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The late quaternary evolution of a twin barrier-island complex, Cape Charles, Virginia (stratigraphy, sedimentology, Wisconsinan, sea-level highstand)

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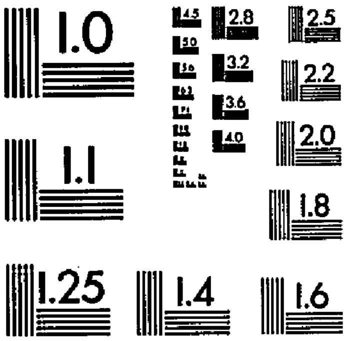

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THE LATE QUATERNARY EVOLUTION OF A TWIN BARRIER-ISLAND COMPLEX, CAPE CHARLES, VIRGINIA

The College of William and Mary in Virginia Ph.D. 1986

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THE LATE QUATERNARY EVOLUTION OF A TWIN BARRIER-ISLAND COMPLEX, CAPE CHARLES, VIRGINIA

A Dissertation

Presented to

The Faculty of the School of Marine Science

The College of William and Mary in Virginia

In Partial Fulfillment

Of the Requirements for the Degree of

Doctor of Philosophy

By

Kenneth Finkelstein

1986

APPROVAL SHEET

This dissertation is submitted in partial fulfillment of
the requirements for the degree of

Doctor of Philosophy

Kenneth Finkelstein

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DEDICATION

This achievement is dedicated to my father who would have been surprised but so proud.

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ACKNOWLEDGMENTS

This study was carried out as part of the research program of the Department of Geological Oceanography, Virginia Institute of Marine Science, College of William and Mary. The project was initially supported by the U.S. Army Corps of Engineer's Coastal Engineering Research Center, Vicksburg, Mississippi (formerly Fort Belvoir, Virginia). The study was completed with the help of funds from a Grant-in-Aid of Research from Sigma Xi (The Scientific Research Society), two research grants from the Southeastern Section of the Geological Society of America, and three minor research grants from the College of William and Mary. A warm thank-you to all of these organizations and my hope that they continue to assist in student research.

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ABSTRACT

A total of 68 vibra-cores and 14 box-cores in conjunction with high-resolution seismic records are used to describe the late Quaternary development of a twin-barrier island complex. Based on the stratigraphy, radiocarbon dates, and microfossils, a transgressive outer Holocene and inner Pleistocene barrier island complex are recognized. The two subaerial sub-parallel barriers are a result of separate marine transgressions that occurred before and after late Wisconsinan glaciation. Pollen assemblages and ten radiocarbon dates from the lagoonal sediments below the older island concur on a date of approximately 30,000 years B.P., hence a probable mid-Wisconsinan age for the overriding barrier island. The uncertainty surrounding a sea level near today's position 30,000 years ago is not unnoticed; neotectonics may be an important consideration in this apparent rise in sea-level.

Holocene sediments deposited in the backbarrier environment show a general shallowing and fining upward sequence. The Holocene stratigraphic sequence indicates a narrowing of the backbarrier region, a decrease in the tidal prism, and an increase in marsh and tidal flat infilling associated with calmer water conditions. Most backbarrier sediments are introduced through tidal inlets.

Despite Holocene, backbarrier deposits greater than 8 meters thick, only 2 meters may be preserved below 75-100 cm thick nearshore sands in some areas. Inlet fill deposits will not be preserved. However inner barrier sands and lower Holocene backbarrier sands and muds have a strong preservational potential. The stacking of transgressive barrier deposits, albeit those from different transgressions, may provide a stratigraphic oil trap.

THE LATE QUATERNARY EVOLUTION OF A
TWIN BARRIER-ISLAND COMPLEX, CAPE CHARLES, VIRGINIA

INTRODUCTION

Overview

Two spatially and chronologically distinct sub-parallel barrier island complexes on the Eastern Shore of Virginia (Figure 1) were respectively deposited during Late Pleistocene and Holocene marine transgressions. This study examines the geomorphic, chronologic, and stratigraphic relationships between the two systems and correlates Pleistocene sediments found herein to adjacent formations. A transgressive stratigraphic sequence underlies both Mockhorn Island, the inner and older island located in the midst of the modern backbarrier environment, and the more seaward Holocene barrier, Smith Island (Figure 2).

Barrier island stratigraphy has received considerable attention during the past three decades. Transgressive and regressive models, depicting the Holocene stratigraphy, are well documented. Some of the more seminal examples are Fisk (1959), Fischer (1961), and Kraft (1971). Most studies include a discussion describing the chronology of barrier development during a single transgression or regression. However, only a speculation of the resulting stratigraphy after a subsequent cycle is available. In addition, where U.S. Holocene and Pleistocene barrier islands are both present the stratigraphic and chronologic relationships are usually only superficially presented.

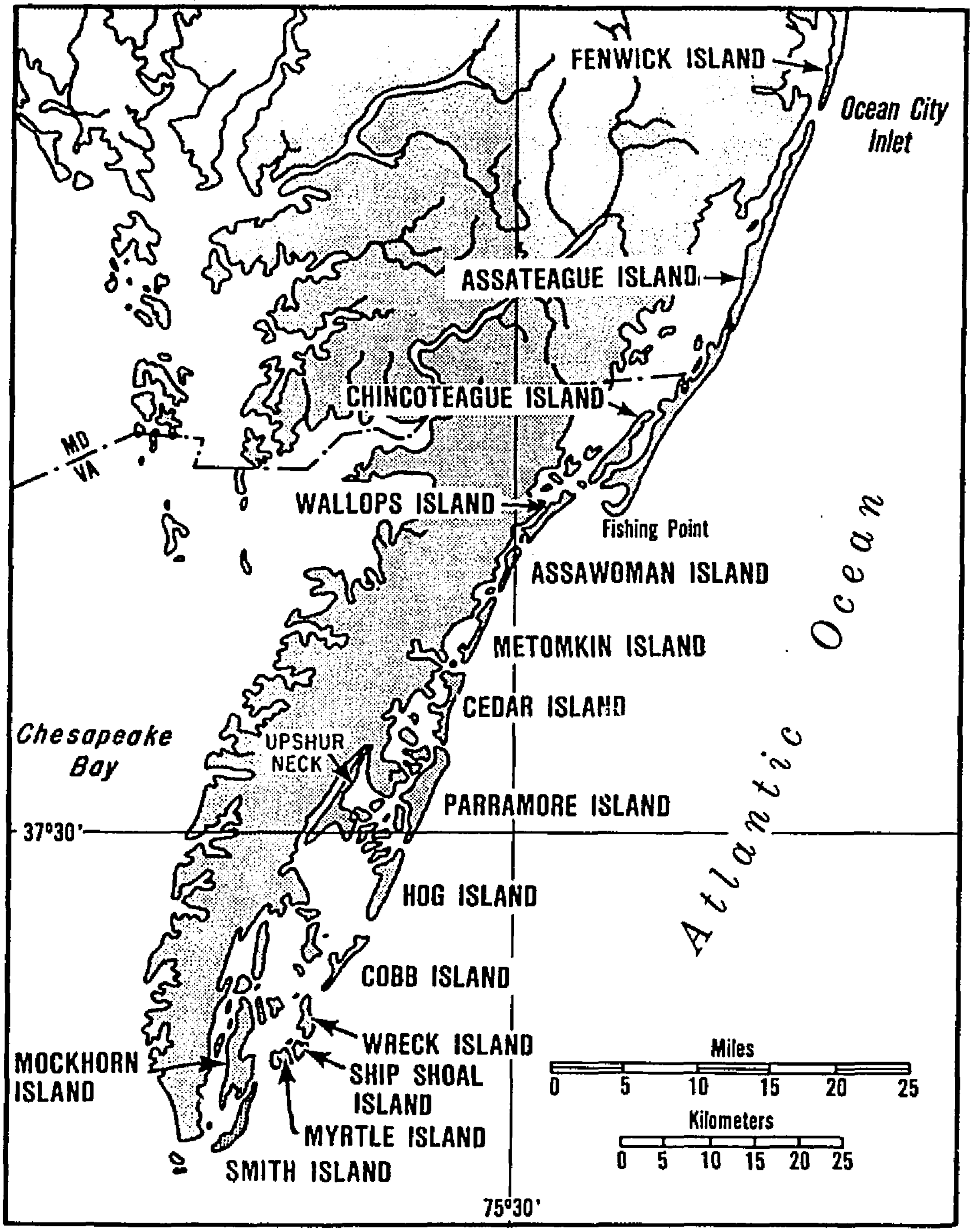


Figure 1. Location map of the lower Delmarva region with Smith Island and Mockhorn Island labeled at bottom.

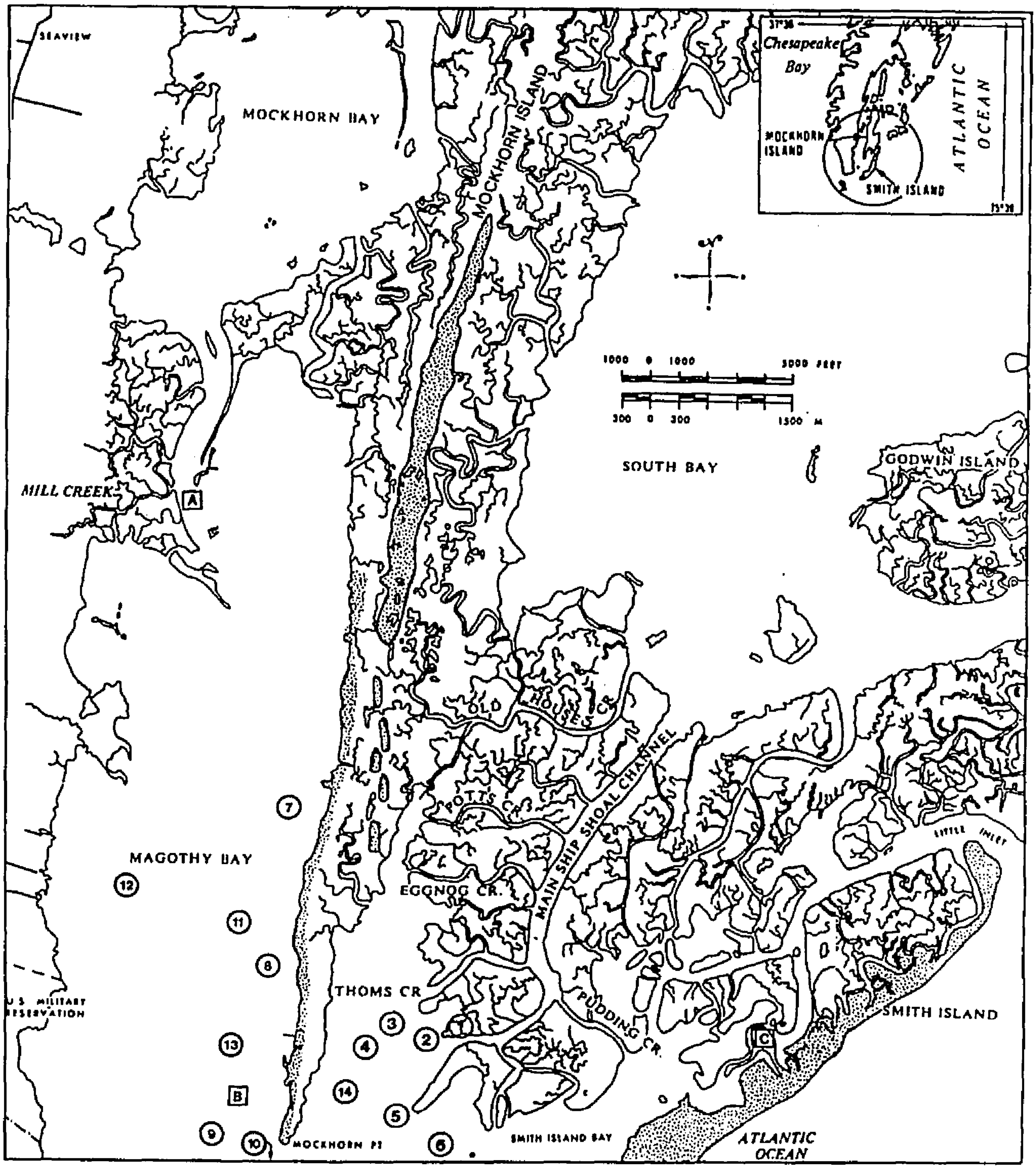


Figure 2. Location map of the study area with boxcore (circle) and grab sample (square) stations noted.

Twin barrier islands provide criteria to determine the age of transgressive cycles and preservational potential of associated deposits. For example, lithologic, paleoclimatic, and radiometric data indicate that Mockhorn Island is a late Pleistocene shoreline whereas the outer barrier is Holocene. In addition the three-dimensional geometry of the barrier complexes, from barrier beach to mainland shoreline, is determined. Previous geological interpretations and age of deposits on the adjacent mainland are examined in light of these results.

Sea-level fluctuations exert a primary control on rates and patterns of oceanic sedimentation and coastal geomorphology. In previous studies of Pleistocene sea-level in coastal areas, the lack of continuous sedimentation, errors in dating, and tectonic movements obscure eustatic fluctuations (Cronin, 1983). In this study high resolution stratigraphic records are used to estimate the timing of sea-level rise and fall. Four requisites of sea-level data (Cronin, 1983) which are necessary to draw an accepted sea-level curve are included; they are (1) accurate dating, (2) an accurate strandline indicator, (3) a high resolution stratigraphic record, and (4) paleoclimatic data. The sea levels discussed in this report are based on direct physical (continuously deposited sedimentary sequences) and biological (fauna and flora) evidence, and not from indirect evidence such as seismic signatures (Pyle et al., 1979) or isotopic fluctuations (Shackleton and Opdyke, 1973). Sediments containing both relative sea-level indicators and paleoclimatic data are analyzed to determine the relationship between sea level and climate.

The geomorphology and stratigraphy of the barrier island systems provide evidence for late Quaternary sea-level fluctuations. Previous studies pointing to a sea near today's level in mid-Wisconsinan time have been severely criticized (Morner, 1971; Thom, 1973; Bloom; 1983). In most cases the close scrutiny is well deserved; dated samples are contaminated (Curray, 1960), mis-identified (Milliman and Emery, 1968), inconsistent (Belknap and Kraft, 1977), or radiometrically dead (Field et al, 1979). In other studies radiocarbon dates are few (Owens and Denny, 1979), from widely spaced locations (Blackwelder et al., 1979), or from potentially suspect mollusk shells (Hoyt et al., 1968). The fundamental problem to the resolution of mid-Wisconsinan sea levels is the lack of a well-dated, stratigraphically complete sequence with a clear barrier facies (e.g. Susman and Heron, 1979; Moslow, 1980). This study is the first to authenticate this high sea-level stand by collectively using an abundance of lithologic, stratigraphic, geochronologic, and paleoclimatologic data from a local region along the mid-Atlantic Bight. Some caution is reserved and neotectonic adjustments are considered.

Pleistocene barriers are found landward or underlying Holocene barriers in Texas and the southeastern regions of the United States and Australia. This study area is the most northerly position along the Atlantic coast where associated Holocene barrier deposits are welded onto a Pleistocene barrier ridge. The best studied and most similar analog to this study are the inner and outer bay barriers of New South Wales, Australia (Thom et al., 1981). A comparison between the respective stratigraphic sequences from the two regions is presented in light of the differences in morphology and hydrodynamic regime.

Conformable and unconformable contacts separate the two barrier island systems of this study. With a continuous rise of Holocene sea level and landward migration of the outer barrier, transgressive inner barrier sediments should be preserved. A stratigraphic model, depicting the stacking of transgressive deposits, is thus created. This model also considers a Holocene stratigraphic sequence of regressive over presently accumulating transgressive sediments should the region become tectonically stable. In this way additional transgressive deposits are preserved as is the case in southeastern Australia (Thom et al., 1981; Thom, 1984).

Hypothesis/Purpose

The hypothesis tested concerned the existence of two barrier ridges, both transgressive barrier islands, one Holocene, and one late Pleistocene. Sediments deposited from each marine transgression were speculated to be distinct but in stratigraphic sequence. This reasoning was based on the geomorphology and a nearby study (Finkelstein and Ferland, in preparation) that utilized barrier and backbarrier vibracore data.

A detailed stratigraphic analysis of a twin barrier-island complex is provided in this study. The objectives are to determine: 1) the preservational potential and facies relationship of barrier deposits from two marine transgressions and 2) sea-level position and paleoclimatic conditions in latest Pleistocene time. Pleistocene sea-level and climatic data are obtained from the same sedimentary sequence on the continental margin of Virginia.

Separate Holocene and Pleistocene barriers, Smith and Mockhorn Island, Virginia, exhibit transgressive stratigraphic sequences. They are backed or surrounded by marsh, tidal flat and tidal channel environments. This geomorphology and late Quaternary stratigraphy is unique to the middle and north Atlantic United States coast. However, the stratigraphic relationships have applications to any barrier coast, past or present, that experiences cyclical marine transgressions.

The morphology and stratigraphy of Mockhorn Island and the island's underlying microfaunal and microfloral assemblages, as well as radiocarbon dates, provide data that accurately identifies a paleoshoreline and establishes the age and position of a previous high stand of sea level. This high sea level is also responsible for deposition of Pleistocene sediments below and adjacent to the present mainland shoreline, thus the need to reevaluate older mainland formations.

This analysis refines present stratigraphic models of complex coastal environments and increases our understanding of Pleistocene/Holocene sea-level movements.

Previous Work

The study area of this investigation exhibits inner and outer barrier sequences of Pleistocene and Holocene age, respectively. Both show a transgressive stratigraphy. Changes in sea level influence the stratigraphic sequence, preservational potential, and geomorphology of these and most other barrier island complexes. Other factors which contribute to the three-dimensional geometry include depth of shoreface erosion, antecedent topography, sediment type and abundance, and tidal range. Nevertheless, the general pattern of sedimentation is a reflection of the cyclical rise and fall of the sea. The literature provides a background for understanding this relationship. In addition, other studies report stratigraphic sequences that may be analogous, and characterize adjacent deposits and barrier and backbarrier processes. However, because passive margins are not totally stable, stratigraphic and climatic records from this study area may not match that from another region kilometers away (Cronin, 1983).

Late Quaternary sea-level studies are presented below because: 1) stratigraphic models are based on the interaction of sea-level movements with depositional processes, 2) the chronology of sea-level fluctuations may contribute to such a model, and 3) the debate over late Quaternary sea-level changes are considered in this study. This review will help determine if previous sea-level chronologies are consistent with the geology of this study area. An approximate late Quaternary time chart is shown in Table 1.

TABLE 1

APPROXIMATE LATE QUATERNARY TIME CHART*

HOLOCENE		Present
		10,000 years B.P.
PLEISTOCENE	Wisconsinan	Woodfordian Substage
		22,000 years B.P.
		Farmdalian Substage
		34,000 years B.P.
		Altonian Substage
		65,000 years B.P.
	Sangamon	Oxygen-Isotope Substages 5A: 65-80,000 years B.P. 5C: 90-105,000 years B.P. 5E: 120-128,000 years B.P.
		125,000 years B.P.

