11	5
Nitzschia denticula	0	0	0	0	0	0	0	0	3	0	7	11	17	5	6	0	0
Pinnularia gentilis	2	1	7	0	2	0	3	0	2	1	2	0	0	0	0	1	2
Pin. microstauron	10	3	0	4	3	0	4	5	3	5	3	3	19	17	16	3	0
Rhoicosphenia curvata	4	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Surirella ovata	2	0	0	0	2	0	0	0	2	1	0	2	4	1	0	2	1
Synedra acus	0	1	0	6	2	0	0	0	0	0	0	0	0	0	0	0	0
S. ulna	31	20	0	42	7	5	0	2	2	4	3	5	4	3	2	0	3
Halophobous																	
Eunotia gracilis	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0
E. parallela	35	13	33	18	10	8	0	0	5	8	17	13	22	41	35	4	3
E. tenella	0	1	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0
E. spp.	34	15	17	15	5	0	0	5	6	9	20	9	15	12	13	5	2
Navicula bacilliformis	0	5	0	4	0	0	1	0	0	0	0	0	0	1	0	1	1
Pinnularia acrosphaeria	0	0	0	0	0	0	1	0	3	0	1	0	0	0	0	0	0

Appendix 18:
List of Pollen and Diatom Species and Their Authorities

Pollen

Acanthus ilicifolius L.(Hargoza)
Acrostichum aureum L.
Aegiceras corniculatum Blanco *var. majus* Gaertn
Amoora cucullata Roxb.
Avicennia marina Forsk. Vierh. *var. officinalies* L.
Barringtonia racemosa Bl.
Bruguiera gymnorhiza Lam. *var. conjugata* Merr.
Ceriops decandra Griff. Ding Hou
Excoecaria agallocha L.
Heritiera fomes Buch.-Ham. *var. minor* Roxb.
Nypa fruticans Wurmb.
Pandanus foetidus Roxb.
Phoenix paludosa Roxb.
Phragmites karka Trin. *var. cincta* Hook f.
Rhizophora mucronata Lam.
Saccharum sponteneum Linn.
Sonneratia apetala Buch.-Ham.
Xylocarpus granatum Koenig
Xylocarpus mekongensis Pierre *var. gangeticus* Parkinson

Diatoms

Achnantes lanceolata Grun.
Actinocyclus divisus Grun.
Coscinodiscus excentricus Ehr.
Coscinodiscus stellaris Rop.
Coscinodiscus africanas
Cymbella tumida Hvh.
Cymbella turgida Cl.
Diploneis smithii Cl.
Eunotia tenella Hust.
Eunotia gracilis Rabh.
Gomphonema longiceps Grun.
Melosira granulata Ralfs.
Navicula bacilliformis Grun.
Navicula pennata Schmidt
Nitzschia linkei Hust.
Nitzschia obtusa W.Sm.
Nitzschia frustulum Grun.
Opephora pacifica Petit.
Pinnularia gentilis Cl.
Pinnularia acrosphaeria
Surirella ovata Kutz.
Synedra ulna Grun.
Thalassionema nitzschiodes Grun.
Achnantes linkei Hust.
Coscinodiscus marginatus Ehr.
Coscinodiscus apiculatus
Coscinodiscus radiatus Ehr.
Cyclotella striata Grun.
Cymbella ventricosa Ag.
Diploneis weissflogii Cl.
Eunotia pectinalis Rabh.
Eunotia parallela Ehr.
Gomphonema parvulum Grun.
Gomphonema angustatum Rabh.
Navicula cruciculoides Brockm.
Navicula cuspidata Kutz.
Navicula halophila Cl.
Nitzschia filiformis Schult.
Nitzschia denticula Grun.
Nitzschia tryblionella Grun.
Paralia sulcata
Pinnularia microstauron O.Mull.
Rhoicosphenia curvata Grun.
Synedra tabulata Kutz.
Synedra acus Kutz.

Appendix 19:

Description of Four Unknown Pollen

Type A:

Pollen grain tricolporate, prolate (rectangular in view) triangular in polar view) grain length $\sim 40\mu$, breadth $\sim 32\mu$, colpa lolongate, about 30μ length about 3μ breadth, pore $\pm$circular, finely articulated, exine $\sim 4\mu$ thick, sexine $\sim 3\mu$ thick. Type: unknown (A).

Type B:

Pollen grain tricolporate with 24-16 psedocolpate, length $\sim 53\mu$, breadth $\sim 38\mu$, colpa lolongate, length $\sim 45\mu$ and breadth $\sim 3\mu$, exine thick, $\sim 5\mu$, well articulated. Type: Unknown (B).

Type C:

Pollen grain tricolporate, prolate, length $\sim 25\mu$, breadth $\sim 18\mu$, colpa lolongate, lengthxbredth ~ 23x$\sim 3\mu$ respectively, pore lalongate, exine $\pm 3\mu$, sexine thick, reticulate. Type: Unknown (C).

Type D:

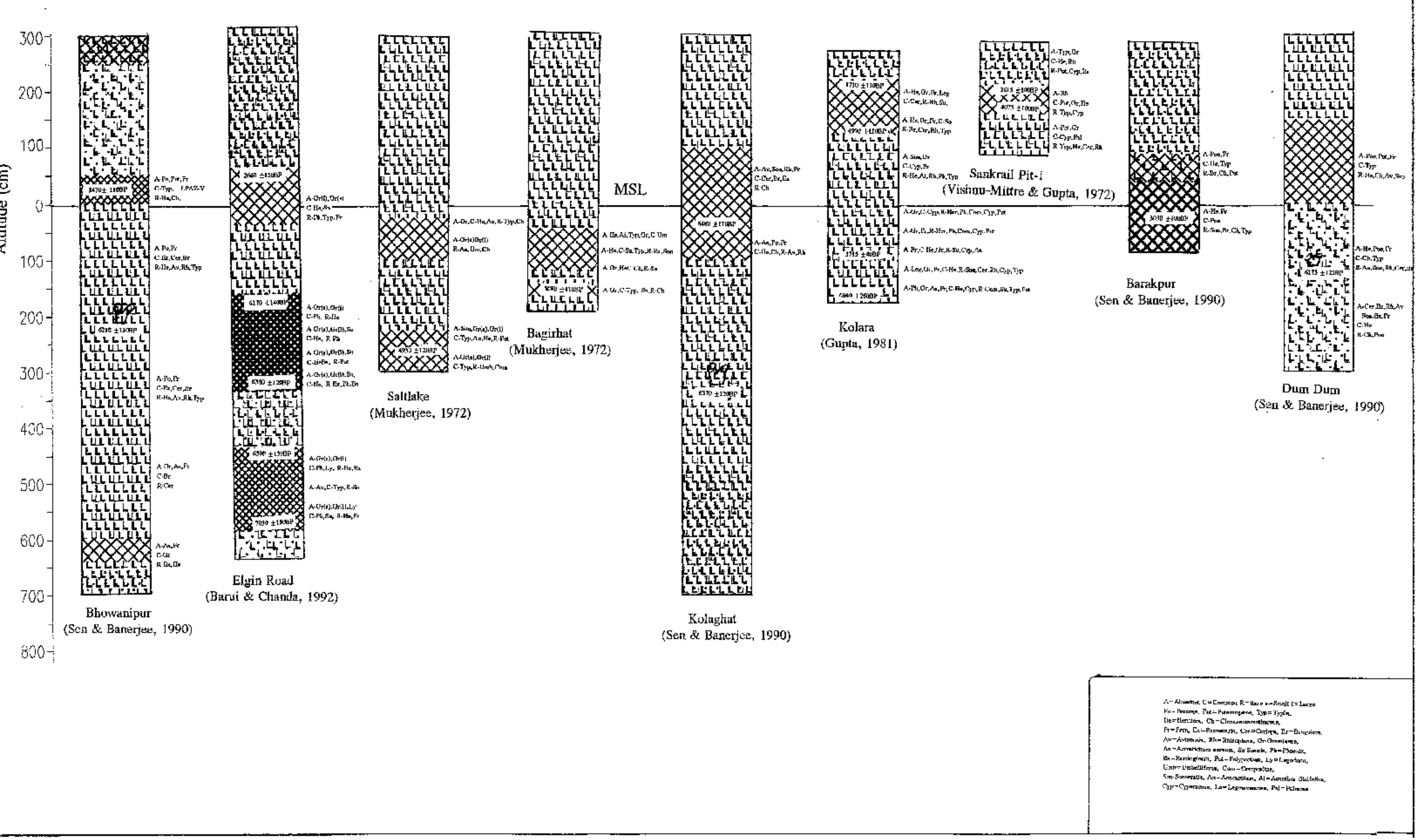
Pollen grain pantaporate, spheroidal, diameter $\sim 65\mu$, number of pores 40-45, pore diameter $\pm 2.4\mu$, exine thick, intectate, sexine $\pm 10\mu$, spines broad at base, gradually tapering towards the apex with rounded tips. Type: Unknown (D).