* Adapted from Shackleton and Opdyke (1973), Bloom et al. (1974), Bowen (1978), Goudie (1979), and Cronin et al. (1981).

Late Quaternary Sea-Level Studies

Geodial change, crustal isostatic response to the removal of the weight of ice sheets, and hydrostatic warping contribute to differing Holocene (10,000 to 12,000 years B.P. to present) world-wide sea-level curves (Kidson, 1982). However, most Holocene sea-level studies agree upon a rapidly rising sea until approximately 6,000 years B.P. (Belknap and Kraft, 1977; Lighty et al., 1982). Classical Holocene sea-level curves are divided into those that indicate a steadily rising sea (e.g. Shepard, 1963; Milliman and Emery, 1968) and those that show fluctuations around an overall trend of rising sea level (e.g. Fairbridge, 1961; 1976). Subsequent to 6,000 years B.P., most studies show a relatively slow continuous rise in sea level, although in some regions, for example, Australia (Chappell, 1983) sea level has fallen or become stable. These differences are likely due to neotectonic movements.

Holocene sea-level studies of Virginia support the relatively slow steady rise of sea level since 6,000 years B.P. A relative rise in sea level at Wachapreague, Virginia was interpreted by Newman and Munsart (1968) to have occurred since 5,500 years B.P. except for a marine regression or coastal upwarping prior to 4,400 years B.P. The latter conclusion was based on two radiocarbon dates from small samples of humic acid and may be in error. A more detailed late Holocene sea-level curve is presented by Finkelstein and Ferland (in press) in a study of the Virginia barrier island chain. This relative sea-level curve shows a phase of moderate sea level rise between 3,800 and 2,200 years B.P. and a time of slower sea-level rise from 2,200 until the last several centuries. Tide gauge data from Hicks et al.

(1983) supported a more dynamic present rate of sea-level rise on the order of approximately 2.0 to 3.6 mm/yr.

Relative Atlantic coastal plain sea-level positions during the last 200,000 years were reported by Cronin et al. (1981). On the basis of multiple paleoenvironmental criteria including Uranium-series dating of corals, three relatively higher than present Sangamon sea levels were found, 7.5 ± 1.5 m at 120,000 years B.P., 6.5 ± 3.5 m at 94,000, and 7.0 ± 3 m at 72,000. This composite sea-level chronology for the Atlantic Coastal Plain is inconsistent with independent estimates of eustatic sea-level positions from New Guinea (6.0 m at 125,000 years B.P., -15 m at 103,000, and -13 m at 82,000) (Bloom et al., 1974), Bermuda (5 m at 124,000 years B.P. and +? m at 97,000) (Harmon et al., 1978) and Barbados (5 m at 125,000 years B.P., -43 m at 105,000, and -45 m at 82,000) (Fairbanks and Mathews, 1978), and only partially follows Shackleton and Opdyke's (1973) oxygen isotope curve. High sea-level stages 5E, 5C, and 5A (Table 1) of the oxygen isotope sea-level curve of Shackleton and Opdyke (1973) correlate with the New Guinea and Barbados (earlier work by Broeker et al., 1968; Mesolella et al., 1969) erosional coral reef terraces dated above. However, Cronin et al. (1981) believed neotectonic mechanisms or incorrect current eustatic sea-level estimates account for the discrepancies between their study and those above. In addition, the Fairbanks and Mathews (1978) sea levels are considerably different from those found earlier (Broecker et al, 1968; Mesolella et al., 1969) and thereby question the assumption of constant terrace uplift. Finally, studies using stratigraphic and geochronologic techniques indicate the possibility of several middle and late Pleistocene transgressions on many coasts that do not correspond to the elevation of the Barbados-New Guinea sea-level model, although the ages of highstands are comparable (Cronin, 1983).

The sea level and sequences of sea-level changes are less known for the Wisconsinan Glaciation. Post-glacial melting has submerged most sea-level indicators. However, submerged shorefaces of Pleistocene and early Holocene age have been recognized on the continental shelf between Chesapeake Bay and Long Island. These indicated a glacial sea-level minimum of approximately -85 m (Dillon and Oldale, 1978) about 18,000 years B.P.

On the basis of radiocarbon dates, all near the upper limit of the age group, many studies reported a mid-Wisconsinan sea level near or at present level. Dates from some studies (Curray, 1960; Milliman and Emery, 1968; Field et al., 1979) have been challenged (Zellmer, 1979; Bloom, 1983). Other studies though, have used fixed sea-level indicators such as salt-marsh peat and shallow lagoon fauna to support a mid-Wisconsinan highstand (Blackwelder et al., 1979; Owens and Denny, 1979; Susman and Heron, 1979). However, data on Pleistocene ice volumes argue strongly against high mid-Wisconsinan sea levels (Thom, 1973; Bloom, 1983). Shackleton and Opdyke (1973) showed sea level no higher than -50 m from 75,000 to 20,000 years B.P. Bloom et al. (1974) estimated -28 m for the 60,000 year paleosea level, -38 m for 41,000, and -41 m for 28,000. In addition, Harmon et al. (1978) found sea level to be at least 8 m below present level 38,000 years B.P. Others who challenged this sea-level highstand were Morner (1971), Thom (1973), Stapor and Tanner (1973), and Thom et al. (1981).

Tectonic uplift bringing a lower mid-Wisconsinan shoreline to present levels, rather than a eustatic rise in sea level was also not acceptable to Bloom (1983). A large uplift of 1 to 2 m/1000 yrs would be required to bring the shoreline from their inferred levels of formation at -38 to -42 m to present sea level. However, Bloom (1983) did concede that some combination of delayed mid-Wisconsinan isostatic depression along the southeastern coast of the United States combined with an abrupt interstadial rise of sea level could have produced a littoral record that is now above or at present sea level.

Paleoclimatic data from a sedimentary sequence can document climatic change thereby possibly establishing a relationship between sea-level change and climate. If the change in climate through time is well-known it can be used to date sediments. The analysis of sediments containing both datable relative sea-level indicators and paleoclimatic data, such as pollen and marine microfossils, is an ideal way to check the timing of a sea-level event. Studies of this kind are rare (Cronin, 1983); however, Sirkin et al. (1977) completed a relevant late Quaternary paleoclimatic study. They analyzed pollen from radiocarbon dated sediments of the central Delmarva Peninsula. The climate 28,000 to 30,000 years B.P. was found to be cooler and drier than at present and supported many floristic elements that today are found in northerly areas. However, during the same time period on Long Island, New York, microfloral assemblages suggest a climatic warming that resulted in temperate conditions (Sirkin and Stuckenrath, 1980).

Stratigraphic Studies of Barrier Complexes

Stratigraphic sequences of the barrier island complex were first studied along the microtidal coast of the Gulf of Mexico (Fisk, 1959; LeBlanc and Hodgson, 1959; Shepard, 1960; Bernard et. al., 1959; 1962). Geologic histories of Padre and Galveston Islands were proposed by Fisk (1959) and Bernard et al. (1962), respectively. These studies showed that Padre Island had experienced a history of vertical aggradation while Galveston Island prograded seaward. These early works became the classics and stood alone in the literature for years. Both Galveston and Padre Island are representative stratigraphic models of barriers in an extremely limited depositional setting; that is, a rapidly subsiding basin with a high fluvial sediment supply in a microtidal, low-wave energy environment (from Moslow, 1980 after Hayes, 1979). Therefore, the limitations of these examples as universal models should be recognized (Moslow, 1980); for example, Reinson (1979) pointed out that marine sandstones were often incorrectly interpreted using only the Galveston Island barrier model.

A review of barrier island stratigraphic sequences was given by Kraft and Chrzastowski (1985). Recent studies based on stratigraphic sequences have shown that barriers can be divided into three categories: (1) stationary or vertical build-up, (2) regressive, and (3) transgressive (Dickinson et al., 1972). Within these stratigraphic sequences tidal inlet deposits are more commonly preserved than other barrier island deposits (Moslow and Tye, 1985). However, fluctuations in sea level and availability of sediment may enhance chances of preservation of regressive and/or transgressive deposits.

The classical example of a vertical build-up barrier island is Padre Island, which has experienced a history of in-place accretion for the last 4,000 years (Fisk, 1959). Ninety Mile Beach in Gippsland, Australia is another example of a barrier of this type (Thom, 1984). U.S. Atlantic coast barriers do not fit this model.

Details of the regressive vertical sequence of sediments produced by seaward, prograding barriers have been described by Bernard et al. (1970), Davies et al. (1971), and Moslow (1980). The most pertinent trends observed include a coarsening upward sequence of sediment and a change from dominantly biogenic (bottom) to dominantly physical (top) structures (Moslow, 1980). Kraft et al. (1978) at Cape Henlopen, Delaware, and Moslow and Heron (1979) at Cape Lookout, North Carolina studied regressive vertical sequences produced by spit accretion within portions of retrograding barrier island chains. A change from a transgressive to a regressive baymouth barrier sequence was shown by Thom et al. (1978; 1981) and Thom (1984) in New South Wales, Australia resulting in preservation of the transgressive sediments. In addition, since 4,000 years B.P. an initial primary transgressive barrier island has been preserved landward of episodic building progradational beach ridge barrier islands in South Carolina (Moslow and Colquhoun, 1981).

A hypothetical transgressive barrier sequence was first described by Fischer in 1961. Specific interest in the stratigraphy of these barrier systems increased little until almost a decade later. In 1971, Kraft presented a detailed borehole study in Delaware that provided a conceptual basis for much future work. Subsequently, Kraft and his co-workers (Kraft et al., 1973; Kraft et al., 1978; Kraft and

John, 1978; Kraft et al., 1979) have thoroughly documented the vertical sequence of transgressive baymouth and estuarine barriers in Delaware. Many modern barriers are similarly retrograding and exhibit a transgressive stratigraphy due to a rising sea level and limited sediment supply (Swift, 1968; Dillon, 1970; Belknap and Kraft, 1977, Wilkenson and Basse, 1978, Moslow and Heron, 1979; Leatherman, 1985; Niedoroda et al., 1985).

The stratigraphy of the backbarrier portion of a Holocene barrier island complex was reported by Boothroyd et al (1985). They found three depositional sedimentary environments behind the wave-dominated microtidal barriers of Rhode Island: flood tidal deltas, subtidal storm-surge platforms, and back-lagoon, low energy basins. A decrease in the size of the lagoon with increased sediment influx was calculated. Peebles (1984) reported a model using coastal plain deposits from Virginia that described the late Pleistocene stratigraphic succession that occurred during a marine transgression. Within backbarrier or embayed environments, basal lag deposits, dominated by Crassostrea virginica, grade upward successively into fine sand, then silt and clay. This model may be applied to the sedimentary sequence found landward of Smith Island.

Under stable tectonic conditions, transgressive barrier sediments are generally thinner than regressive deposits and are often destroyed during barrier retrogradation. Nevertheless, their cycling with regressive deposits may create thick sand bodies as marine sequences become stacked (Ruby, 1981). The preservational potential of transgressive barrier deposits is a function of the depth of shoreface erosion (Fischer, 1961), as well as pre-existing topography, wave energy, sediment supply, erosion resistence, tidal range, and rate of sea-level change (Belknap and Kraft, 1981). Preserved transgressive sequences were recognized in the rock record by Bridges (1976) and Cotter (1983). Transgressive barrier systems were also shown preserved as highstand shorelines in a time stratigraphic fashion in southeastern Delaware (Demarest et al., 1981).

Local Geology

1. Coastal geology: Several geomorphic, sedimentologic, and local stratigraphic studies of the southern Atlantic side of the Delmarva Peninsula have been completed. Most of these are adjacent to or overlap the study area.

Analyses of historical shoreline records for the entire Virginia barrier islands were shown in reports by Rice et al. (1976) and Rice and Leatherman (1983). Smith Island has retreated, more or less steadily, to the northwest, since 1853 (Rice et al., 1976). Mean Smith Island retreat or erosion rates ranging between 4 and 15 meters per year may, for example, be compared with Core Banks, North Carolina (1.0 meters per year erosion) and Atlantic City, New Jersey (0.8 meters per year accretion) (Rice et al., 1976; Dolan et al., 1979; Rice and Leatherman, 1983).

A high resolution seismic survey and 12 shallow cores outline the general stratigraphic relationship between Tertiary, Pleistocene, and Holocene sediments (Shideler et al., 1984). They found the morphological development of the area was controlled by glacio-eustatism and paleotopographic features. Newman and Munsart (1968) undertook a subsurface study in a small area near Wachapreague, Virginia, approximately 50 kilometers north of Smith Island (Figure 1). They determined that the barrier islands and lagoons in that area have been in existence for at least the last 5,500 years. Furthermore, they found that marsh colonization began about 1,000 years B.P. Morton and Donaldson's (1973) work on tidal inlets at nearby Parramore Island, Virginia (Figure 1) indicated the inlets have been relatively stable throughout the Holocene. The surficial sediments from the southern Delmarva tidal flats were described by Harrison (1972). Biggs (1970) discussed in general terms the origin and geological history of Assateague Island, Maryland and Virginia (Figure 1), briefly reporting on the barrier islands south of Assateague Island. Based on the presence of a peat layer interpreted as a salt marsh deposit in a number of borings, Biggs (1970) hypothesized a barrier island system existed seaward of the present one approximately 4,000 to 5,000 years B.P. Biggs did not formulate any depositional models of the system. Several jet pump borings in the backbarrier environment to the north of the study area were taken by Halsey (1978) who used them to construct three lithologic cross-sections for paleoenvironmental interpretation. Unlike Fisher (1968), who postulated the origin of segmented barrier islands by inlets breaching spits, Halsey (1978) determined that the present configuration of the Virginia segmented barriers had been maintained through the Holocene transgression. Halsey (1978) developed the "nexus" model of barrier development by generally studying the Holocene and pre-Holocene sediments of the entire Delmarva Peninsula. This model designates the inlets as fluvial paleochannels with the

Virginia barrier islands, of which Smith Island is one of, perched and retreating upon interfluve divides.

The offshore stratigraphic record seaward of nearby Assateague Island was described by Field (1980). He found the ocean bottom to be a highly bioturbated reworked sand presumably derived from eroding barrier islands. Underneath this unit a truncated 3.0 to 4.5 m thick fine grained deposit of Holocene estuary, tidal flat, or lagoonal origin rests upon pre-Holocene fluvial or estuarine sediments.

Sedimentation within backbarrier regions similar to that of Virginia was addressed by Lucke (1934). Lucke stated that the presence of many inlets was responsible for rapid lagoonal filling far from the headland source. He suggested that sand, silt and clay are transported through inlets and then trapped and deposited within the backbarrier environment. In addition, a stable backbarrier salinity would tend to foster marsh growth which in turn would aid in the trapping and deposition of fine sand, silt, and clay. The upper sediments of much of the nearby Delaware lagoons are dominantly sand and silt. Migrating tidal deltas, overwash and eolian processes, and eroding backbarrier highlands contribute sand to the backbarrier region (Kraft, 1971). Meade (1982) found that the most likely sinks for river sediment along the southeast Atlantic seaboard are the extensive salt marshes that lie behind the barrier islands. Large estuaries prevent coarse-grained river sediments from reaching the backbarrier environments of the mid-Atlantic region. However, Kelley (1980) recognized that suspended sediment from Delaware Bay is deposited in southern New Jersey lagoons. Similarly, suspended sediment from Chesapeake Bay may be deposited behind the Virginia barrier islands.

2. Mainland geology: The adjacent mainland geology of the southern Delmarva Peninsula was reported by Mixon (1985). The marginal-marine Wachapreague Formation borders the study area to the west and includes the Upshur Neck-Bell Neck sand ridge complex 35 km to the north. The depth to the Wachapreague Formation below mainland fringing Holocene deposits is discussed later. The Wachapreague Formation may incorporate two chronostratigraphic units. Landward and stratigraphically below the Wachapreague Formation are the marine Joynes Neck Sand and the Butlers Bluff member of the Nassawadox Formation. The latter was interpreted to represent barrier-spit and nearshore-shelf environments. Mixon (1985) described the Wachapreague Formation as coarsening upward. He believed it was a part of the final regressive phase of a Sangamon transgressive-regressive cycle rather than a separate major transgression in mid-Wisconsinan time. Mockhorn Island was postulated to be part of the Wachapreague Formation and and thus late Sangamon-early Wisconsinan in age, but more detailed studies to bracket the age of Mockhorn Island were suggested (Mixon, 1985).

Owens and Denny (1979) postulated a different late Pleistocene geological history. Their Sinepuxent Formation documented a mid-Wisconsinan high stand approximately 30,000 years B.P. The Sinepuxent Formation may correlate with the Mockhorn Island deposits of this study.

Belknap (1979) also reported on the regional coastal plain geology. He made paleogeographic reconstructions of the entire Atlantic side of the Delmarva Peninsula from 1.8 million years B.P. to the present based on amino acid racemization dating and analysis of lithology, paleoecology, and geomorphology. During the late Pleistocene, deposition of marine sediments on the present mainland were found to occur during four time periods: 1) 60-70,000 years B.P., 2) 85-95,000 years B.P., 3) 110,000 years B.P., and 4) 120,000 years B.P.

In the Norfolk, Virginia region, Peebles (1984) reassigned the late Pleistocene formations of Oaks and Coch (1973) (the Great Bridge, Sandbridge, Londonbridge, and Kempsville Formations) to the Sedgefield and Lynnhaven members of the Tabb Formation (Johnson et al., 1981). Both these members probably pre-date the Wachapreague Formation.

Confusion remains on the timing of events during the late Pleistocene. For example Mixon (1985) showed the Mappsburg Scarp, the scarp between the Wachapreague Formation and Joynes Neck Sand, to have formed about 80,000 years B.P. while Demarest and Leatherman (1985) reported it was 600,000 years old. Mixon's (1985) Butlers Bluff, Joynes Neck, and Wachapreague units may be respectively correlative to the three members of the Sangamon Tabb Formation of Johnson et al. (1981) from the York-James Peninsula. Belknap showed that his four depositional units may actually be three and therefore they might correlate with units from the other two studies. Johnson (1976) called the latest Sangamon unit the Poqouson Member of the Tabb Formation which formed, as a mostly regressive deposit, when sea level was 3 m above to approximately 1.5 m below present sea level. The age of this Member was estimated at 65,000 years B.P. (Johnson et al., 1985) and may correlate with the youngest Pleistocene Delmarva shoreline of Demarest and Leatherman (1985) and the Wachapreague Formation of Mixon (1985). However, the height of the Poquoson does not exactly match that of the Wachapreague Formation. Furthermore, Mixon (1985) shows a contact separating upper and lower Wachapreague Formation deposits. Although this chronology is uncertain, the establishment of mid-Wisconsinan deposits, which Mockhorn Island may be a part of, and its correlation to other regions is even less clear. A study to correlate the coastal plain geology of Virginia is in progress (Berquist et al., in preparation).