Appendix 20:

Published Lithostratigraphic Records, ^{14}C Dates and Pollen Data from Calcutta and Surrounding Regions

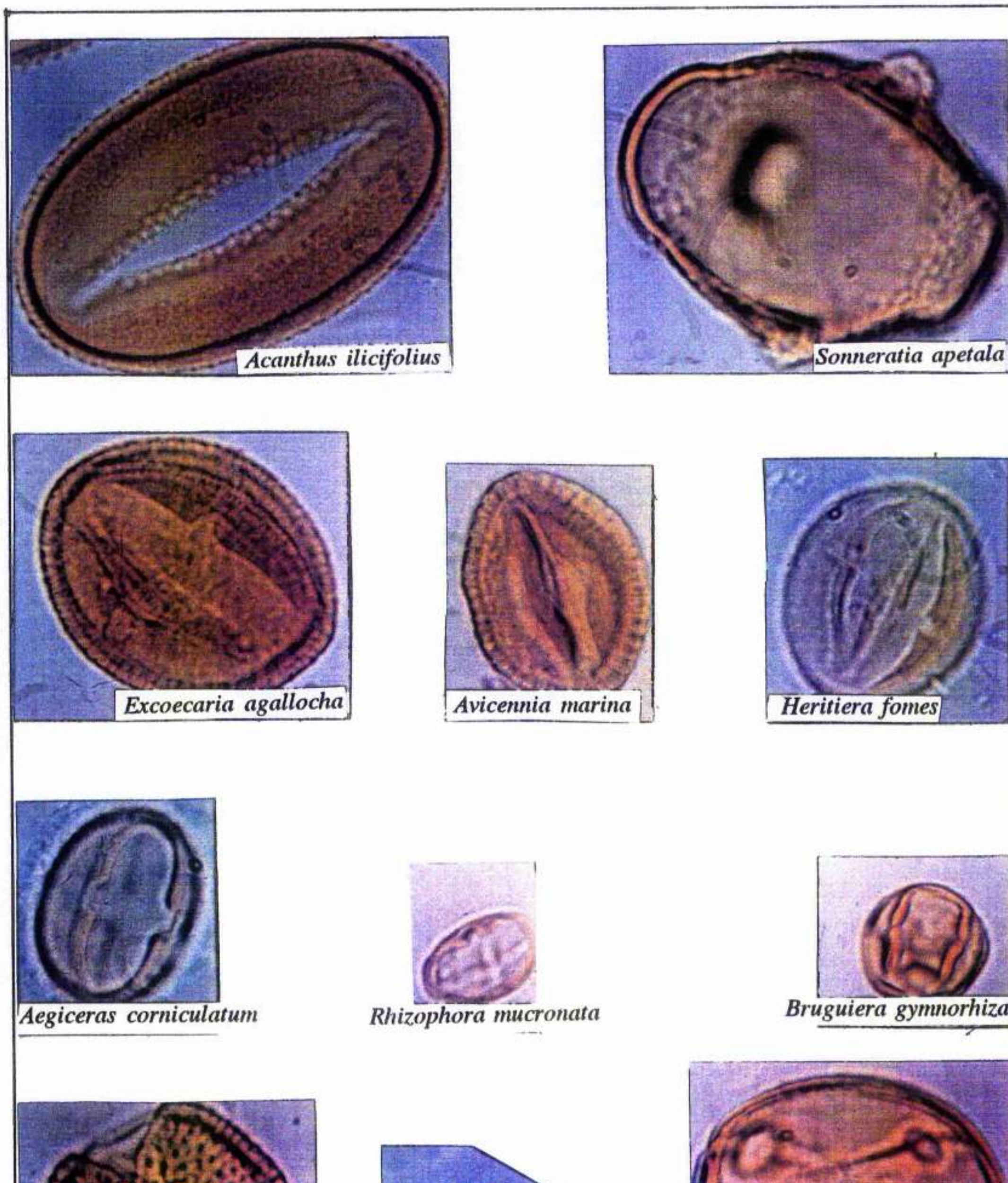
Lithology is shown following the Troels-Smith Scheme