3. Neotectonic geology: Studies of vertical crustal movement (Holdahl and Morrison, 1974) and glacial isostatic adjustments (Clark, 1981) have indicated a possibility for locally slower Holocene relative sea-level rise along Virginia's southern barrier islands as compared to those in the north. This may explain the large southern backbarrier area because of a relatively "slower" barrier island landward migration. Current rates of subsidence are 1.2 mm/yr at Cape Charles, 1.6 mm/yr at Wachapreague Inlet and 2.0 mm/yr at Assateague Island (Holdahl and Morrison, 1974) (Figure 1). Caution must be used in extrapolating these current subsidence rates back throughout the entire Holocene. For example, present use of groundwater may be causing higher local subsidence rates. Additionally a 2.0 mm/yr subsidence rate over 4000 years would give 8 m of subsidence; this is considerably higher than shown by the sea level curves of Newman and Munsart (1968) and Finkelstein and Ferland (in press). North-south

trending Mockhorn Island is higher and better developed in the south and appears to dip below the marsh in the north indicating a greater subsidence in the north since the development of this feature.

Regionally, hydroisostasy (the crustal isostatic adjustment to the redistribution of mass from continental ice to ocean water during glacial-interglacial transitions) may account for emerged pre-Holocene marine deposits on the Coastal Plain. Coastal uplift occurred as an increase in water volume depressed ocean basins and adjacent continents rose from redistribution of mantle mass (Walcott, 1972). Evidence for Holocene adjustment of this type is shown by Belknap and Kraft (1977). They find a strong seaward tilt of the outer continental shelf whereby the outer shelf over the Baltimore Canyon trough geosyncline has subsided approximately 40 m in the last 10,000 years. For a single deglaciation with a 100 m sea-level rise, coastal uplift is predicted (Cronin, 1981). But in areas of the collapsing peripheral forebulge, such as this study area, submergence will result from mantle flow back into glaciated regions (Clark et al., 1978). Lithospheric flexure from sediment unloading due to erosion may have caused some longer term isostatic uplift (Cronin, 1981; Cronin et al., 1981).

Harrison et al. (1965) called for between 12 and 49 m of uplift at the Chesapeake Bay mouth in the last 18,000 years. Their conclusion was based on the difference in elevation between a deep channel near Annapolis, Maryland, and a deep channel near the mouth of the Chesapeake Bay. The Annapolis channel is six meters lower than the Chesapeake Bay mouth channel. However, evidence is inconclusive that these two channel locations were cut contemporaneously (Peebles, 1984). Additionally, the Susquehanna River channel was found to cut across the southern Delmarva Peninsula during the middle and late Pleistocene, north of the present Chesapeake Bay mouth location (Mixon, 1985).

Summary

Transgressive and regressive sedimentary records of barrier island systems are available from many coastal regions. Transgressive/regressive cycles provide a means for preserving transgressive barrier island deposits. These sequences are often correctly tied with changes in sea level but should not be accepted as proof of a sea level oscillation. In addition, preservation of marginal marine sediments is dependent upon other factors besides sea-level movement. Nevertheless, sea-level fluctuations during the late Quaternary are responsible for deposition of several distinct lithologic units. The time and type of deposit has been a subject of much interest, on the Delmarva Peninsula and world-wide. Confusion over the height and timing of late Pleistocene sea levels still exist despite innovative analytical tools. Some authors have looked toward neotectonism for an answer. Unfortunately, paleoclimatic data, which relates climate and sea level and, indirectly time, are lacking in many stratigraphic and sea-level studies.

Geological studies adjacent to, or within the study area are often specific in their type of data. Combined, they provide either background information or can be incorporated into the prospective depositional and sea-level history. For instance, rates of shoreline change, a sea-level curve, and inlet geometry are available for the late Holocene. Studies also have been completed on the older deposits of the adjacent mainland and subsurface. Similar sedimentary environments studied elsewhere have been clearly described and characterized.

Physical Setting

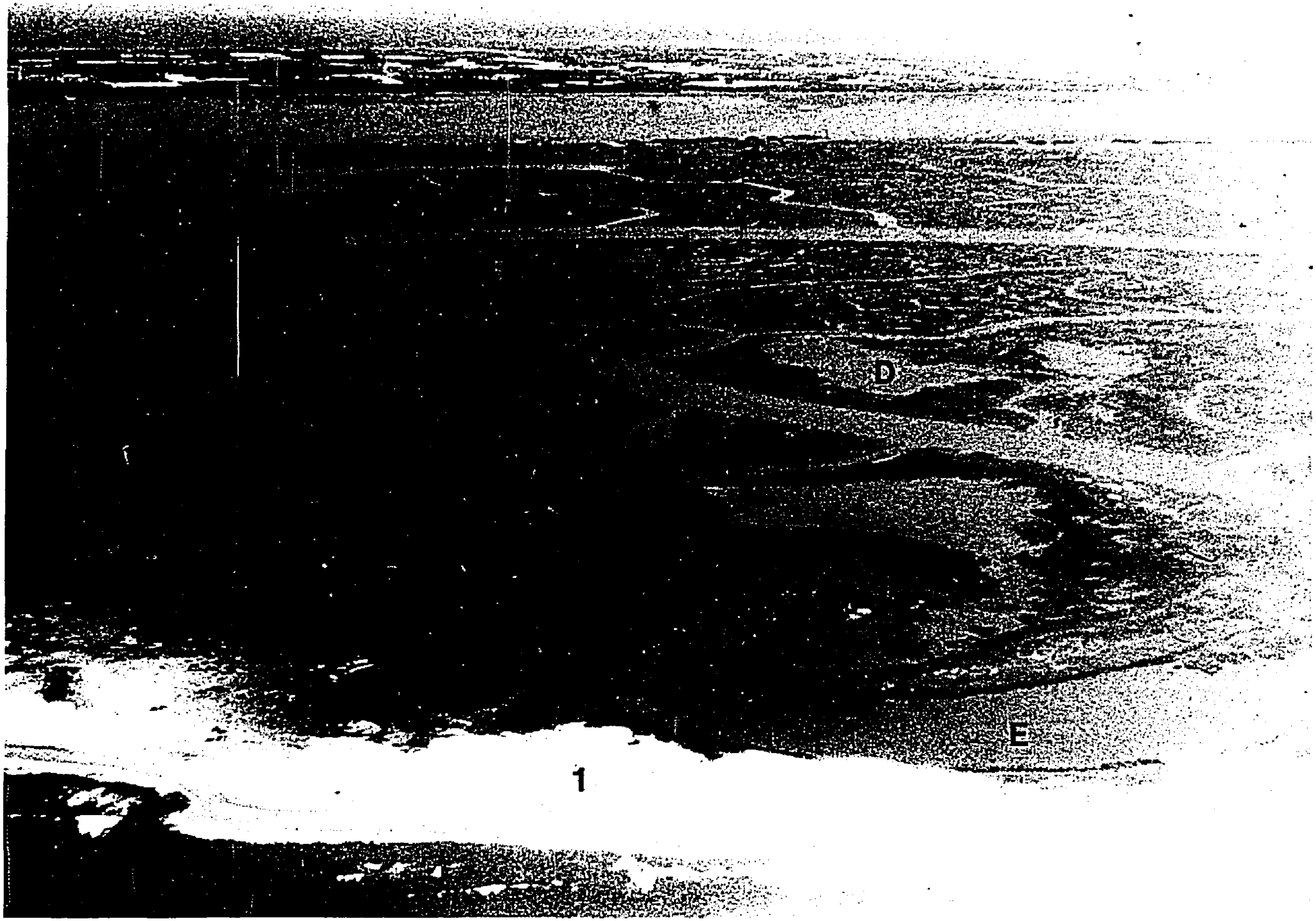
The area of investigation comprises an inner and outer barrier island, Smith Island and Mockhorn Island, Virginia, and their adjacent nearshore and backbarrier sub-environments (Figure 2). Located on the southern Delmarva Peninsula, the study area is bounded by Myrtle Island and the Chesapeake Bay entrance on the north and south, respectively (Figure 1). The east-west limits of this study are the shoreface of Smith Island and the mainland backbarrier shoreline (Figure 2). These barrier islands are separated from each other and the mainland by broad expanses of marsh, mud flats, and tidal creeks. Bordering the mainland shoreline and landward of Mockhorn Island is Magothy Bay, a 2-3 km wide body of salt-water. Magothy Bay is only about 1 m deep except for a 4-10 m deep, 200 m wide, partially dredged, tidal channel.

The region is a natural barrier system relatively unmodified by man. Evidence of barrier retrogradation and/or erosion is shown by relict marsh cropping out on the lower foreshore and shoreface of Smith Island. The study area covers a wide range of coastal environments, facies associations, and geologic time. Nearly all sub-environments of the barrier system are represented. They include barrier islands, tidal inlets and deltas, salt marshes, tidal flats, subtidal lagoon or bay, and tidal channels (Figure 3). The upper ten meters of unconsolidated Holocene and Pleistocene sediment are the primary consideration of this paper; however deeper sedimentary units appear in seismic sub-bottom records.

The southern Delmarva Peninsula is part of the Atlantic Coastal Plain province. This province consists of a sequence of mainly unconsolidated clastic deposits that dip gently and thicken eastward (Shideler et al., 1984). Upper Pleistocene sediments are primarily of barrier, backbarrier, and foreshelf origin (Field, 1980; Mixon, 1985). Therefore, truncated yet similarly generated pre-Holocene deposits should be found below present day accumulating Holocene sediments.

Smith Island is approximately 11 km long. The northern 8 km of the island is 200 m in width and no more than 1.5 m high above mean sea level (MSL). The southern portion is a broad beach ridge area. The distance from the Smith Island to the mainland ranges from about 10 km at the north end of the study area to 5.5 km at the south end. The backbarrier region is approximately one third open bay and tidal channel and two thirds tidal flat, salt marsh, and barrier island. Smith Island is rapidly retrograding at a historical rate ranging between 4 and 15 m per year (Rice et al., 1976; Dolan et al., 1979; Rice and Leatherman, 1983). Forested beach ridges at the southern end of the island, of about 2 meters in height (MSL), are evidence for lateral progradation though the southern end of the island has retreated north a net distance of about 630 m since 1853 (Rice et al., 1976). The island is presently bounded on the north and south by two small inlets. On the northern flank is the approximately 2 to 3 m deep mean low water (MLW) Little Inlet and to the south is Smith

Figure 3. The geomorphic relationship between the two barriers, Smith Island (1) and Mockhorn Island (2), is shown. The major backbarrier subenvironments include A. marsh; B. tidal flat; C. open lagoon; D. sheltered lagoon; E. tidal channel/creek; F. mainland shoreline.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Island Inlet, a wide but very shallow inlet with a maximum depth of only 1 m (MLW). Several ephemeral inlets are recognized on Smith Island; two of which, now closed, have been reported open for extended periods over the last 50 years. One is Bungalow Inlet, which is located near the center of the island and shown open on the 1979 Ship Shoal, Virginia USGS 7 1/2 minute quadrangle. The other is unnamed but is shown on historical maps and charts and older aerial photographs. It is located just north of the beach ridges at the southern end of the island.

Mockhorn Island (Figures 2, 3, 4), located near the center of the backbarrier region, is approximately 12 km long and generally less than 300 m wide and 2 m (MSL) high (Figure 5). It trends north-northeast parallel to the mainland and has a steeper western flank. Mockhorn Island diminishes in elevation to the north. It is a Pleistocene barrier.

The boundary between the backbarrier or mainland shoreline and the upland is defined by a sharp linear contact. Marshes and sand beaches lie between the upland and Magothy Bay. Pleistocene fluvial and marine silts, sands and gravels (Mixon, 1985) are as high as 3 m, 500 m from this shoreline.

The Atlantic coast of the Delmarva Peninsula has a semidiurnal tide with a range of about 1 m (Field, 1979). The tidal range is assumed constant for the late Quaternary. The southern Delmarva Atlantic Coast is open to attack by both tropical storms (hurricanes) and extratropical storms (northeasters). Hurricanes are generally the most severe type of storm along the Delmarva Peninsula (U.S. Army Engineer District, Baltimore, 1972) but northeasters, though usually

Figure 4. An aerial photograph of Mockhorn Island is shown. The adjacent and encroaching Holocene backbarrier environments can be recognized. Also note the nearly parallel orientation of the island when compared to the mainland (at top).

Figure 5. In this photo the position and height of Mockhorn Island is shown relative to the encroaching salt marsh vegetation. The height of the Island ranges between 1.5 to 2.0 m.

having lower velocity winds associated with them, are generally of longer duration and occur more frequently. The last significant hurricane in this region occurred in 1960 and the last major northeaster was the great "Ash Wednesday" storm of March 1962.

The predominant wind directions are from the northwest to northeast, prevalent during autumn and winter, and with winds of magnitude often greater than 32 km/hr (U.S. Army Engineer District, Norfolk, 1971). The northerly winds produce currents and a wave approach direction from the north which results in a net southerly longshore transport of sediment. Prevailing winds from the south range in velocity from 14.5 to 22.5 km/hr (U.S.. Army Engineer District, Norfolk, 1971) and occur most frequently during the spring and summer.

METHODS

Sampling Program

To determine the depositional geology and chronology of the study area, the surface and subsurface sediments were examined using boxcores and vibracores. Initially, sampling stations were widely spaced, but, as a general picture of the subsurface geology developed, more stations were added to better determine the thicknesses, contact relationships, and diagnostic characteristics of units, facies, and depositional environments. To provide the three-dimensional geometry of deposits associated with Mockhorn Island, sampling was particularly closely spaced on or nearby the island. In this way the stratigraphic sequence, age, and preservational potential of these deposits could be found. Transects were set up shore-parallel and shore-normal to Mockhorn Island. The latter transects provided an understanding of the relationships between deposits from the two barrier island systems. The geology between cores was confirmed using seismic records from subbottom profiles. Thus sediments associated with the Mockhorn Island barrier could be followed to depths below that possible by coring. In addition deeper and older units were delineated.

Core Collection and Description

The data base for this study consisted principally of vibratory and boxcores from the barrier islands and backbarrier region. Locations of each core are shown in Figures 2 and 6. Vibracores, unlike jet pump borings or augering, provided a mostly undisturbed sedimentary record with well preserved physical and biogenic sedimentary structures. In addition, vibracore subsamples were subject to paleontological, mineralogical, and geochemical analyses without the concern of contamination from deeper or shallower sediment horizons. These data allowed for recognition of sedimentary facies and depositional sedimentary environments.

After field packaging and transportation to the laboratory, vibracores were split by a rotary saw with a carbide bit. All cores were carefully cut in half, lengthwise, using an electro-osmotic knife (Chemlick, 1967) or piano wire, both of which caused a minimum of disturbance to structures. Photography of the cores followed. Description of each core included the major physical and biological sedimentary structures and the remains of most micro and macro fossils. Sediment samples were selected from the middle of each sedimentary facies or depositional environment. Textural, organic matter, and mineralogical analyses were completed using techniques described by Ball (1964), Gross (1971), and Folk (1974). Representative cores containing backbarrier sediments were selected for X-radiographs using methods of Bouma (1969) and Howard and Frey (1975). Radiocarbon dates were obtained where suitable organic material was present. Pollen was analyzed from pre-Holocene sediments

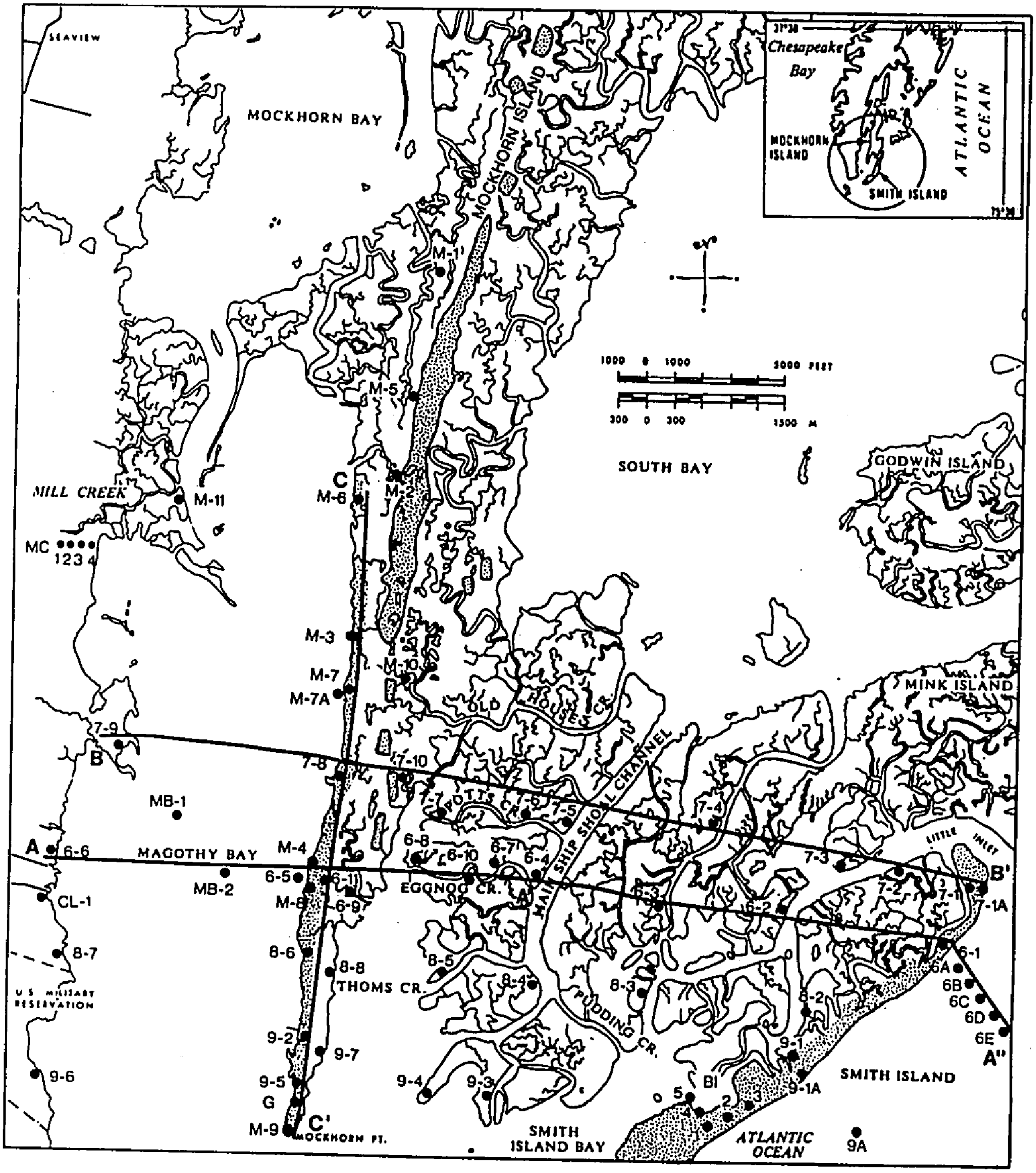


Figure 6. Location map of the study area with vibracore stations and principal transect lines noted.

for paleoclimatic information and compared to similar pollen described nearby that was absolutely age dated. Whenever possible, two methods, isotopic and paleontologic, were used for dating sediments (see Brush et al., 1982).

Boxcores were collected from modern environments (Figure 2). They were taken to determine the physical and biological characteristics of most barrier sub-environments. These characteristics were compared to the vibracore sediments to better categorize older units. In addition two grab samples were taken from Mockhorn Channel and one from the former flood tidal delta of an ephemeral Inlet (Figure 2).

Vibracores and Pound Cores

Transect lines and core locations were first determined and then drawn on topographic maps. These sites were located in the field and, with the aid of a U.S. Army helicopter, most were marked by stakes prior to the core collection. The geomorphology and boat accessibility played a role in determining the location of each core. Nevertheless, cores along and between transects were generally less than 1 km apart, especially where the stratigraphy was most changeable (e.g., near Mockhorn Island) (Figure 6). Tide tables and diagnostic marsh grasses were used to determine the approximate elevations of the core hole sites. An attempt was made to take most cores at mean sea level (MSL) and this level was used as a datum for all cross sections. The elevation of each core is given in Appendix I.

Subsurface stratigraphic data from 68 boreholes were obtained. 65 were vibracores and 3 were short diver intruded cores from the upper shoreface of Smith Island (core 6A, 6B, 6C) (Figure 6). Aluminum irrigation pipe, 7.6 cm in diameter, was used for all cores. Core length varied depending upon the location and methodology. Diver intruded cores were pounded into the sediment with a sledgehammer type device (borrowed from CERC, Waterways Experiment Station. Vicksburg, MS) but were less than 70 cm because the shoreface sands were not fully penetrated. Nearshore vibracores (core 6D, 6E, 9A) were less than 3 m long. The majority of the vibracores were 3 to 9 m in length. The shorter of these were taken on Mockhorn Island or the mainland beach where Pleistocene sediments are at, or near, the surface. One of the vibracores, core G on Mockhorn Island, was from Shideler et al. (1984). A complete lithologic description and environmental interpretation are provided in Appendix I.

The vibracorer consists of a four-horsepower Briggs and Stratton gasoline engine modified concrete compactor described by Finkelstein and Prins (1981) after the methodology of Lanesky et al. (1979). The vibrator head was attached to the 7.6 cm irrigation pipe with a hinged clamp. The piping was held in a vertical position and the combination of gravity and vibration caused the pipe to intrude into the sediment. The vibration sets up a low amplitude (0.1 to 1.0 mm) standing wave which fluidized and displaced sediment adjacent to the core pipe (Lanesky et al., 1979). Cores were extracted with comealongs and a 4.2 m tall aluminum tripod . The three nearshore vibracores were extracted using the boat's winch.

Boxcores

Eleven boxcores (approximately 14x21x26.5 cm) were taken from Smith Island and Magothy Bays (Figure 2). Three more were collected, two from the tidal flat and one from the marsh adjacent to Smith Island Bay (Figure 2). The cores were collected following a method described by Howard and Frey (1975) and Shipp (1980). Essentially, the boxcorer consisted of a 7.5 liter heavy aluminum can with the bottom cut out. The can was oriented and forced into the sediment. The cores were excavated, sealed and transported to the laboratory for analysis. In the laboratory, some boxcores were extruded by slowly increasing the pressure in the top of the core box with forced air and allowing the core to slide out the bottom; others simply slid out. Each boxcore, including its associated modern depositional environment, is described in Table 2.

Seismic Subbottom Profiles

To supplement the vibracore data, high resolution seismic subbottom profiles were collected (Figure 7). The strong core control allowed the more distinctive stratigraphic units to be recognized in the seismic record. Of great interest was the Pleistocene/Holocene unconformity that marks the Mockhorn Island transgression. Unfortunately, the water depth 2 km east and 1 km west of Mockhorn Island is less than 2 m. In places the closeness of the hydrophone to the channel floor interfered with the seismic signal and blurred much of the record. However, some subbottom record was obtained from below shallow water environments. Subbottom data was also collected below

TABLE 2

LITHOLOGIC DESCRIPTION AND DEPOSITIONAL ENVIRONMENT OF BOX CORES

Box Core No., Surface Depth, and Thickness[1]	Description[2]	Depositional Environment
1, 0 cm, 25 cm.	Grey mud, little sand. Much *S. alterniflora* vegetation	Marsh
2, 15 cm, 24 cm.	Grey sand and mud. Much bioturbation, some small polychaete burrows, one large crab burrow. Mud snails and articulated shells of razor clams and oysters on surface.	Tidal Flat
3, 30 cm, 25 cm.	Grey sand and mud. Much bioturbation. Many mud snails (*I. obsoletus*) on surface.	Tidal Flat
4, 90 cm, 23 cm.	Grey sand and mud. Bioturbated. Many articulated oyster shells. A few thin sand beds.	Open Lagoon
5, 120 cm, 23 cm.	Grey sand and mud. Coarsens downward. Several lenticular sand beds and polychaete burrows.	Open Lagoon
6, 150 cm, 25 cm.	Much sand, some mud. Bioturbated with many polychaete burrows. A few lenticular beds and razor clam shells.	Open Lagoon
7, 105 cm, 21 cm.	Tan sand at surface, the rest mostly grey sand. Several mud-filled polychaete burrows. An intact worm (Chaetopteroid) seen at center.	Open Lagoon
8, 120 cm, 26 cm.	Tan medium sand at surface. Reduced, slightly muddy fine sand below. Two razor clam shells at bottom. Some shell debris throughout. Much bioturbation near top.	Open Lagoon
9, 150 cm, 24 cm.	Tan fine sand at surface. Dark grey homogeneous sand below. An occasional round burrow.	Open Lagoon

TABLE 2 (Continued)

Box Core No., Surface Depth, and Thickness[1]	Description[2]	Depositional Environment
10, 165 cm, 22 cm.	Tan fine sand at surface. Dark grey fine homogeneous sand below. Some shell debris at bottom. Taken in very swift tidal current.	Open Lagoon
11, 120 cm, 27 cm.	Dark grey muddy sand. Some shell debris and plant vegetation. A few vertical burrows and a worm tube at surface. Many heavy minerals in sand.	Open Lagoon
12, 120 cm, 21 cm.	Dark grey muddy sand. Much like core 11. Many broken shells and some plant vegetation.	Open Lagoon
13, 120 cm, 25 cm.	Very compacted mostly dark tan sand. A few flaser beds at bottom. One round burrow at center.	Open Lagoon
14, 150 cm, 30 cm.	Dark grey mud and sand. Worm tubes and plant vegetation at surface. No sedimentary structures but much oyster shell debris. A large ark, bay scallop, and mud snail.	Sheltered/Open Lagoon

1. Depth is below mean sea level (MSL). For location of box cores see Figure 2.

2. Box core sample analyses for grain size, percent organic carbon, and foraminifera are shown in Tables 3, 4, and 6, respectively.

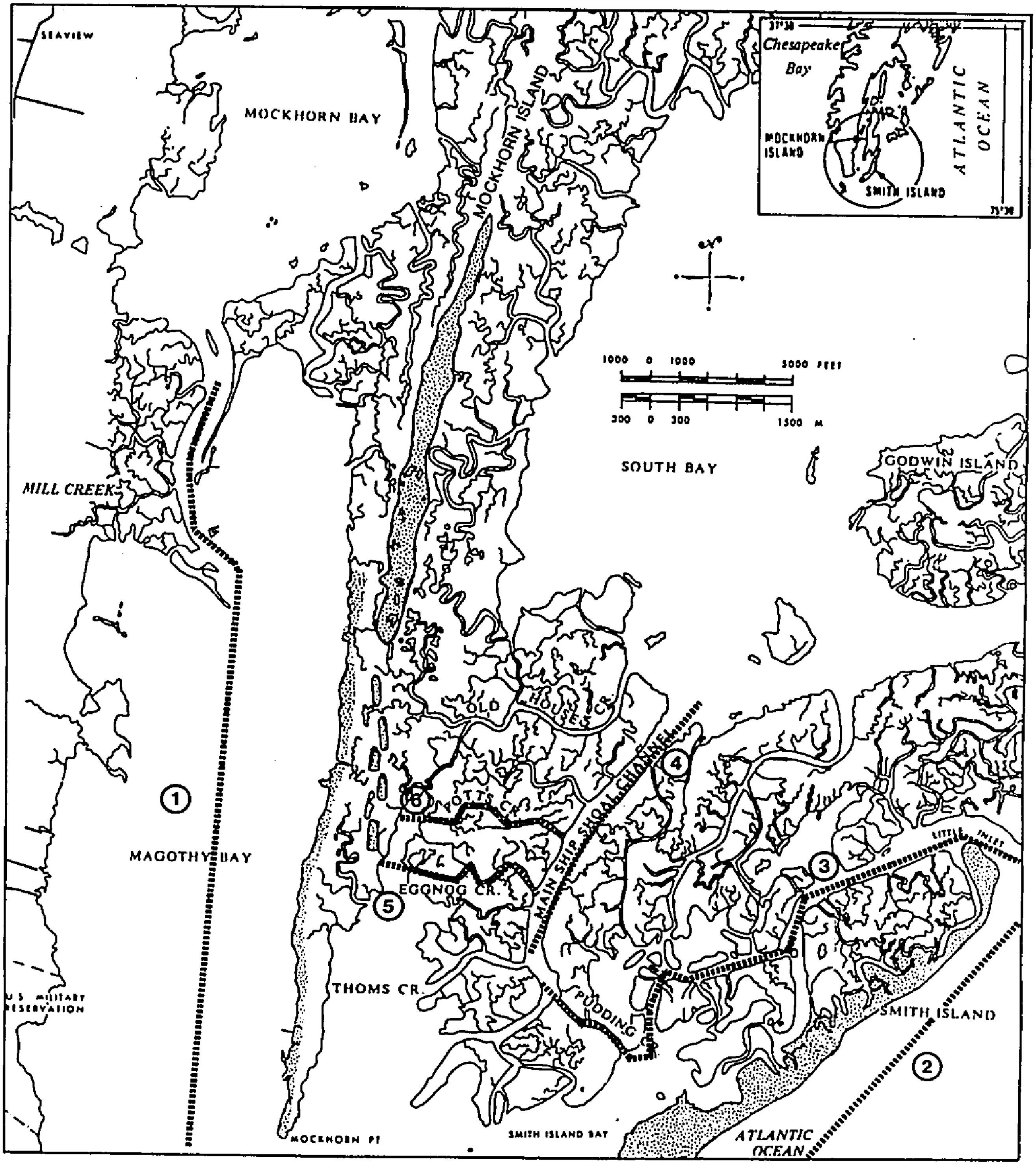


Figure 7. Location map of the study area with seismic subbottom transects noted.

deeper water environments such as backbarrier channels, the nearshore zone, and Mockhorn channel in Magothy Bay (Figure 7).

Two high resolution subbottom profiling instruments were used in this study. One was the Ferranti O.R.E. Geopulse system. This is a medium power (105 to 455 joules) multi-frequency (400 Hz to 14 kHz) unit with a surface towed catamaran. An EPC 1600 single channel recorder was used. The other unit used was a Datasonics SBP 5000. Because depth of penetration was relatively shallow, the two-way travel time was based upon the speed of sound in water which is 1500 m/sec (Sheriff, 1977). A vertical record of less than 30 m, and usually no more than 20 m, was collected.

Grain Size Analysis

Textural analysis of 159 sediment samples from 49 vibracores, 16 sediment samples from 14 boxcores, and 3 grab samples were determined (Table 3). These samples were analyzed by either sieve, pipette, or settling tube (rapid sediment analyzer-RSA). Samples composed of 100% fine or medium sand were analyzed with the RSA; coarser samples were sieved. The pipette was used for finer samples to find the sand/silt/clay percentage. The RSA was used to determine the grain size distribution of the sand fraction unless the sand percentage was too low.

A preliminary sedimentary facies or depositional sedimentary environment was identified before samples were collected (see

TABLE 3

GRAIN-SIZE MEASUREMENTS

Core or	Depth	Depositional	Pipette Sand/	RSA[3] (ϕ)	Sieve (ϕ)
Sample No.[1]	(cm)[2]	Envt./Facies	Silt/Clay (%)	Mean/Stand. Dev.	
6A	120	Shoreface	93/04/03	2.64/0.24	
6B	180	Shoreface	81/11/08	2.80/0.24	
6D	450	Shoreface	89/10/01	3.24/0.30	
6D	565	Tidal Flat	15/63/22	3.63/0.38	
6D	660	Pleistocene? Mud	38/41/21	3.59/0.39	
6E	563	Shoreface	87/06/07	3.12/0.30	
6E	698	Tidal Flat	04/70/26	3.52/0.44	
6E	768	Pleistocene? Mud	12/57/31	3.86/0.46	
6-2	61	Marsh	49/39/12	2.67/0.86	
6-5	157	Pleistocene Sand		1.95/0.55	
6-6	178	Pleistocene Sand		1.50/0.63	
6-7	10	Marsh	35/51/14	2.56/0.97	
6-7	370	Open Lagoon	71/26/03	2.71/0.38	
6-7	480	Open Lagoon		2.70/0.56	
6-7	700	Pleistocene Sand		2.89/0.70	
6-8	0	Marsh	53/42/05	2.82/0.48	
6-8	100	Tidal Flat	53/43/04	3.16/0.66	
6-8	300	Pleistocene Sand		1.78/0.52	
6-8	380	Pleistocene Sand		2.44/0.57	
6-9	120	Pleistocene Sand		1.40/0.69	
6-9	250	Pleistocene Sand		1.33/0.50	
6-9	340	Pleistocene Sand		1.08/0.66	
6-10	61	Marsh	17/78/05	3.03/0.84	
6-10	183	Tidal Flat	30/43/27	3.11/0.50	
6-10	366	Tidal Flat	35/34/31	3.01/0.49	
6-10	549	Open Lagoon	64/18/18	2.84/0.55	
6-10	700	Open Lagoon	83/13/04	3.00/0.45	
6-10	780	Pleistocene Sand		3.03/0.77	
6-11	122	Pleistocene Sand		2.03/1.04	
6-11	198	Pleistocene Sand		2.07/0.57	
6-11	336	Pleistocene Mud	8/48/44		
7-1A	+50	Barrier Beach		2.17/0.53	
7-1A	170	Tidal Flat	28/36/36	3.03/0.63	
7-1A	330	Tidal Flat	55/41/04	2.93/0.49	
7-1	+50	Washover		2.55/0.62	
7-1	102	Marsh	14/83/03	2.55/1.31	
7-1	178	Tidal Flat	35/55/10	2.81/0.95	
7-1	438	Open Lagoon	85/08/07	3.02/0.56	
7-1	634	Sheltered lagoon	32/37/31	2.93/0.70	

TABLE 3 (Continued)

Core or Sample No.[1]	Depth (cm)[2]	Depositional Envt./Facies	Pipette Sand Silt/Clay (%)	RSA[3] (ϕ)	Sieve (ϕ)
				Mean/Stand. Dev.	
7-3	366	Sheltered Lagoon	32/47/21	3.21/0.61	
7-3	610	Open Lagoon	64/21/15	2.94/0.53	
7-5	240	Open Lagoon	67/28/05	2.87/0.45	
7-5	450	Sheltered Lagoon	34/26/40	2.91/1.01	
7-5	650	Open Lagoon	69/18/13	2.67/0.83	
7-5	750	Pleistocene Sand		2.89/0.53	
7-5	800	Pleistocene Mud	06/58/36		
7-5	830	Pleistocene Mud	20/68/14		
7-5	850	Pleistocene Sand		2.85/0.60	
7-7	10	Marsh	29/65/06	2.97/0.73	
7-7	110	Tidal Flat	63/32/05	2.67/1.02	
7-7	270	Sandy Tidal Flat	90/02/08	1.62/0.75	
7-7	330	Pleistocene Sand		1.87/0.75	
7-7	400	Pleistocene Sand		1.68/0.82	
7-8	30	Pleistocene Sand		1.42/0.71	
7-8	150	Pleistocene Sand		1.89/0.74	
7-8	230	Pleistocene Sand		1.92/0.61	
7-8	250	Pleistocene Mud	15/41/44		
7-9	100	Marsh	10/48/42		
7-9	190	Pleistocene Sand		1.98/1.12	
7-9	300	Pleistocene Sand		2.45/0.53	
7-9	380	Pleistocene Sand		1.45/0.87	
7-10	200	Transgressive Lag			-0.59/1.78
8-3	244	Tidal Flat	32/43/25	2.98/0.46	
8-3	427	Sheltered Lagoon	11/45/44	3.24/0.62	
8-4	50	Marsh	13/47/40	2.23/1.04	
8-4	240	Tidal Flat	50/35/15	3.19/0.80	
8-5	75	Tidal Flat	62/27/11	3.18/0.55	
8-5	280	Tidal Flat	75/13/12	2.95/0.48	
8-5	400	Sheltered Lagoon	10/50/40		
8-5	575	Open Lagoon		2.65/0.90	
8-6	0	Pleistocene Sand		1.55/1.14	
8-6	140	Pleistocene Sand		2.08/0.71	
8-6	210	Pleistocene Sand		2.07/0.97	
8-6	270	Pleistocene Mud	7/43/50		
8-7	+50	Backbarrier Beach		1.59/0.53	
8-7	+10	Backbarrier Beach		1.86/0.97	
8-7	50	Marsh	19/38/43		
8-7	230	Pleistocene Sand		2.11/0.64	
8-8	+30	Sandy Marsh	71/18/11	1.60/0.74	
8-8	25	Tidal Flat	23/46/31	2.29/1.02	
8-8	160	Sandy Tidal Flat	97/1/2	1.83/0.70	
8-8	250	Pleistocene Sand		1.43/0.79	

TABLE 3 (Continued)

Core or Sample No.[1]	Depth (cm)[2]	Depositional Envt./Facies	Pipette Sand/ Silt/Clay (%)	RSA[3] (ϕ)	Sieve (ϕ)
				Mean/Stand. Dev.	
9A	506	Shoreface	94/03/03	2.92/0.19	
9-1	+50	Washover		2.43/0.39	
9-1A	+50	Barrier Beach		2.41/0.45	
9-1A	88	Washover		2.17/0.71	
9-2	50	Sandy Marsh	67/23/10	1.77/0.75	
9-2	127	Pleistocene Sand		2.04/0.94	
9-2	305	Pleistocene Mud	58/27/15	2.74/0.70	
9-2	381	Pleistocene Sand		2.52/0.57	
9-4	160	Tidal Flat	41/37/22	3.10/0.54	
9-5	130	Pleist. Sand/Msh	87/03/10	1.70/0.61	
9-5	230	Pleistocene Sand		1.57/0.53	
9-5	270	Pleistocene Sand		2.19/0.59	
9-5	300	Pleistocene Mud	29/46/25	2.88/0.80	
9-5	370	Pleistocene Sand		2.82/0.72	
9-6	60	Marsh	37/36/27	2.11/0.88	
9-6	110	Pleistocene Sand			-0.90/1.80
9-6	170	Pleistocene Sand			-0.62/1.85
9-6	190	Pleistocene Sand		2.43/0.63	
9-6	210	Pleistocene Sand			-0.94/2.24
9-7	122	Pleistocene Sand		2.05/0.75	
9-7	244	Pleistocene Sand		2.00/0.61	
9-7	335	Pleistocene Mud	03/35/62		
M-1	180	Sandy Tidal Flat	79/13/08	1.97/0.56	
M-1	240	Transgressive Lag?		0.92/0.80	
M-1	280	Pleistocene Sand		1.42/1.14	
M-1	300	Pleistocene Sand		2.04/0.65	
M-2	15	Sandy Marsh		1.31/0.77	
M-2	75	Open Lagoon		1.21/1.11	
M-2	125	Rwkd? Pleist Sand		1.09/1.47	
M-2	165	Rwkd? Pleist Sand		0.84/0.87	
M-3	+50	Backbarrier Beach		1.31/0.64	
M-3	130	Sandy Marsh		1.76/0.67	
M-3	210	Pleistocene Sand		1.58/0.67	
M-3	260	Pleistocene Mud	19/34/47	2.42/0.97	
M-4	+20	Pleistocene Sand		1.94/0.96	
M-4	0	Pleistocene Sand		1.71/0.76	
M-4	80	Pleistocene Sand		2.06/0.70	
M-4	220	Pleistocene Mud	22/47/31	2.78/0.88	
M-4	300	Pleistocene Mud	04/36/60		