Altitude for each stratum is not properly maintained


Altitude (cm)
300
200
100
0
100
200
300
400
500
600
700
800
MSL
Bhowanipur
(Sen & Banerjee, 1990)
Elgin Road
(Barui & Chanda, 1992)
Saltlake
(Mukherjee, 1972)
Bagirhat
(Mukherjee, 1972)
Kolaghat
(Sen & Banerjee, 1990)
Kolara
(Gupta, 1981)
Sankrail Pit-I
(Vishnu-Mittre & Gupta, 1972)
Barakpur
(Sen & Banerjee, 1990)
Dum Dum
(Sen & Banerjee, 1990)

Appendix 21:

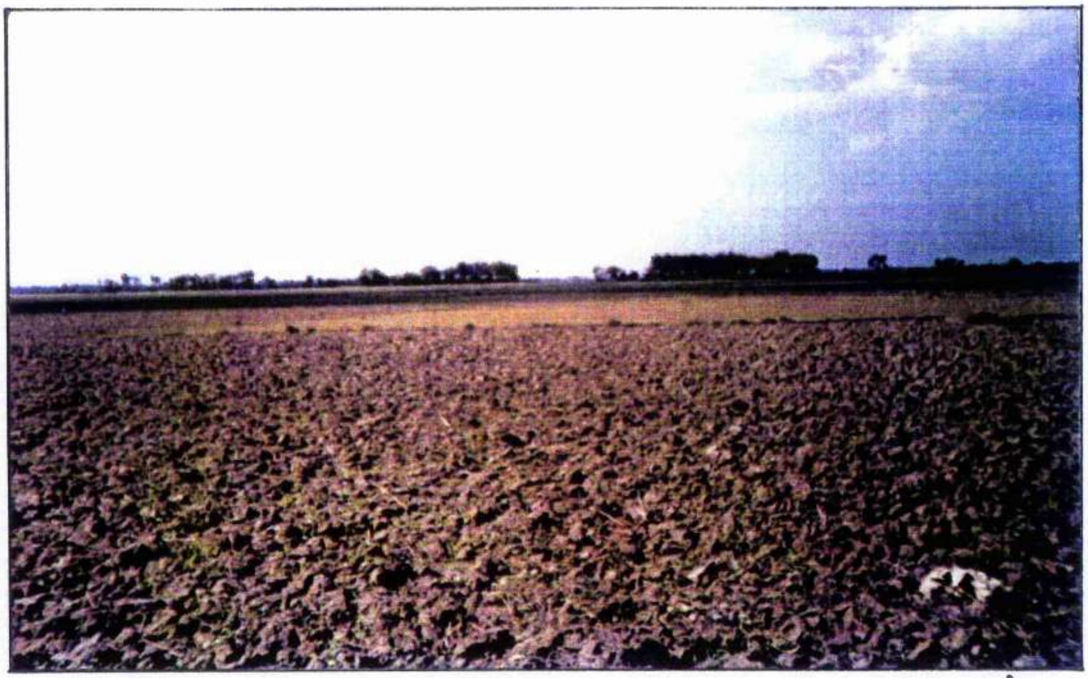
Mangrove Pollen Keys (x1000)



(Photograph by the author from Type Slides)

Appendix 22:

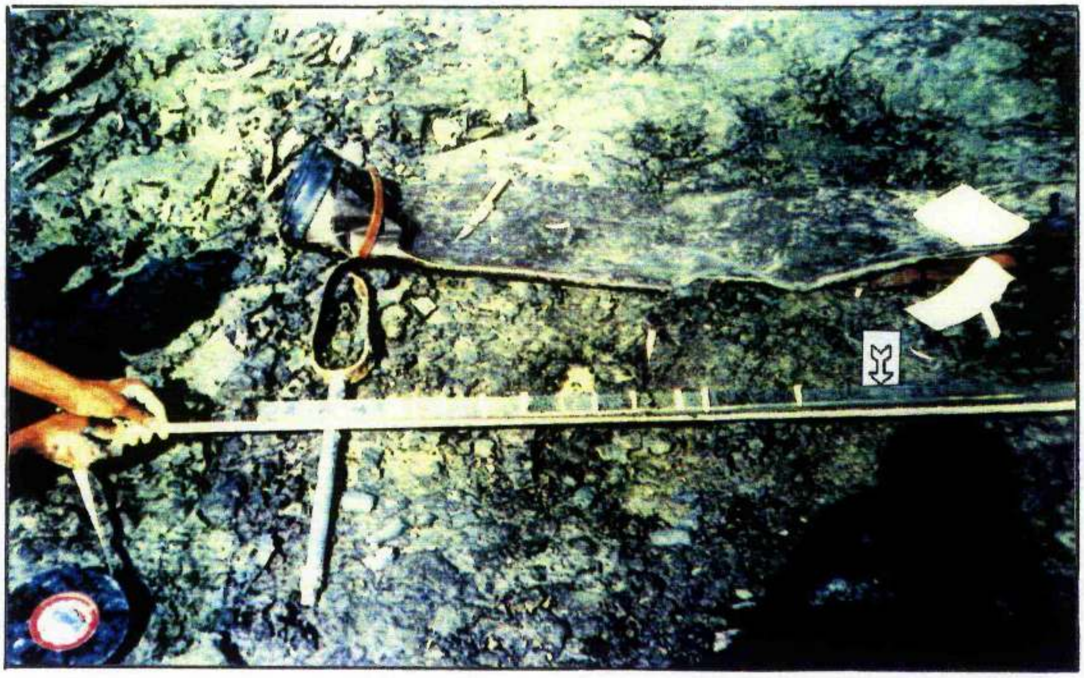
Photographs



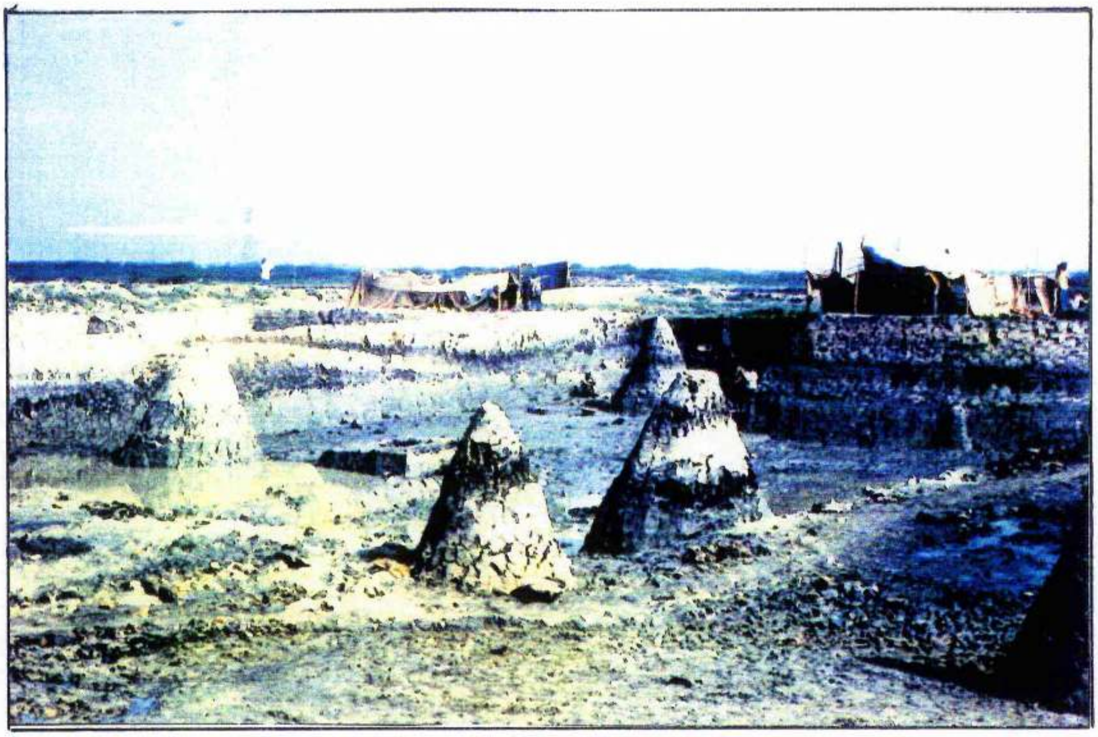
a). A Typical Landscape of the Site at Panigati Showing the Panigati Village in the Distance

b). A View of the Sundarban Forests from a Boat in the Passur River (Photograph by the author)