TABLE 3 (Continued)

Core or Sample No.[1]	Depth (cm)[2]	Depositional Envt./Facies	Pipette Sand/Silt/Clay (%)	RSA[3] (φ)	Sieve (φ)
				Mean/Stand. Dev.	
M-5	150	Rwkd? Pleist Sand		1.49/0.71	
M-5	210	Rwkd? Pleist Sand		0.80/0.77	
M-6	+50	Backbarrier Beach		1.18/0.68	
M-6	163	Pleistocene Sand		1.68/0.61	
M-6	285	Pleistocene Mud	03/49/48		
M-6	331	Pleistocene Mud	05/54/41		
M-6	407	Pleistocene Mud	71/16/13	2.95/0.52	
M-7A	15	Pleistocene Sand		1.45/0.79	
M-7A	76	Pleistocene Sand		1.52/0.78	
M-7A	290	Pleistocene Mud	18/53/29	2.71/1.00	
M-8	0	Pleistocene Sand		1.92/0.70	
M-8	137	Pleistocene Sand		1.92/0.74	
M-8	229	Pleistocene Sand		1.37/0.86	
M-8	251	Pleistocene Mud	26/45/29	2.80/0.76	
M-8	305	Pleistocene Mud	52/22/29	2.41/0.72	
M-8	351	Pleistocene Mud	87/07/06	2.07/0.83	
M-8	427	Pleistocene Sand		2.08/0.71	
M-9	+30	Backbarrier Beach		1.40/0.64	
M-9	107	Sandy Tidal Flat	61/25/14	1.70/0.66	
M-9	275	Pleistocene Mud	30/42/28	2.70/0.81	
M-10	244	Pleistocene Sand		2.44/0.65	
M-10	350	Pleistocene Sand		1.26/1.47	
M-11	49	Marsh	12/83/05	3.19/0.62	
M-11	274	Sheltered Lagoon	09/52/39		
M-11	427	Sheltered Lagoon	37/36/27	2.18/0.98	
M-11	640	Open Lagoon		3.02/0.72	
M-11	701	Sheltered Lagoon	16/58/26	2.96/0.84	
M-11	732	Open Lagoon	75/18/07	2.22/0.88	
CL-1	+35	Sandy Marsh		1.72/1.09	
CL-1	87	Marsh	48/30/22	2.05/0.90	
CL-1	194	Pleistocene Sand		2.60/0.70	
CL-1	255	Pleistocene Sand			-0.48/1.39
BI-4	+50	Washover		2.44/0.42	
BI-4	26	Washover	86/07/07	2.36/0.50	
MB-1	360	Open Lagoon	78/22/Tr	3.49/0.32	
MB-2	370	Pleistocene Sand	99/Tr/Tr	1.62/0.54	

TABLE 3 (Continued)

Core or Sample No.[1]	Depth (cm)[2]	Depositional Envt./Facies	Pipette Sand Silt/Clay (%)	RSA[3] (ϕ) Sieve (ϕ) Mean/Stand. Dev.
BC-1	15	Marsh	13/58/25	3.03/0.75
BC-2	30	Tidal Flat	34/46/20	3.02/0.87
BC-3	45	Tidal Flat	36/46/18	3.04/0.78
BC-4	105	Open Lagoon	56/31/13	3.05/0.57
BC-5	135	Open Lagoon	42/39/19	3.12/0.57
BC-6	165	Open Lagoon	64/24/12	3.21/0.56
BC-7	107	Open Lagoon	99/Tr/Tr	1.94/0.45
BC-7	133	Open Lagoon	99/Tr/Tr	1.86/0.44
BC-8	122	Open Lagoon	99/Tr/Tr	1.86/0.34
BC-8	143	Open Lagoon	99/Tr/Tr	1.84/0.37
BC-9	164	Open Lagoon	99/Tr/Tr	2.97/0.19
BC-10	178	Open Lagoon	99/Tr/Tr	2.96/0.25
BC-11	135	Open Lagoon	78/14/08	2.40/0.35
BC-12	135	Open Lagoon	87/06/07	3.05/0.20
BC-13	135	Open Lagoon	94/03/03	2.98/0.22
BC-14	165	Sheltered/Open Lagoon	49/33/18	3.17/0.33
GS-A	422	Open Lagoon	97/01/02	2.90/0.20
GS-B	457	Open Lagoon	59/22/19	2.10/0.78
GS-C	60	Flood Tidal Delta	73/17/10	2.78/0.49

1. BC are box cores, GS are grab samples, all others are vibracores.

2. The depth is the position sampled below mean sea-level unless noted by + (above mean sea-level).

3. RSA = Rapid Sediment Analyzer. Pure sand samples were placed in the RSA to find mean grain size and standard deviation. Coarser sands and pebbles were sieved. The sand fractions from those samples pippeted were also run through the RSA to find the mean grain size and standard deviation of that portion. In some cases, sand fractions of pippeted samples were too small for RSA analysis.

Stratigraphic Units). Samples were then taken from the center of these stratigraphic units so that diagnostic textural analysis could be accomplished. The facies or environment with its associated grain size is shown in Table 3.

Percent Total Organic Matter

The abundance of organic matter often provides information about the depositional environment, such as productivity and the strength of bottom currents (Gross, 1971). Samples were analyzed for total organic matter after the methodology of Gross (1971) by combustion at 550^0 C in a muffle furnace for 4 hours (ignition loss). Weight percents of 58 samples from 27 cores were calculated (Table 4). Samples were chosen to include the primary sedimentary facies and depositional environments. Units believed to be rich in organics, such as marsh and the Pleistocene mud facies, were particularly sampled.

Micropaleontology

Microfossils help one discern the environment of deposition, relative age, and paleoclimate of the sedimentary unit in which they are found. Two microfauna, foraminifers and ostracodes, and one microflora, pollen, were separated and identified. Several dinoflagellates were found with the separated pollen but not identified.

TABLE 4

ORGANIC COMBUSTION (PERCENT ORGANIC MATTER)

Vibracore or Box Core (BC) No.	Depth (cm) Below MSL[1]	Sediment Type	% Organic Matter[2]
6-7	10	Mud and Marsh Vegetation	10.2
6-7	200	Mud and Sand	8.8
6-7	370	Mud and Sand	5.6
6-7	480	Gray Fine Sand	2.3
6-7	700	Brown/Tan Sand	0.1
6-8	0	Mud (Intertidal Mud Flat)	3.2
6-10	8	Mud and Marsh Vegetation	13.3
6-10	30	Mud and Marsh Vegetation	13.5
6-10	180	Mud	10.8
6-10	365	Mud	12.7
6-10	550	Mud and Sand	6.1
6-10	700	Gray Fine Sand	1.3
6-11	335	Pleistocene Mud With Much Clay, Some Vegetation	10.8
6-11	450	Pleistocene Mud With Much Clay and Vegetation	12.0
7-4	15	Mud and Marsh Vegetation	19.3
7-4	55	Mud and Marsh Vegetation	20.3
7-4	90	Mud and Marsh Vegetation	23.1
7-4	135	Mud and Marsh Vegetation	5.8
7-7	10	Mud and Marsh Vegetation	12.2
7-8	250	Pleistocene Clay/Peat	11.2
8-2	30	Mud and Marsh Vegetation	9.3
8-2	60	Mud and Marsh Vegetation	15.5
8-2	90	Mud and Marsh Vegetation	4.1
8-6	270	Pleistocene Mud With Some Sand and Vegetation	8.0
8-8	+30	Sand With Some Vegetation	3.2
8-8	25	Mud and Sand With Much Marsh Vegetation	11.9
9-2	0	Mud and Sand with Much Marsh Vegetation	3.9
9-3	15	Mud and Marsh Vegetation	10.9
9-3	45	Mud and Marsh Vegetation	6.7
9-3	60	Mud and Marsh Vegetation	9.0

TABLE 4 (Continued)

Vibracore or Box Core (BC) No.	Depth (cm) Below MSL[1]	Sediment Type	% Organic Carbon[2]
9-4	30	Mud and Marsh Vegetation	13.7
9-5	300	Pleistocene Mud With Some Sand.	3.8
M-3	260	Pleistocene Mud/Peat	9.0
M-4	220	Pleistocene Mica Enriched Mud	3.0
M-4	300	Pleistocene Mud/Peat	7.0
M-6	250	Pleistocene Peat	29.8
M-6	285	Pleistocene Mud, Much Clay, Some Mica	7.3
M-6	330	Pleistocene Mud, Much Clay, Some Mica	9.2
M-6	410	Pleistocene Mica Enriched Fine Sand	2.3
M-7A	254	Pleistocene Peat	37.1
M-7A	290	Pleistocene Mud, Much Clay, Some Mica	15.7
M-8	305	Pleistocene Mud, Some Sand and Mica	7.4
M-8	350	Pleistocene Mud and Sand	1.9
M-8	380	Pleistocene Peat	9.5
M-9	+30	Sand	0.2
M-9	270	Pleistocene Mica Enriched Mud	5.4
M-11	0	Mud and Marsh Vegetation	13.0
M-11	30	Mud and Marsh Vegetation	19.1
M-11	75	Mud and Marsh Vegetation	14.8
M-11	120	Mud and Marsh Vegetation	14.8
M-11	170	Mud and a Little Marsh Vegetation	7.9
M-11	260	Mud	11.4
BC-1	15	Mud and Marsh Vegetation	9.3
BC-2	15	Mud	5.5
BC-3	45	Mud	8.9
BC-4	105	Mud and Sand	7.5
BC-5	135	Mud and Sand	3.1
BC-6	165	Mud and Sand	3.1

[1] Below mean sea-level (MSL) unless noted by (+), above mean sea-level

[2] Mean of three trials

Foraminifera are protistans characterized by the presence of a test with one or more chambers. The forams were separated from the sediment by immersing an unconsolidated sample in tetrachlorethylene, a heavy fluid of specific gravity 1.61. This allowed the clastic materials to sink and the lighter forams to float.

Two distinct assemblages occur, calcareous and agglutinated (arenaceous). Agglutinated foraminifera are generally characteristic of lower salinity environments such as marshes. The foraminiferal species identified are shown in Table 5. Table 6 lists the number of calcareous and agglutinated forams in each of 69 core samples per gram (dry weight) of sediment coarser than 62 um.

Ostracodes are mostly microscopic aquatic crustaceans. Four samples were analyzed by Dr. Thomas Cronin of the United States Geological Survey (USGS) Reston, Virginia. The species identification and count are shown in Table 7.

Pollen and spores were extracted from 17 Pleistocene samples. The extraction technique followed standard procedures outlined by Faegri and Iversen (1975). Approximately 1 gm samples were processed by the following steps:

1. Removal of carbonates by heating (40^0C) with 10% hydrochloric acid.
2. Alkali maceration by boiling the samples for 10-15 minutes with 8% NaOH. Samples were then sieved to remove coarse detritus. A 150 um sieve was usually used in clastic material or well-humified peats, whereas some of the dense, fibrous peats encountered in the study were sieved with a 250 um sieve.

TABLE 5

Barrier and Backbarrier Foraminiferal Species

A. Calcareous species	B. Agglutinated species
Ammonia beccarii (Linne)	*Ammoastuta salsa* (Cushman and Bronnimann)
*Buccella frigida** (Cushman)	*Arenoparrella mexicana** (Kornfeld)
Elphidium discoidale (D'Orbigny)	*Haplophragmoides hancocki* (Cushman and McCulloch)
Elphidium excavatum (Terquem) = *Elphidium clavatum* (Cushman)*	*Miliammina fusca* (Brady)
Elphidium gunteri (Cole)	*Tiphotrocha comprimata* (Cushman and Bronnimann)
Haynesina paucilocula (Cushman)	*Trochammina inflata** (Montagu)

* Most Abundant

TABLE 6

No. of Calcareous (Calc.) and Agglutinated (Agglut.) Foraminifera Per Gram (Dry Weight) of Sediment Coarser than 62 um

Core and Depth (Below MSL)	Sediment Type	Depositional Envt./Facies	Calc.	Agglut.
6-5 240 cm	Compacted Mud/Sand	Pleistocene Mud	0	0
6-7 10 cm	Mud and Marsh Veg.	Marsh	0	0
6-8 10 cm	Mud and Marsh Veg.	Marsh	0	8
6-10 30 cm	Mud and Marsh Veg.	Marsh	0	0
6-10 180 cm	Sandy Mud	Tidal Flat	17	0
6-10 540 cm	Muddy Sand	Open Lagoon	0	0
6-10 700 cm	Fine Sand	Open Lagoon	0	0
6-11 120 cm	Medium Sand	Pleistocene Sand	0	0
6-11 195 cm	Medium Sand	Pleistocene Sand	0	0
6-11 335 cm	Silt and Clay	Pleistocene Mud	0	0
6-11 460 cm	Mud and Vegetation	Pleistocene Mud	0	0
7-1 +50 cm	Washover Sand	Barrier Beach	38	5
7-1 100 cm	Mud and Marsh Veg.	Marsh	0	10
7-1 175 cm	Sandy Mud	Tidal Flat	35	0
7-1 435 cm	Muddy Sand	Open Lagoon	22	0
7-1 635 cm	Sand, Silt and Clay	Sheltered Lagoon	31	0
7-1 730 cm	Fine Sand	Open Lagoon	0	0
7-5 240 cm	Muddy Sand	Open Lagoon	18	0
7-5 450 cm	Sand, Silt and Clay	Sheltered Lagoon	0	0
7-5 650 cm	Muddy Sand	Open Lagoon	17	0
7-5 750 cm	Fine Sand	Pleistocene Sand	0	0
7-5 850 cm	Fine Sand	Pleistocene Sand	0	0
7-7 10 cm	Mud and Marsh Veg.	Marsh	0	5
7-7 110 cm	Muddy Sand	Tidal Flat	22	0
7-7 270 cm	Poorly Sorted Sand	Transgressive Lag	0	0
7-7 330 cm	Medium Sand	Pleistocene Sand	0	0
7-7 400 cm	Medium Sand	Pleistocene Sand	0	0
7-8 30 cm	Medium Sand	Pleistocene Sand	0	0
7-8 150 cm	Medium Sand	Pleistocene Sand	0	0
7-8 230 cm	Medium Sand	Pleistocene Sand	0	0
7-8 250 cm	Peat and Mud	Pleistocene Mud	0	0
7-9 100 cm	Mud and Marsh Veg.	Marsh	0	0
7-9 190 cm	Medium Sand	Open Lagoon	0	0
7-9 300 cm	Medium Sand	Pleistocene Sand	0	0
7-9 380 cm	Coarse Sand	Pleistocene Sand	0	0
8-6 260 cm	Compacted Mud/Sand	Pleistocene Mud	0	0
8-8 +30 cm	Sand/Mud and Mrsh Veg	Marsh	0	4
8-8 30 cm	Mud and Marsh Veg.	Marsh	7	6

TABLE 6 (Continued)

Core and Depth (Below MSL)		Sediment Type	Depositional Envt./Facies	Calc.	Agglut.
9-2	45 cm	Sand/Mud and Mrsh Veg.	Marsh	0	12
9-4	30 cm	Mud and Marsh Veg.	Marsh	0	18
9-5	300 cm	Compacted Mud/Sand	Pleistocene Mud	0	0
M-3	260 cm	Mud/Peat	Pleistocene Mud	0	0
M-4	+20 cm	Medium Sand	Pleistocene Sand	0	0
M-4	0 cm	Medium Sand	Pleistocene Sand	14	0
M-4	220 cm	Silt/Clay/Sand	Pleistocene Mud	6	2
M-4	300 cm	Mud/Peat	Pleistocene Mud	0	0
M-6	+50 cm	Medium Sand	Backbarrier Beach	0	0
M-6	250 cm	Peat/Mud	Pleistocene Mud	0	0
M-6	285 cm	Silt/Clay	Pleistocene Mud	0	0
M-6	410 cm	Muddy Sand	Pleistocene Mud	18	4
M-7A	15 cm	Medium Sand	Pleistocene Sand	0	0
M-7A	254 cm	Peat/Mud	Pleistocene Mud	0	0
M-7A	275 cm	Compacted Sandy Mud	Pleistocene Mud	9	1
M-8	0 cm	Medium Sand	Pleistocene Sand	14	2
M-8	140 cm	Medium Sand	Pleistocene Sand	6	0
M-8	230 cm	Medium Sand	Pleistocene Sand	0	0
M-8	305 cm	Muddy Sand	Pleistocene Mud	0	0
M-8	350 cm	Muddy Sand	Pleistocene Mud	0	0
M-8	380 cm	Peat/Mud	Pleistocene Mud	0	0
M-8	430 cm	Medium Sand	Pleistocene Sand	0	0
M-9	+30 cm	Medium Sand	Backbarrier Beach	0	0
M-9	275 cm	Silt/Sand/Mud	Pleistocene Mud	0	0
M-11	265 cm	Silt and Clay	Sheltered Lagoon	11	0
BC-1	30 cm	Mud and Marsh Veg.	Marsh	0	5
BC-2	30 cm	Sandy Mud	Tidal Flat	4	1
BC-3	30 cm	Sandy Mud	Tidal Flat	9	0
BC-4	30 cm	Muddy Sand	Open Lagoon	15	0
BC-5	30 cm	Muddy Sand	Open Lagoon	12	0
BC-6	30 cm	Muddy Sand	Open Lagoon	21	0

TABLE 7

Ostracode Species Lists and Counts*

Core, Depth (Below MSL)	Depositional Envt./Facies	Species and Count	
6-1, 300 cm	Tidal Flat	*Cyprideis mexicana* (Sandberg, 1964)	16
		Cytheromorpha newportensis (Williams, 1966)	1
		Cytherura cf. *C. forulata* (Edwards, 1944)	5
		Cytherura sp. A	1
		Cytherura sp. B	2
		Hulingsina spp.	5
		Proteoconcha sp. A	1
6-1, 400 cm	Open Lagoon	*Baffinicythere emarginata* (Sars, 1865)	1
		Bensonocythere americana (Hazel, 1967)	6
		Bensoncythere spp.	1
		Cushmanidea seminuda (Cushman, 1906)	6
		Cyprideis mexicana (Sandberg, 1964)	16
		Cytheromorpha curta (Edwards, 1944)	2
		Cytheromorpha newportensis (Williams, 1966)	2
		Cytherura forulata (Edwards, 1944)	6
		Cytherura "valentinei" (Hazel, 1967)	1
		Cytherura sp. A	10
		Hulingsina rugipustulosa (Edwards, 1944)	9
		Hulingsina spp.	15
		Leptocythere nikraveshae (Morales, 1966)	6
		Loxoconcha matagordensis (Swain, 1955)	45
		Loxoconcha sperata (Williams, 1966)	5
		Malzella floridana (Benson and Coleman, 1963)	2
		Muellerina ohmerti (Hazel, 1967)	2
		Paradoxostoma delicata (Puri, 1954)	2
		Peratocytheridea bradyi (Stephenson, 1938)	8
		Peratocytheridea setipunctata (Brady, 1869)	15
		Proteoconcha gigantica (Edwards, 1944)	10
		Proteoconcha nelsonensis (Grossman, 1967)	3
		Sahnia spp.	3
6-1, 745 cm	Sheltered Lagoon	*Actinocythereis captionis* (Hazel, 1981)	3
		Hulingsina spp.	3
6-5, 240 cm	Pleistocene Mud (Lagoon)	No Ostracodes	

* Identification and counts by Dr. Thomas Cronin, USGS Reston.