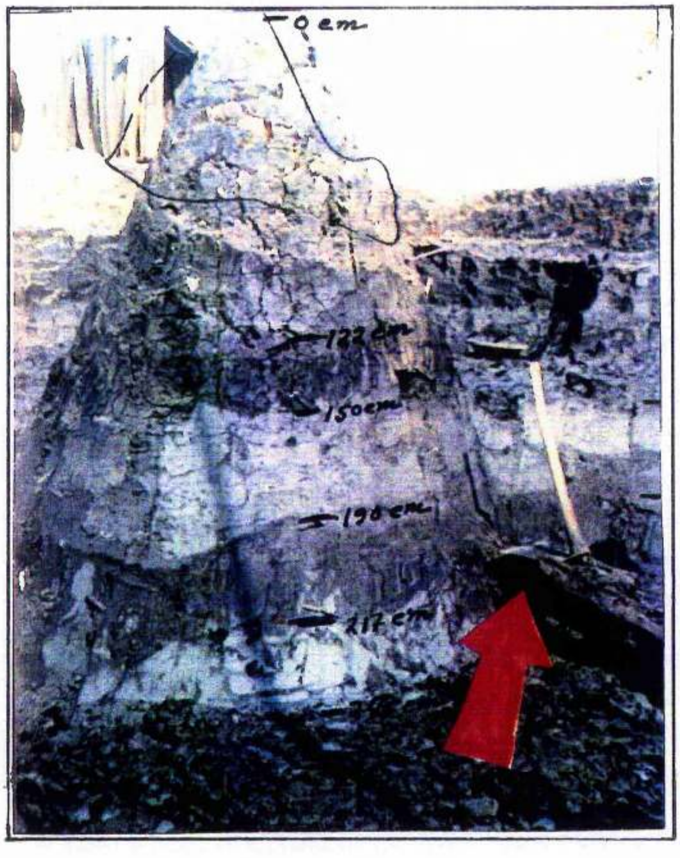
c). Sediment Inside a Gouge Sampler Showing Two Peat Layers Separated by a Minerogenic Layer at Panigati (Photograph by the author)



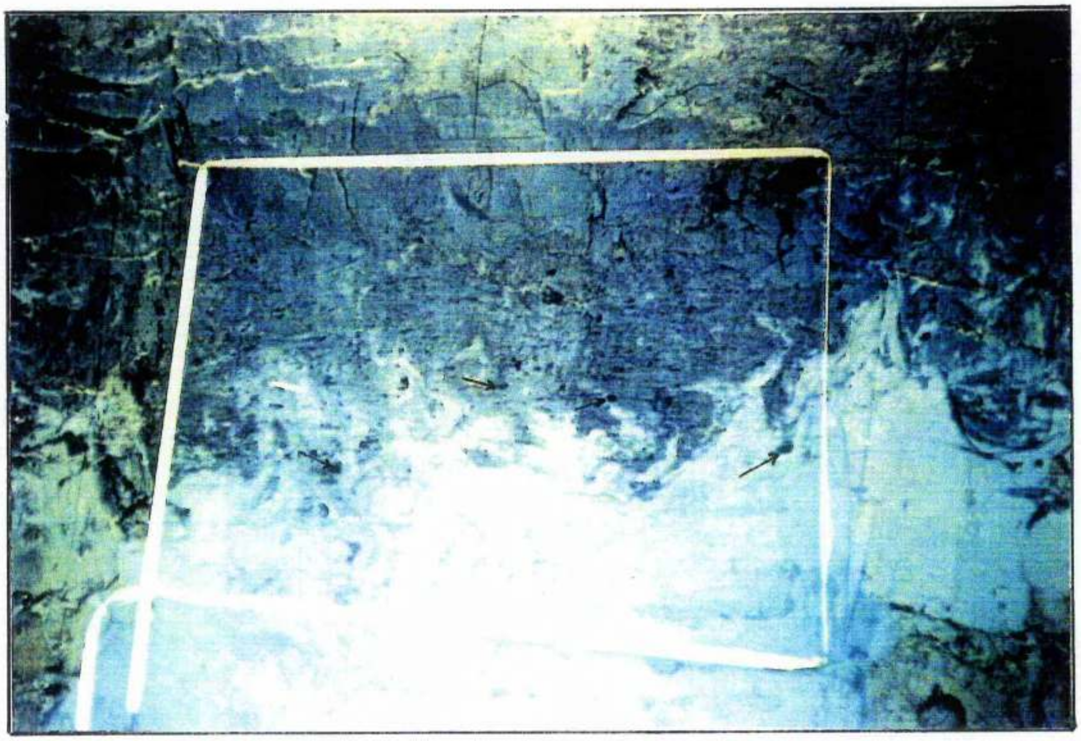
d). Sediment Inside a Gouge Sampler Showing Alternating Thin Layers Sediment Overlaying the Pleistocene Clay (Shown by an Arrow) (Photograph by the author)