3. Removal of silicates by boiling with 40% hydrofluoric acid for 10-15 minutes. Silico-fluorides were removed afterwards by treating the samples with hot 10% hydrochloric acid.

4. Removal of cellulose material by using Erdtman's acetolysis method (1-2 minutes at 95^0C).

5. Staining the palynormorphs with a 1:3 saffranin-O and water solution.

6. Dehydration in an alcohol series (95% alcohol followed by tertiary butyl alcohol).

7. Embedding the residue in silicon oil and storing the mixture in small vials.

Dr. Michael Kearny, Department of Geography, University of Maryland, identified most of the pollen and spores and drafted Figure 8. These identifications were made with the aid of several standard keys (Kapp, 1969; McAndrews et al., 1973; Bassett, et al., 1978) and by comparison with reference slides. Pollen sums are based on at least a count of 200 arboreal grains. The conventions used in this study to indicate the degree of confidence associated with the identification of pollen and spores follows Birks (1973). These conventions are described below:

1. Family level, e.g., Cruciferae, Gramineae. Pollen and spores in this group have not been identified below family level either because reference material was not available or because pollen taxonomic difficulties associated with several of these groups preclude confident subdivisions at present. Included at this level of

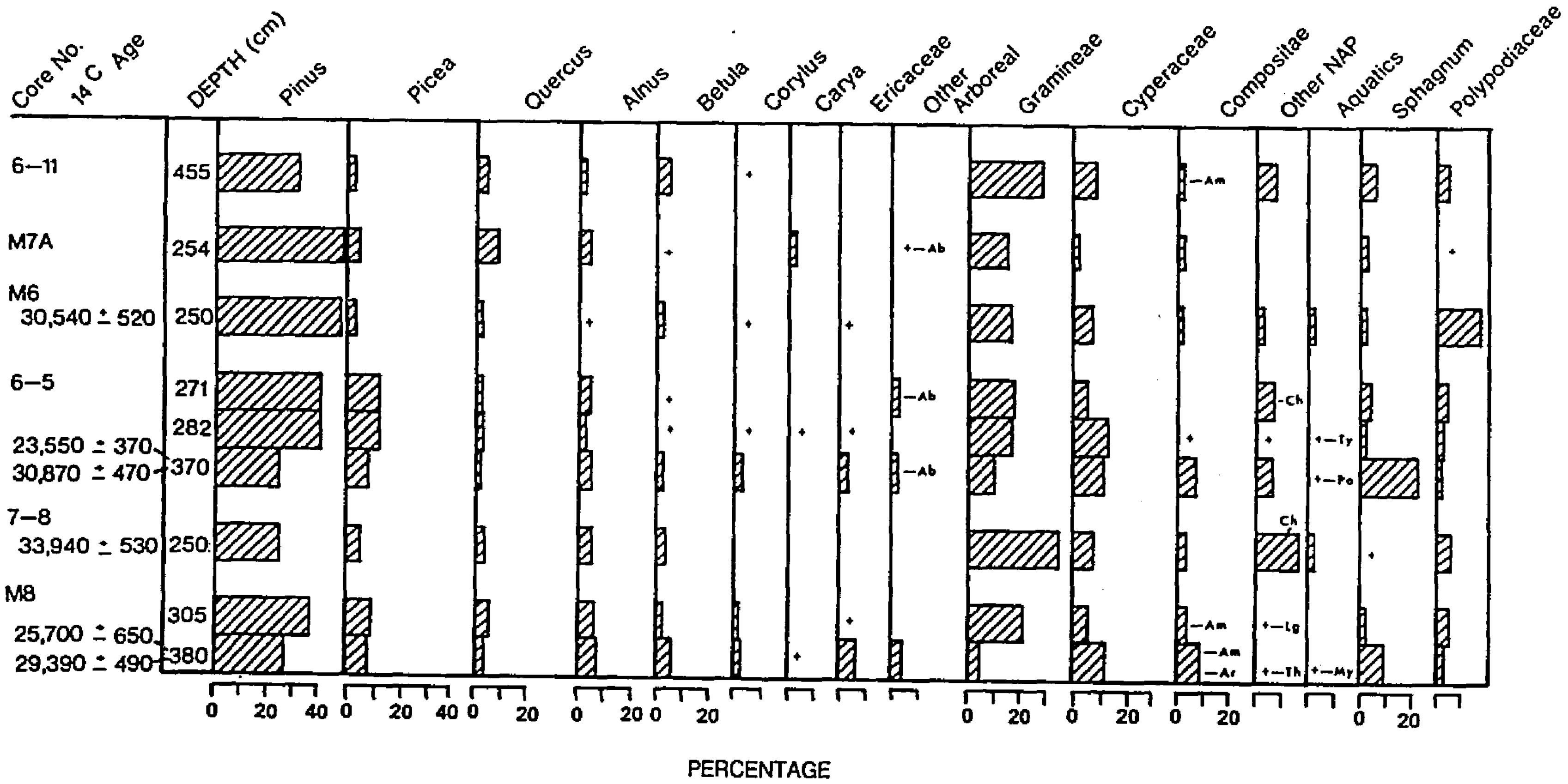


Figure 8. A pollen diagram showing the percentages of species found in Pleistocene lagoonal sediments. These samples have either been C-14 dated or are adjacent to dated samples. Most samples are dominated by an interstadial assemblage of pollen.

confidence besides the two families mentioned are: Ericaceae, Liliaceae, Leguminosae, Umbelliferae, Cyperaceae.

2. Type, e.g., *Ambrosia*-type. The type category is used in instances where generic level identification is not certain but other considerations (e.g. current range, paleoecology) make the genus indicated the preferred choice.

3. Confere (cf.), e.g., *Betula* cf *glandulosa*. Tentative specific level identifications are made when morphologic criteria suggest that the species indicated is the probable representative.

Mineralogy

Analyses of specific minerals often give information pertaining to the local environment or provenance of the sands and the type of transport conditions. Heavy minerals in selected barrier, backbarrier, and mainland creek sand samples were separated in bromoform (specific gravity 2.90) and identified. Glauconite and mica particles were also counted. Samples were prepared by washing the sample in a 63 um sieve to separate and clean the sand-size particles. Analysis of the residue, and ultimately the percentage of each constituent, was made by visual examination under a binocular and/or petrographic microscope.

Where frequency counts of selected particle types were made the following procedure was used. A counting tray was prepared by drawing grid lines on a 9 x 12 cm double thick white illustration board which was then heavily coated with a clear plastic film by repeated spraying with krylon. For calibration, samples were strewn on the tray in a moderate density. The total particles on a number of grid lines were then counted to obtain an average particle number per line. This proved to be about 1000 particles per line of squares. Counting splits of each sample were as close as possible to the density used in calibration. Where the constituent to be counted was relatively sparse, 10 lines or about 10,000 particles were scanned.

These data are expressed in Tables 8 through 13. Table 8 shows the percentage of heavy minerals and mica in Smith Island foreshore samples. A frequency count of mica and glauconite is also included. The percentage of heavy minerals in backbarrier samples and selected creek samples are listed in Tables 9 and 10, respectively. Frequency counts of glauconite and mica in creek and backbarrier samples are respectively shown in Tables 11 and 12.

A detailed study of two cores, 7-1A and 9-1A (Figure 6) was completed by Johnston (1985). The cores were split into five units, depending on the lithology, with subsequent mineralogical analysis. The results of this study are shown in Table 13.

Radiocarbon Dating

Twenty-six samples of peat, marsh vegetation, wood, or shell were analyzed for carbon-14 age determination. Two of the peats were dated twice thus providing a total of 28 dates (Table 14). Nine of the dated material were of shell material. Six of the shell samples were articulated and two were thick shell horizons believed to be part of an oyster bed. Several peaty clay samples had less than expected

TABLE 8

HEAVY MINERALS, MICA, AND GLAUCONITE IN TWENTY-SIX SMITH ISLAND, SURFACE, FORESHORE SAMPLES (2-3 ϕ SIZE FRACTION)

Heavy Minerals and Mica (Mean Percent)

Epidote	11.6
Garnet	16.6
Hornblende	48.5
Hypersthene	3.9
Pyroxene	1.5
Kyanite	2.5
Sillimanite	1.6
Staurolite	1.9
Tourmaline	2.0
Zircon	2.9
Opaques	5.0
Mica	2.0

Mica Particles and Glauconite Pellets (Frequency Counts)

Mica in 10 lines* = 4
Glauconite in 10 lines* = 37

* 1000 particles per line.

TABLE 9

HEAVY MINERALS IN SELECTED BACKBARRIER CORE SAMPLES (%) (2-3 ϕ SIZE FRACTION)

Very Fine to Fine Sands (Mud Removed)

	CORE 7-4	CORE 7-3	CORE 7-3	CORE 7-5	CORE 6-2
(Below MSL)	500 cm	450 cm	150 cm	300 cm	77 cm
Depositional Environment	Tidal Flat	Open Lagoon	Open Lagoon	Open Lagoon	Tidal Flat
Epidote	8.9	9.0	6.7	12.5	6.2
Garnet	14.9	10.6	9.7	12.8	10.4
Hornblende	49.4	65.7	71.8	57.6	68.6
Hypersthene	---	0.6	---	1.3	0.5
Kyanite	7.8	3.2	3.4	2.0	4.4
Sillimanite	3.4	2.2	1.6	1.3	---
Staurolite	6.0	4.5	2.0	3.4	2.9
Tourmaline	8.6	3.9	4.8	9.4	7.0
Zircon	1.0	0.3	---	---	---

Fine, Medium, or Coarse Sand

	CORE 7-3	CORE 7-9	CORE 7-1	CORE 8-7	CORE 6-5
(Below MSL)	600 cm	300 cm	760 cm	250 cm	100 cm
Depositional Envt./Facies	Open Lagoon	Backbarrier Beach	Open Lagoon	Backbarrier Beach	Pleist. Sand
Epidote	15.6	8.5	5.4	13.7	11.9
Garnet	28.6	15.4	26.5	24.8	25.6
Hornblende	33.7	62.8	40.6	42.8	52.9
Hypersthene	2.3	0.9	2.2	3.0	1.5
Kyanite	1.9	0.9	1.3	0.7	0.9
Sillimanite	2.3	3.0	1.3	2.3	3.0
Staurolite	7.5	5.2	12.1	6.7	3.2
Tourmaline	3.2	2.4	2.2	3.3	2.0
Zircon	4.9	0.9	8.6	2.7	---

TABLE 10

HEAVY MINERALS IN SELECTED CREEK SAMPLES (%)
(2-3 ϕ SIZE FRACTION)

	Mill Creek (Sand)	Walls Landing Creek[2] (Sand)	Tommys Ditch[3] (Mud)
Epidote	13.1	16.6	14.2
Garnet	21.1	41.1	24.2
Hornblende	50.2	18.2	36.8
Hypersthene	1.7	2.3	2.1
Rutile	1.7	1.7	0.6
Kyanite	1.3	2.0	3.3
Sillimanite	---	3.3	1.5
Staurolite	6.1	9.9	9.7
Tourmaline	4.8	4.6	7.6
Zircon	---	1.3	---
Weight Percent	3.8	6.1	2.7

1. Mill Creek enters Magothy Bay at Core M-11.

2. Walls Landing Creek enters Magothy Bay at Core 7-9.

3. Tommys Ditch enters Magothy Bay at Core 8-7.

TABLE 11

GLAUCONITE PELLETS AND MICA IN CREEK SAMPLES (2-3 ϕ SIZE FRACTION)

	Mill Creek[1] (Sand)	Walls Landing Creek[2] (Sand)	Tommys Ditch[3] (Mud)
Glauconite Pellets in 10 lines*			
Sample 1	4	0	0
Sample 2	0	3	0
Mica Particles in 10 lines*			
Sample 1	2	0	2
Sample 2	0	0	0

* 1000 particles per line.

1. Mill Creek enters Magothy Bay at Core M-11.

2. Walls Landing Creek enters Magothy Bay at Core 7-9.

3. Tommys Ditch enters Magothy Bay at Core 8-7.

TABLE 12

GLAUCONITE PELLETS AND MICA PARTICLES IN BACKBARRIER FINE SAND AND SANDY-MUD DEPOSITS (2-3 ϕ SIZE FRACTION)

	Depositional Envt./Facies	Glauconite (in 10 lines*)	Mica (in 10 lines*)
CORE 6-1, 770 cm	Sheltered Lagoon	25	250
CORE 6-2, 77 cm	Washover (Sand/Mud)	75	29
CORE 6-2, 520 cm	Sheltered Lagoon	30	290
CORE 6-2, 565 cm	Sheltered Lagoon	80	285
CORE 6-5, 300 cm	Pleistocene Mud	25	130
CORE 6-5, 370 cm	Pleistocene Mud	80	610
CORE 7-1, 760 cm	Open Lagoon	54	128
CORE 7-3, 150 cm	Open Lagoon	90	150
CORE 7-3, 450 cm	Open Lagoon	5	70
CORE 7-3, 600 cm	Open Lagoon	24	56
CORE 7-4, 500 cm	Tidal Flat	10	440
CORE 7-5, 300 cm	Open Lagoon	27	73
CORE 7-9, 300 cm	Backbarrier Beach	20	40

* 1000 particles per line.

TABLE 13

HEAVY MINERALS AND MICA IN SELECTED SMITH ISLAND CORES (%) (2-3 ϕ SIZE FRACTION)

CORE 7-1A*	36 cm	136 cm	242 cm	395 cm	440 cm
Depositional Environment	Barrier Beach	Marsh	Tidal Flat	Open Lagoon	Open Lagoon
Apatite	1.3	1.7	2.5	2.3	2.6
Chlorite	---	5.7	6.2	10.5	9.1
Epidote	18.0	11.4	13.3	9.2	13.1
Garnet	19.3	6.5	6.2	4.6	5.6
Hornblende	24.8	20.9	26.1	31.3	23.6
Hypersthene	2.3	2.1	0.6	0.6	1.0
Kyanite	4.0	4.6	1.3	1.3	2.6
Pyroxene	3.0	5.5	1.0	1.3	1.6
Rutile	4.0	4.0	5.5	5.6	5.9
Sillimanite	1.0	0.6	2.3	0.9	1.3
Sphene	0.5	0.6	0.6	0.9	1.3
Staurolite	1.6	2.1	2.3	2.0	2.6
Tourmaline	4.0	1.5	1.3	1.3	2.0
Zircon	4.0	2.7	3.3	2.0	1.6
Micas	1.0	20.6	18.0	13.8	12.7
Opaques	9.5	5.2	5.5	8.0	7.9
Others	1.6	4.0	3.6	3.6	4.9
Weight Percent	2.16%	0.06%	0.07%	0.11%	0.12%

*Analysis by M.L. Johnston (B.S. honors thesis), College of William and Mary, Williamsburg, VA

Sample depths below mean sea level (MSL).

TABLE 13 (continued)

CORE 9-1A*	33 cm	106 cm	185 cm	270 cm	355 cm
Depositional Environment	Barrier Beach	Overwash Sediments	Tidal Flat	Tidal Flat	Open Lagoon
Apatite	---	0.3	0.6	---	---
Chlorite	0.3	1.0	10.1	10.3	12.8
Epidote	15.7	11.2	13.1	9.6	7.8
Garnet	17.7	16.3	3.9	5.0	4.9
Hornblende	41.8	40.7	27.3	29.0	20.8
Hypersthene	1.0	1.0	2.3	1.6	0.8
Kyanite	3.5	4.0	2.0	3.2	3.6
Pyroxene	1.2	1.0	1.3	1.0	0.8
Rutile	1.2	1.9	2.0	4.2	3.4
Sillimanite	1.6	1.0	1.3	2.2	0.8
Sphene	0.9	1.0	2.0	1.0	0.8
Staurolite	1.6	2.9	1.6	2.5	1.8
Tourmaline	3.2	3.5	1.0	2.5	1.8
Zircon	1.2	2.9	4.6	3.8	6.0
Opaques	3.5	6.7	4.0	5.1	21.9
Micas	2.9	2.5	20.7	16.7	10.1
Others	2.2	1.9	2.0	2.0	1.5
Weight Percent	1.63%	1.10%	0.09%	0.10%	0.06%

*Analyses by M.L. Johnston (B.S. honors thesis), College of William and Mary, Williamsburg, VA
Sample depths below mean sea level (MSL).

TABLE 14

RADIOCARBON AGE DATES

Core Number	Depth Below MSL	Lab Number	Dated Material	C-14 Age Yrs. B.P. + 1 [1]
6-5*	370 cm	Beta-1949	Peaty Clay	23,550 ± 370
6-5*	370 cm	Beta-3423	Peaty Clay	30,870 ± 470
6-6	41 cm	Beta-1948	*Spartina patens*	1,430 ± 80
6-6	80 cm	Beta-1950	Willow or Tulip Poplar	1,740 ± 100
6-10	425 cm	Beta-6668	Articulated *C. virginica* Shell	1,120 ± 60
6-11	455 cm	Beta-6669	Organic Debris	26,960 ± 320
7-1$^+$	110 cm	Beta-6071	*S. alterniflora*	1,670 ± 80
7-1$^+$	180 cm	Beta-6072	Articulated *C. virginica* Shell	480 ± 60
7-1A	165 cm	Beta-6077	Articulated *C. virginica* Shell	470 ± 60
7-1A	250 cm	Beta-6078	Articulated *M. mercenaria* Shell	1,110 ± 80
7-7	140 cm	Beta-6075	*C. virginica* Shells	Modern
7-7	190 cm	Beta-6074	*C. virginica* Shells	460 ± 80
7-8	250 cm	Beta-5033	Organic Rich Mud/Peat	33,940 ± 530
7-9	110 cm	Beta-5034	*S. alterniflora*	2,050 ± 80
8-5	280 cm	Beta-6079	Articulated *C. virginica* Shells	350 ± 70
8-7	50 cm	Beta-5035	*Spartina patens*	1,070 ± 80

TABLE 14 (Continued)

Core Number	Depth Below MSL	Lab Number	Dated Material	C-14 Age Yrs. B.P. ± 1[1]
9-1	305 cm	Beta-6069	Articulated *E. directus* Shell	1,230 ± 220
9-1A	10 cm	Beta-6070	*S. alterniflora*	Modern
9-1A	100 cm	Beta-6068	*S. alterniflora*	950 ± 90
M-2	+75 cm	Beta-6080	Cedar Tree Stump	150 ± 60
M-3	260 cm	Beta-5030	Organic Rich Mud/Peat	23,340 ± 770
M-4	300 cm	Beta-5032	Organic Rich Mud/Peat	27,980 ± 1510
M-6	250 cm	Beta-6671	Peaty Clay	30,540 ± 520
M-7A	254 cm	Beta-6672	Peaty Clay	28,930 ± 580
M-8*	380 cm	Beta-6670	Peaty Clay	25,700 ± 650
M-8*	380 cm	Beta-6673	Peaty Clay	29,390 ± 490

1. These dates are reported as radiocarbon years before 1950 A.D. by Beta Analytic Inc, Coral Gables, Florida. By international convention, the half-life of radiocarbon is taken as 5568 years and 95% of the activity of the National Bureau of Standards Oxalic Acid used as the modern standard. The quoted errors are from the counting of the modern standard, background, and sample being analyzed. They represent one standard deviation statistics (68% probability), based on the random nature of the radioactive disintegration process. No corrections are made for DeVries effect, reservoir effect, or isotope fractionation in nature.

The pretreatment of the peats and organic horizons consisted of first picking out any apparent rootlets. The materials were then stirred into hot acid to eliminate carbonates and then repeatedly rinsed to neutrality, taken to dryness and combusted in an enclosed system. The shell samples were pretreated by etching away the outer layers with dilute acid.

* Note replicate samples.

\+ Age dates and depth not in sequence.

percentage of organic matter (Table 4) and are called organic-rich muds.

The radiocarbon dates for these peats and organic-rich deposits are near the upper limit of the age group. All of these samples are from vibracores and many are believed to be sea-level indicators. For example the oysters are upper subtidal and the peat and marsh vegetation intertidal. Although these materials may not reflect mean sea level, they may be used in a sea-level curve. The datum error will be small as the local tidal range is only approximately 1 m.

These dates are reported as radiocarbon years before 1950 A.D. by Beta Analytic Inc, Coral Gables, Florida. By international convention, the half-life of radiocarbon is taken as 5,568 years and 95% of the activity of the National Bureau of Standards Oxalic Acid used as the modern standard. The quoted errors are from the counting of the modern standard, background, and sample being analyzed. They represent one standard deviation statistics (68% probability), based on the random nature of the radioactive disintegration process. No corrections are made for DeVries effect, reservoir effect, or isotope fractionation in nature (Beta Analytic Laboratory Report, 1982).

The pretreatment of the peats and organic horizons consisted of first picking out any apparent rootlets. The materials were then stirred into hot acid to eliminate carbonates and then repeatedly rinsed to neutrality, taken to dryness and combusted in an enclosed system. The shell samples were pretreated by etching away the outer layers with dilute acid.

Because of the controversy surrounding a high interstadial sea level during the last glaciation, Thom (1974) attempted to rate all mid-Wisconsinan C-14 dates according to their quality. Ten C-14 dates from this study fall within this time frame. Thom (1974) lists five conditions that must be met before accepting the dates of organic materials. If three out of the five conditions are satisfied, the date may get a S? rating, but if only two or less are fulfilled then the rating will be inferior (Thom, 1974). The conditions are:

> 1. Evidence that geomorphologically and stratigraphically the sample can be related to a high sea-level stand and does not come from an event which can be shown to possibly pre-date or post-date the last glaciation.
> 2. The material dated is _in situ_.
> 3. The laboratory conducting the assay has specified the pretreatment techniques to which the sample has been subjected.
> 4. Cross-checks have been conducted by radiocarbon dates on other samples from the same unit, as well as on a background control sample, of identical type, from a more ancient horizon.
> 5. Ideally, further cross-checks should have been undertaken by the uranium-series dating technique on samples from the unit in question and on older material.

The 10 dates of this study were tested against these five criteria. 1) The stratigraphy and geomorphology of Mockhorn Island supports a high sea-level stand (discussed later). 2) The dated material are in place peats or organic rich muds. 3) Beta Analytic discussed the pretreatment techniques. However, it is possible that a more advanced pretreatment process may have been required. 4) Ten radiocarbon dates are from the same unit. A control sample is not available. 5) No calcium carbonate is available from this unit, therefore the uranium-series technique is not applicable.

From the discussion above, the mid-Wisconsinan dates from this study met four of five conditions. Furthermore, it was not possible to satisfy condition 5.

STRATIGRAPHIC UNITS

Introduction

Four stratigraphic units represent the sedimentary deposits found adjacent and below Smith and Mockhorn Islands. The oldest stratigraphic unit, believed to be the Pliocene Yorktown Formation, is only recognized in the subbottom seismic records. The lower Wachapreague Formation, part of a late Pleistocene stratigraphic unit, is also not directly sampled; its description is based upon the work of Mixon (1985). Because the major emphasis of this study concerns the latest Pleistocene and Holocene stratigraphy, sedimentary units composed of sediments from these two time frames were extensively sampled and more precisely described.

Sediments comprising 1) the latest Pleistocene barrier island deposits and 2) Holocene barrier island deposits are a mixture of dominantly terrigenous sand, silt, and clay. Sands are mostly orthoquartzitic and are locally burrowed or cross-bedded. Grains of authigenic glauconite, mollusk shells, shell fragments, and microfaunal tests comprise most of the non-terrigenous component of the sediment.

Two separate latest Pleistocene barrier island facies and eight Holocene barrier island depositional environments have been identified surficially and/or in the subsurface. They include Pleistocene sand facies (barrier, shoreface, flood tidal delta), Pleistocene mud facies (lagoon, marsh), Holocene barrier depositional environments that include barrier beach (and washover) and shoreface, and Holocene backbarrier depositional environments that include marsh, tidal flat, open (high energy) lagoon, sheltered (low energy) lagoon, transgressive lag, and backbarrier beach. The facies or depositional environments associated with each unit were delineated through variation in their texture, microfauna, macrofauna, stratigraphic position, physical and biogenic sedimentary structures, carbon-14 dates, and contact characteristics. Boxcores provided characteristics from several modern depositional environments. A brief descriptive summary of each latest Pleistocene and Holocene deposit is presented in Table 15 and shown in a schematic drawing in Figure 9.

Yorktown Formation

Underlying the latest Pleistocene and Holocene sediments is the Yorktown Formation. This unit extends over a wide geographic region, from the Fall Zone eastward to beneath the continental shelf, northward to the Potomac River, and southward into North Carolina, and is composed of fossiliferous, marine quartzose and calcareous sand and silt (Johnson et al., 1985). In the subsurface of the southern Delmarva area, Mixon (1985) found the Yorktown Formation to be composed of glauconitic sand, silt, and clay.

The Pliocene/Pleistocene contact is reported as the upper surface of the Yorktown Formation in this region by Shideler et al. (1984) and

TABLE 15

PRIMARY DEPOSITIONAL ENVIRONMENTS AND THEIR PHYSICAL AND BIOGENIC CHARACTERISTICS
(See text for further information)

Depositional Environment	Texture-Lithology	% Sand/ Silt/Clay	Primary Sedimentary Structures	Thickness (m)	Contacts Top/Bottom	Biota
Pleistocene Barrier Sands	Medium well-sorted orange-tan sand, $\bar{X} = 1.81$ ϕ		Heavy mineral laminations. Planar, mostly horizontal beds. Round burrows	3.5 to 5.0	None/sharp but conformable	None
Pleistocene Lagoon	Dewatered mud, often mottled. Much mica.	20/44/36	Occasional lenticular sand bed. Interbedded peat and organic-rich horizons.	>2.5	Sharp but conformable/ None	A few calcareous and agglutinated foraminifera, a few dinoflagellates
Barrier Beach and Washover	Fine well-sorted tan sand, $\bar{X} = 2.35$ ϕ		Low-angle and horizontal planar beds	1.0 to 2.5	None/sharp but conformable	Mollusk shells Foraminifera
Shoreface	Fine grey sand, $\bar{X} = 2.90$ ϕ	89/07/04	A few horizontal heavy mineral beds, several round burrows.	0.70 to 0.95	None/sharp but conformable	Some shell fragments
Holocene Salt Marsh	Dark grey organic-rich mud. Heavily vegetated.	27/55/18	None	0.5 to 1.0	Gradational/ gradational	*S. alterniflora*, *S. virginica*, *D. spicata*. Agglutinated forams.
Tidal Flat (Fine-grained)	Dark grey sandy mud. Oyster shells in layers up to 2 m thick	40/40/20	Completely bioturbated.	0.5 to 3.0 $\bar{X} = 1.5$ to 2.0	Gradational/ gradational	Many oyster shells, some articulated. Many mud snail shells. Calcareous forams.

TABLE 15 (Continued)

Depositional Environment	Texture-Lithology	% Sand/ Silt/Clay	Primary Sedimentary Structures	Thickness (m)	Contacts Top/Bottom	Biota
Open (High Energy) Lagoon (Muddy Sands)	Dark grey muddy sand. Analogous to mixed flat environment	70/20/10	Flaser, wavy, lenticular and coarsely and thinly inter-layered bedding. Increased bioturbation towards top.	1.0 to 5.0 $\bar{X} = 2.5$	gradational/ gradational	Some oyster shells, a few M. lateralis, ostracodes, and calcareous forams.
Sheltered (Low Energy) Lagoon	Massive mud with some plant debris	20/48/32	Some sand laminae, mostly bioturbated.	0 to 3.0	Gradational/ gradational	Calcareous forams, two ostracode spp., and plant debris.
Transgressive Lag	Coarse sand to gravel		None	0.2 to 0.5	Gradational/ erosional	Broken shell material, occasionally.
Backbarrier Beach	Fine to medium tan sand. $\bar{X} = 1.79\ \phi$		Horizontal planar bedding	0.5 to 2.0	None/ gradational	Mollusk shells and marsh vegetation on surface.

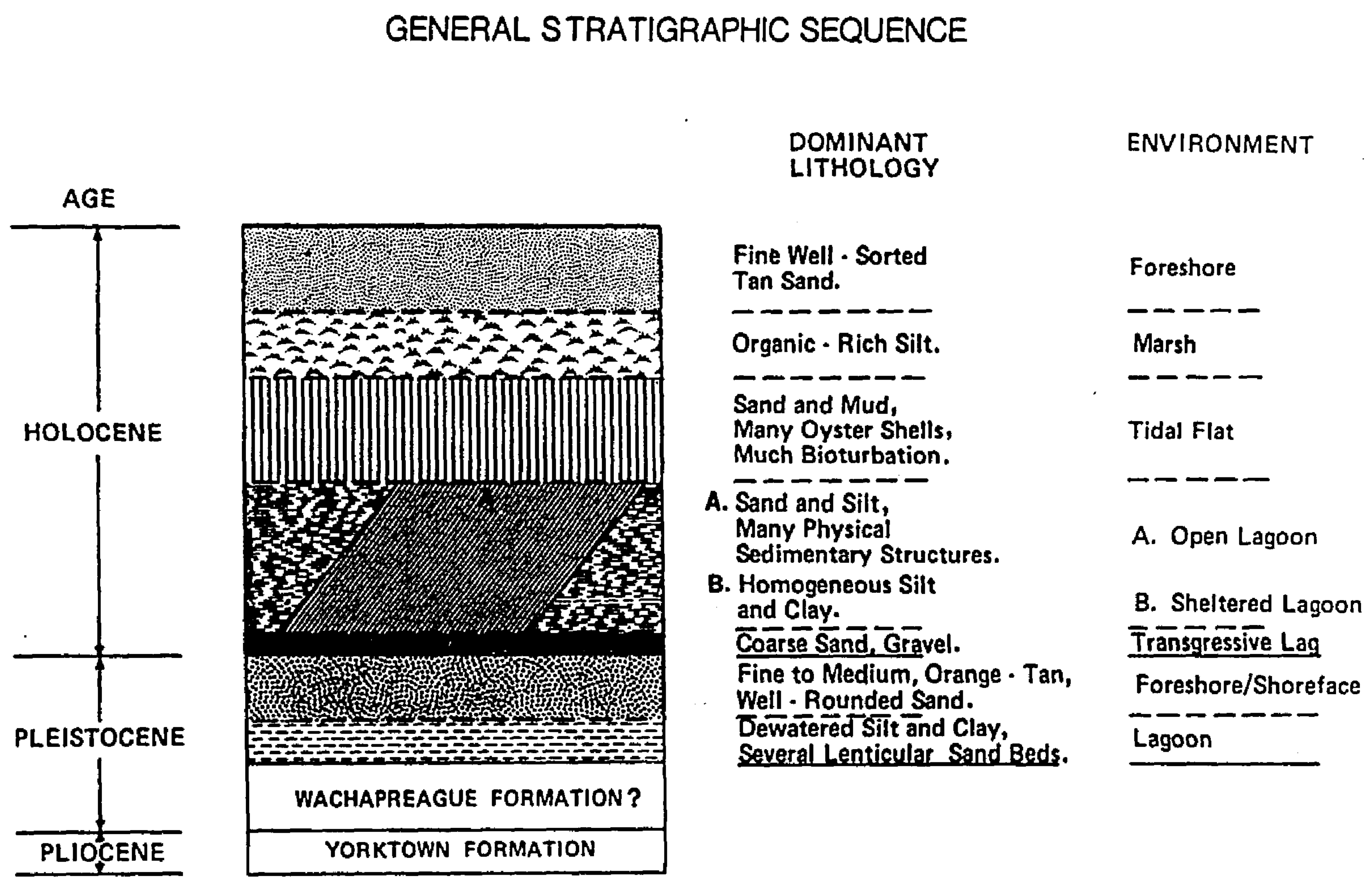


Figure 9. A schematic drawing depicting the stratigraphic position of individual sedimentary facies, depositional environments, and Formations. This sequence was not seen in it's entirety at any one place. It is a composite of the oberved Holocene and Pleistocene stratigraphy.

Mixon (1985). It is easily recognized on the subbottom seismic records (Figure 10). A substantial acoustic impedance contrast between overconsolidated Pliocene strata and normally consolidated overlying Pleistocene deposits is responsible for the strong seismic reflector (Shideler et al., 1984). Shideler et al. (1984) report strong and persistent parallel to subparallel reflectors, indicating a relatively indurated and fairly uniform lithology. The records from this study generally agree with this description except that steeply dipping reflectors below the contact are recognized locally (Figure 10). In addition, the depth to the Yorktown Formation between Smith and Mockhorn Islands is between 16 and 22 m (Figure 10). This depth is supported by Mixon (1985) but differs with Shideler et al. (1984) who report a 30 to 45 m depth at this location. However, below the nearshore, their contact at 45 to 50 m agree with seismic subbottom records of this study.

Wachapreague Formation

As defined by Mixon (1985), the Wachapreague Formation is located adjacent to the study area and extends north-south as a narrow coastal lowland bordering Magothy Bay. Mixon (1985) believes this unit to be the lowest and presumably the youngest depositional surface of Pleistocene age on the Atlantic side of the Delmarva Peninsula. However, an internal contact exists in the Wachapreague Formation. Thus, two chronologically distinct sections may exist in this Formation. Pleistocene sediments situated around Mockhorn Island are

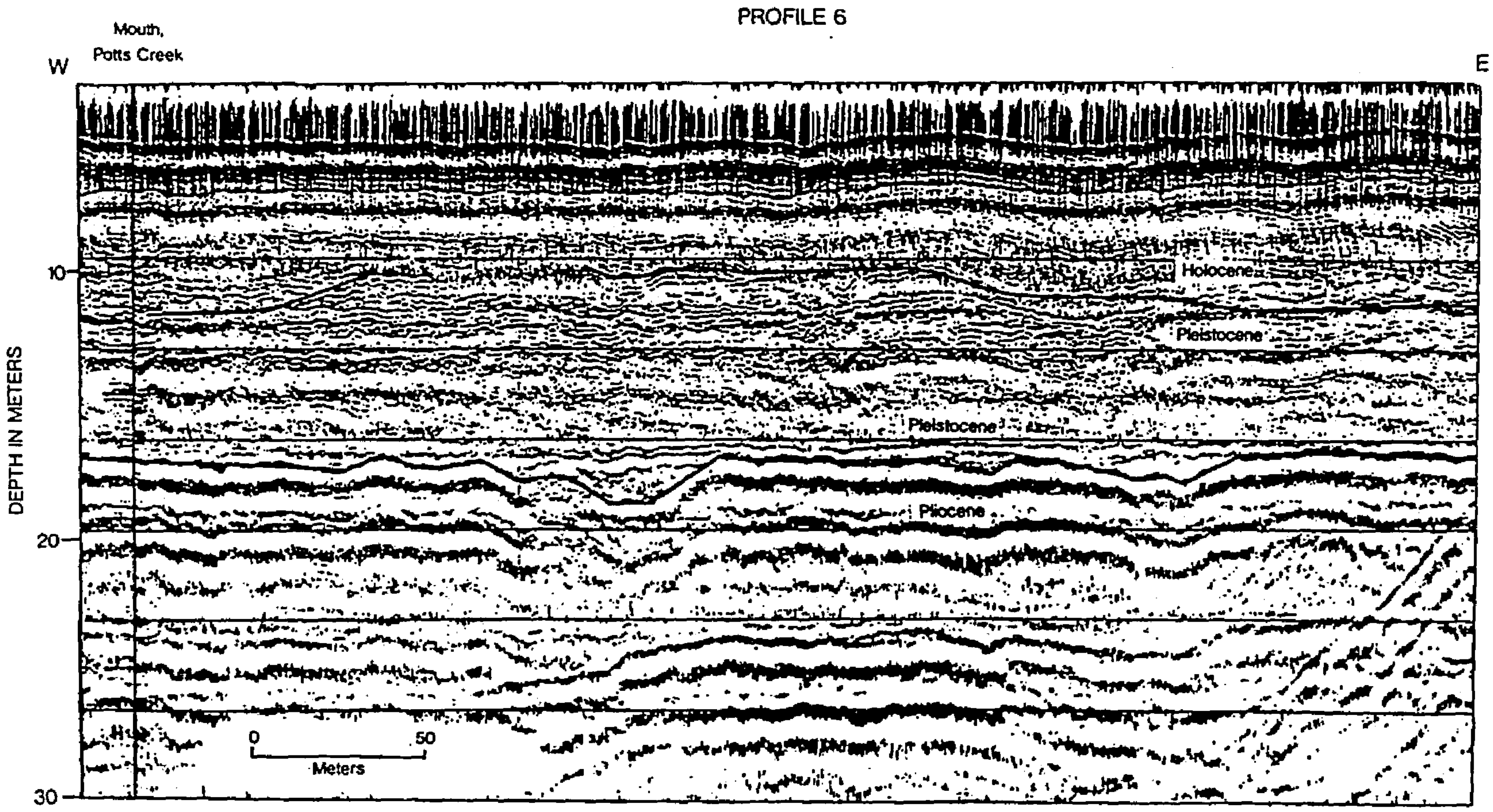


Figure 10. Shown above is a portion of seismic, subbottom profile 6 (see Figure 7 for location). The strong seismic reflectors at about 17 meters is the Pliocene Yorktown Formation surface. The Holocene/Pleistocene contact is less readily apparent. The Pleistocene surface is irregular, probably scoured when subaerily exposed.

surmised in this study to be correlative to the upper section of the Wachapreague Formation. The depth to the Pleistocene surface (Wachapreague Formation?) lessens toward the mainland or Mockhorn Island. The topography of this surface is outlined in Figure 11.