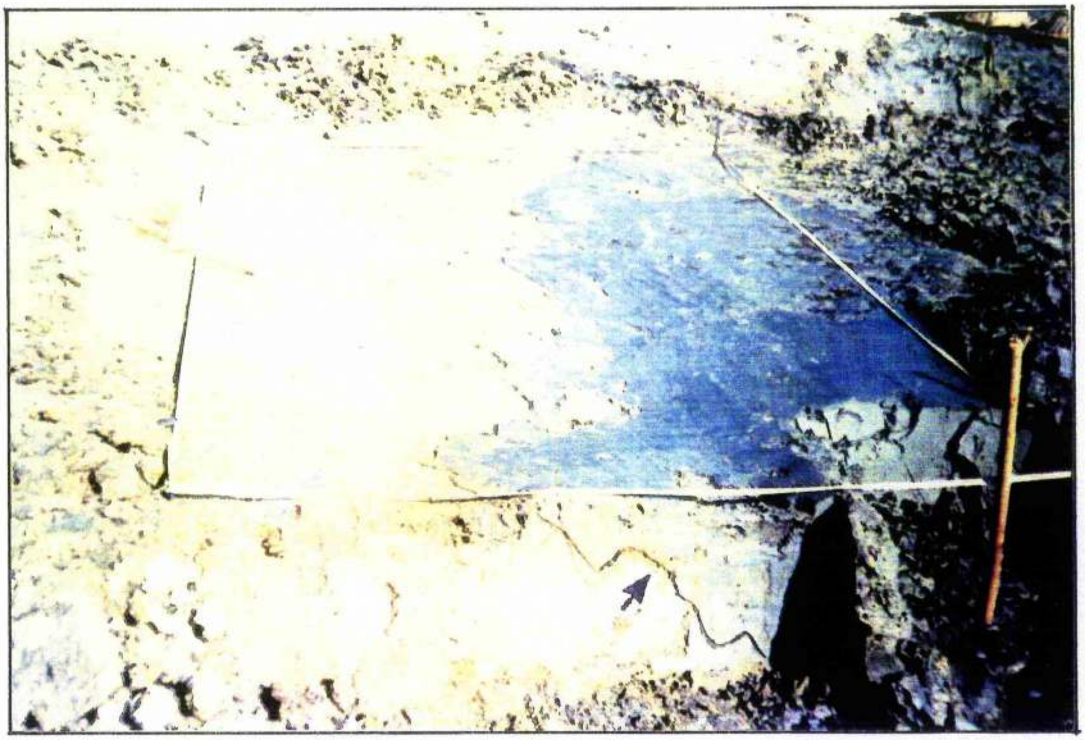
e). Excavated Site at Matuail Showing *Shakhies* (middle), Northern Exposed Faces (back left), Eastern Exposed Face (back right) and Two Temporary Tents for the Workers (back) (Photograph by Professor M.J. Tooley)



f). A *Shakhi* at Matuail Showing the Lithostratigraphy and an *in situ* Sundari (*Heritiera fomes*) tree (Shown by an arrow) (Photograph by the author)



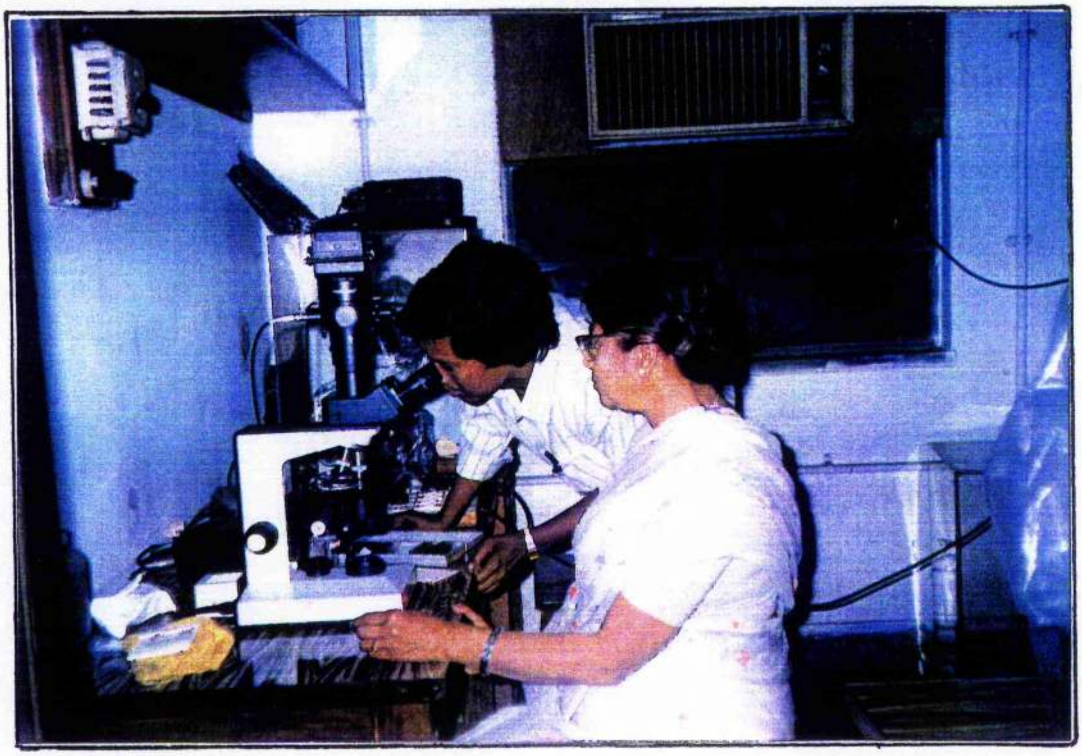
g). Boundary Between Lithological Phases 4 &5 Showing Inclusions from One Layer into Another and Many Undetermined Organic Fragments (Shown by Arrows) (Photograph by the author)



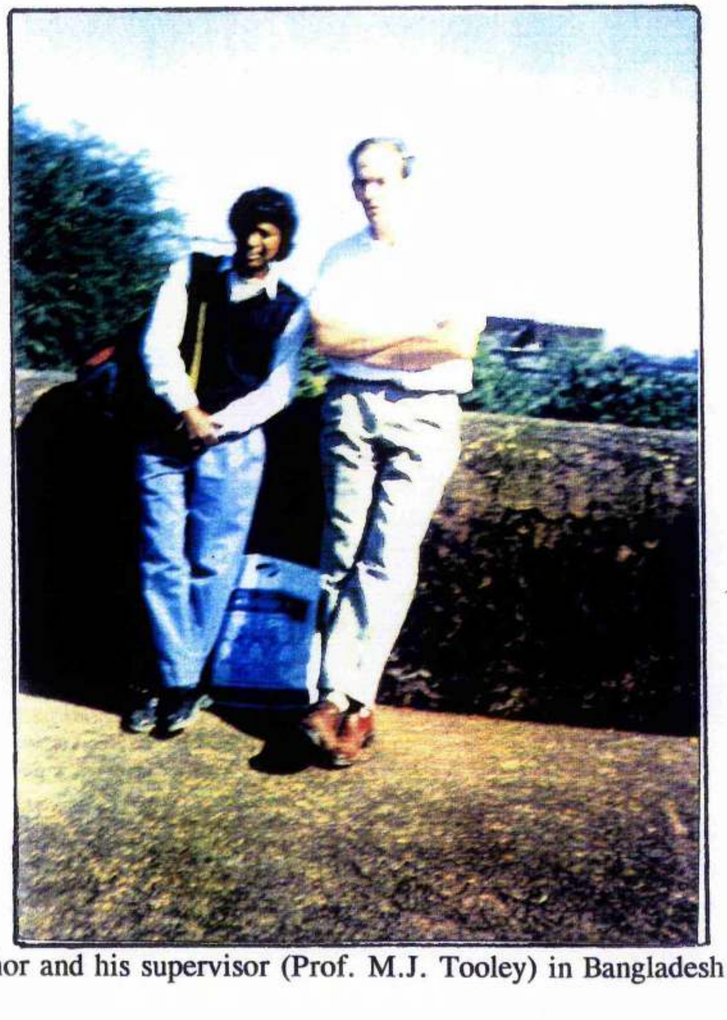
h). The Boundary Between the Pleistocene and the Holocene Sediments (Shown by an Arrow) (Photograph by the author)

i). A Broken Pot Embedded in South Exposed Face at the Lower Level of the Sediment Phase-7 (Shown by an Arrow) (Photograph by Professor M.J.Tooley)

j). A Broken Bone of a Vertebrae Embedded in South Exposed Face at the Upper Level of the Sediment Phase-5 (Photograph by the author)



k). Prof. Manju Banerjee at her laboratory in Calcutta is instructing the author on Mangrove Pollen under Microscope



l). The author and his supervisor (Prof. M.J. Tooley) in Bangladesh.