The entire Wachapreague Formation as defined by Mixon ranges in altitude from -1.8 m at its eastern border to approximately 4.5 m (MSL). Of the two distinct lithic sections, the lower one is composed of clay and silty, fine to very fine sand and clay-silt. Texture and microfossil assemblages, indicate deposition in shallow nearshore-shelf water. The upper unit consists of medium to very coarse gravelly sand. Mixon (1985) states that the entire Formation coarsens upward, however, cores from this study (e.g. MC-4, Figure 12) show the upper section to fine upward. The pollen and marine faunas indicate a change from warm temperate climatic conditions in earliest Wachapreague time to cool- or cold-temperate conditions in middle and late Wachapreague time. A reliable absolute age is not available but, based on the stratigraphic position and several isotopic dates from the lower section, Mixon (1985) suggested a Sangamonian to early Wisconsinan age. In summary, Mixon (1985) believes the paleoclimatology, typically coarsening upward trend, seaward decrease in altitude of the Wachapreague depositional surface, and the absolute age estimates point to deposition occurring during the final regression of the sea at the end of the Sangamonian Interglaciation.

The Mill Creek cores taken in this study (MC-1 to 4) and Mixon (1985) (T-16) (Figure 12) show the stratigraphic relationship between the two sections of the Wachapreague Formation and the respectively

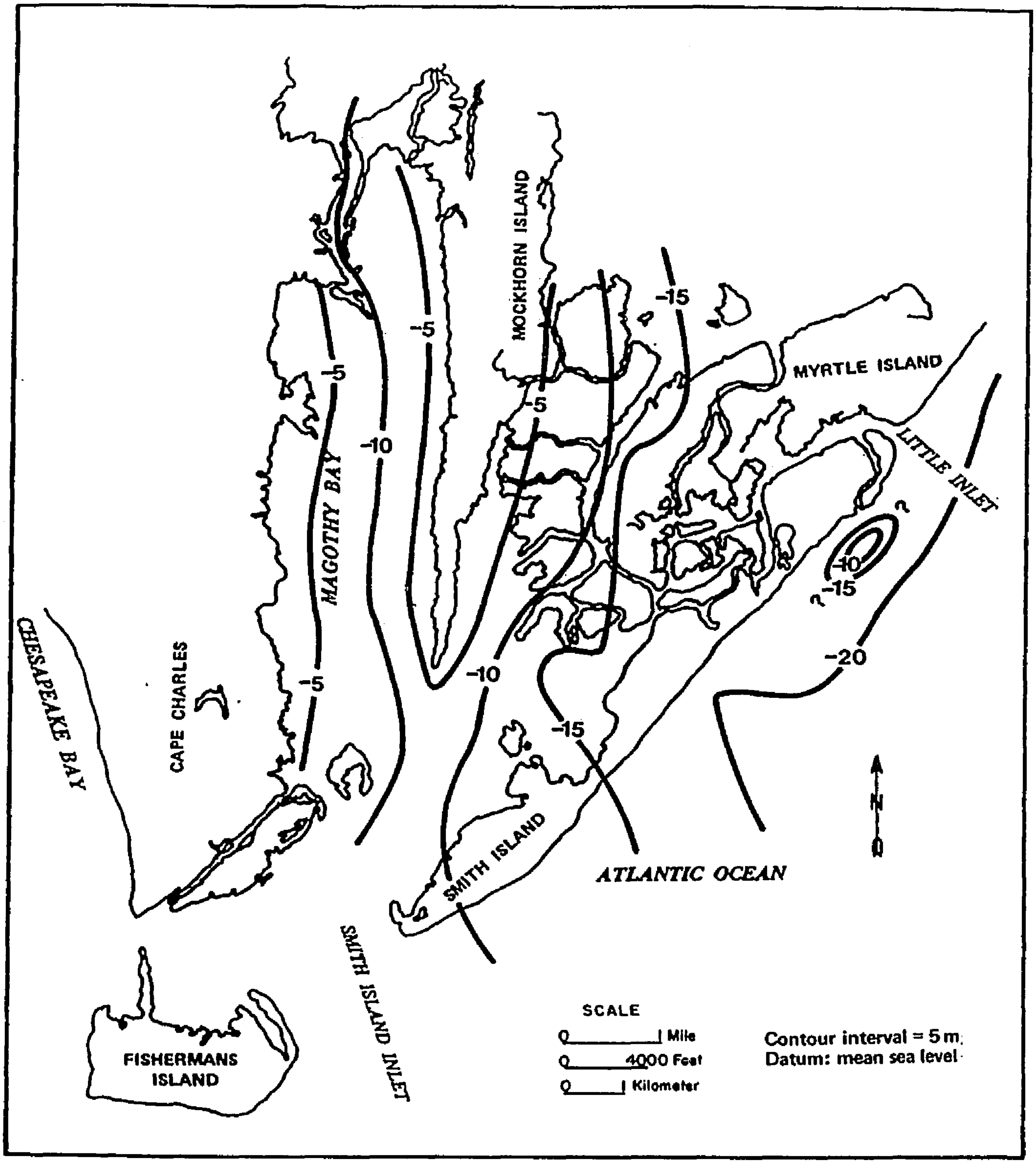
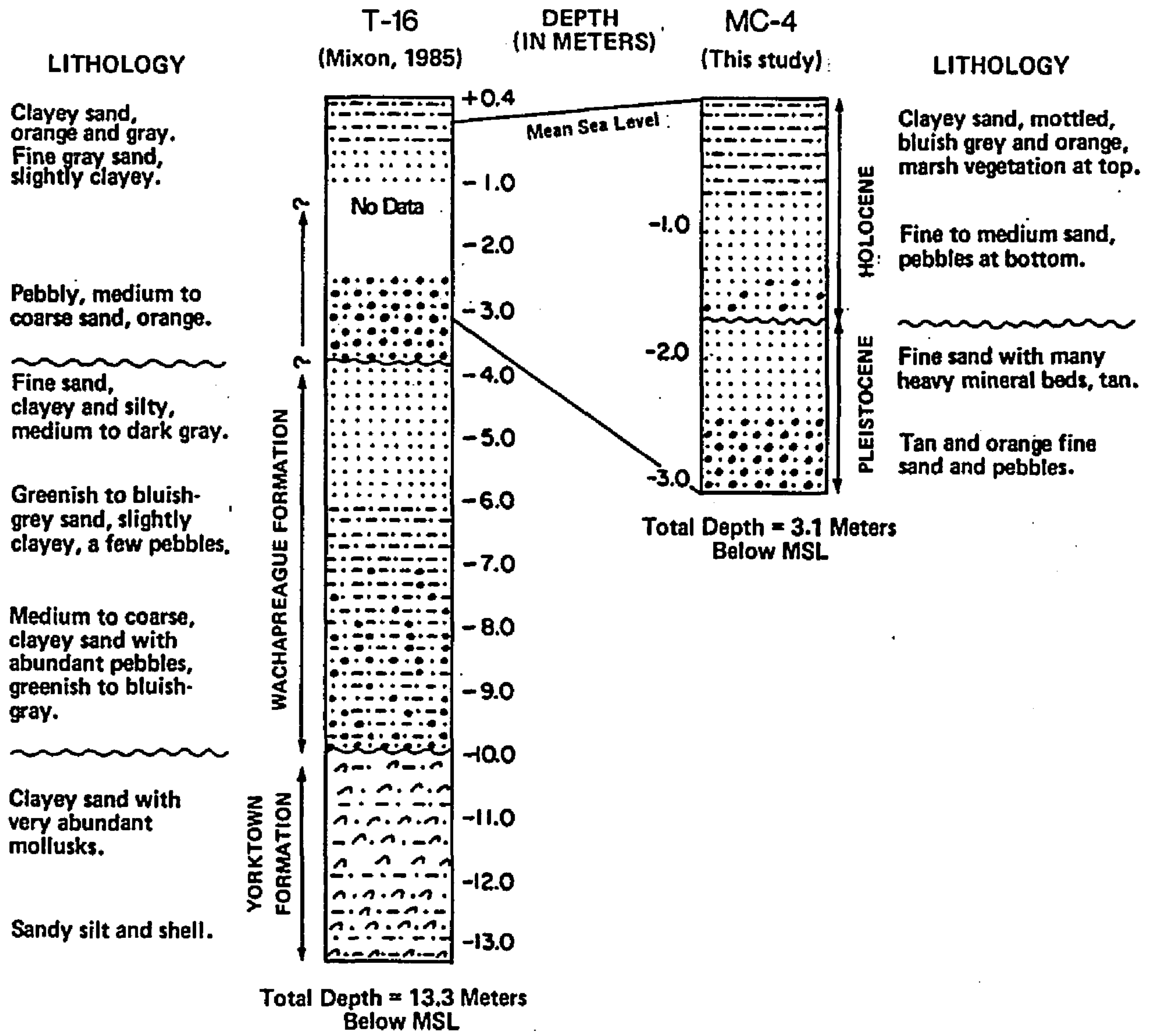


Figure 11. Vibracores and seismic subbottom records were used to determine the general topography (depth below MSL) of the Pleistocene surface, shown above.

Figure 12. Stratigraphic columns of the same Mill Creek core from Mixon (1985) (T-16) and this study (MC-4) (see Figure 6 for location) are shown. The Holocene/Pleistocene contact is located in MC-4 and falls in the zone of no data from T-16. The contact at -3.9 m in T-16 separates sediments correlative to Mockhorn Island and the Wachapreague Formation below.

MILL CREEK CORES



older and younger Yorktown Formation and Holocene deposits. MC-1 to 4 were retrieved from the mainland fringing marsh and beach west of Magothy Bay (Figure 6). Although MC-4 was taken nearly at the same location as T-16, it did not reach the top of the lower section of the Wachapreague Formation. Pleistocene sediments from cores MC-1 to 4 are fine and coarse sands. A soil horizon above these sands was also locally recognized (Cores 6-6 and MC-1, Appendix I). These sediments may be from mainland fringing backbarrier beaches that formed concurrently with the latest Pleistocene Mockhorn Island barrier island complex. Unfortunately, a contact between the lower section of the Wachapreague Formation and the proposed younger Pleistocene sediments (upper Wachapreague section or Mockhorn formation-see below) has not been precisely located in cores from this study. It probably lies below MC-1 to 4, Magothy Bay and/or, Mockhorn Island.

Previously Unnamed Latest Pleistocene Barrier Island Deposits (Mockhorn Formation, Late Sangamonian to Mid-Wisconsinan)

Seaward and stratigraphically above the lower section of the Wachapreague Formation is a relatively thick sequence of orange-tan barrier associated sands locally atop dewatered muds. These deposits are informally called the Mockhorn formation. Mockhorn Island and the adjacent regions underlying Holocene deposits are composed of this unit. Deposits associated with this unit are interpreted to represent the barrier island complex of the last Pleistocene marine transgression. The transgressive stratigraphy of Mockhorn formation sediments cannot be lithologically correlated with regressive Type Section deposits of late Wachapreague time (Mixon, 1985). However, Mockhorn formation deposits are believed equivalent to the upper section of the Wachapreague Formation. The stratigraphic position of this unit indicates a younger age than the lower section of the Wachapreague Formation, hence, a very late Sangamonian to mid-Wisconsinan age. A Pleistocene rather than Holocene age for this unit is based upon sediment color, grain size, fauna, and sediment consolidation that is clearly different from similar depositional environments that are known as Holocene.

Pleistocene Sand Facies (Beach, Shoreface, Flood Tidal Delta)

Based upon the sedimentary characteristics, the sand facies is divided into three different but associated depositional environments. These are beach, shoreface, and flood tidal delta. All three are characterized by an orange-tan color and a lack of most fauna.

The most distinctive Pleistocene sand deposits are those found on Mockhorn Island (Figure 13). This interpretation as a barrier beach is based on the geomorphology, stratigraphic sequence and the following sedimentary characteristics. The grain size of this sand deposit is quite uniform. Textural analysis of 26 samples show a range of means between 2.19 ϕ and 1.37 ϕ (Table 3) and a combined sample mean and standard deviation of 1.81 ϕ and 0.77 ϕ, respectively. These sands average one half phi size larger than those from the Holocene barrier, Smith Island (Table 3). The Pleistocene sand varies between 2.0 to 3.0 m thick below MSL (Table 16) and when combined with

Figure 13. Shown in this photograph are Mockhorn Island beach sands. Note the medium grain size of the sand and the horizontal bedding.

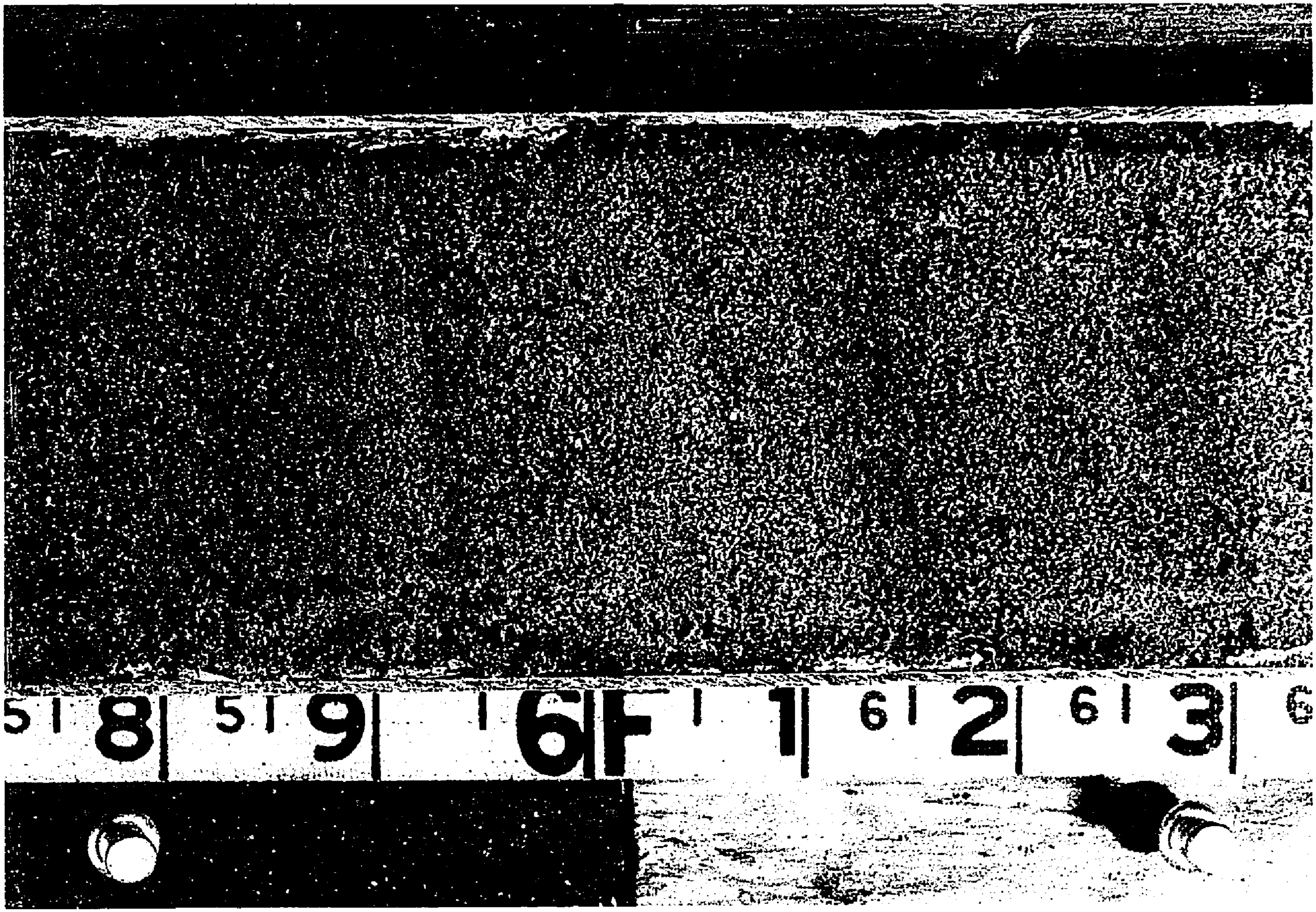

5 8 5 9 6 F 1 6 2 6 3 6

TABLE 16

MOCKHORN ISLAND SAND OR SAND-AND-HOLOCENE MARSH THICKNESS
South to North

Core Number	Sand Thickness (Below MSL)
M-9	200 cm (additional 30 cm of sand above MSL)
G	255 cm (additional 30 cm of marsh above MSL)
9-5	284 cm
9-7	282 cm
9-2	282 cm
8-6	245 cm
M-8	250 cm
6-11	283 cm
6-5	230 cm
M-4	200 cm (additional 20 cm of sand above MSL)
7-8	240 cm
M-7A	238 cm
M-3	240 cm (additional 70 cm of sand above MSL)
M-6	230 cm (additional 50 cm of sand above MSL)
M-2*	200 cm (additional 75 cm of sand and marsh above MSL)
M-5*	280 cm (additional 50 cm of sand and marsh above MSL)
M-1*	328 cm

*Cores did not reach the sand/mud contact. The depth shown is the total core depth relative to mean sea-level (MSL).

1.5 to 2.0 m of intertidal and subaerial Mockhorn Island sands amounts to a deposit 3.5 to 5.0 m thick. Sedimentary structures are usually not present but in some cases include heavy mineral laminations and planar, mostly horizontal beds. Round burrows are present in some places. Pedogenic evidence, is seen in some cores, for example core M-7A (Figure 14), and some of the heavy minerals are etched. The contact with the mud facies below is always sharp but conformable; it looks much like the modern barrier/lagoon and nearshore/lagoon contacts recognized in cores 9-1A and 6D (Figure 15). One sample analyzed for percentage of heavy minerals shows no apparent difference from that found in Holocene sands (Table 9). Four samples were studied by J.P. Owens (United States Geological Survey, Reston, Virginia) who also found high concentrations of hornblende. In addition, the heavy minerals are well rounded, a characteristic which is usually diagnostic of an oscillatory wave dominated environment.

Mockhorn Island sands are presently being reworked by an encroaching sea due to the Holocene marine transgression. Erosion is very apparent on the western shore of Mockhorn Island where Magothy Bay provides a large fetch (Figure 16). Reworking of intertidal and subtidal sands is recognized by the presence of a tan color, mollusk shells and shell fragments, and, in some places, calcareous foraminifers (Table 6).

Mainland Pleistocene sediments on the western side of Magothy Bay underlie Holocene marsh or backbarrier beaches composed of Holocene and reworked Pleistocene sand. These sediments are interpreted as a backbarrier beach associated with the Mockhorn barrier (Figure 17).

Figure 14. Mockhorn Island beach sands from Core M-7A that exhibit possible pedogenic evidence. Note mottling and etched heavy minerals.

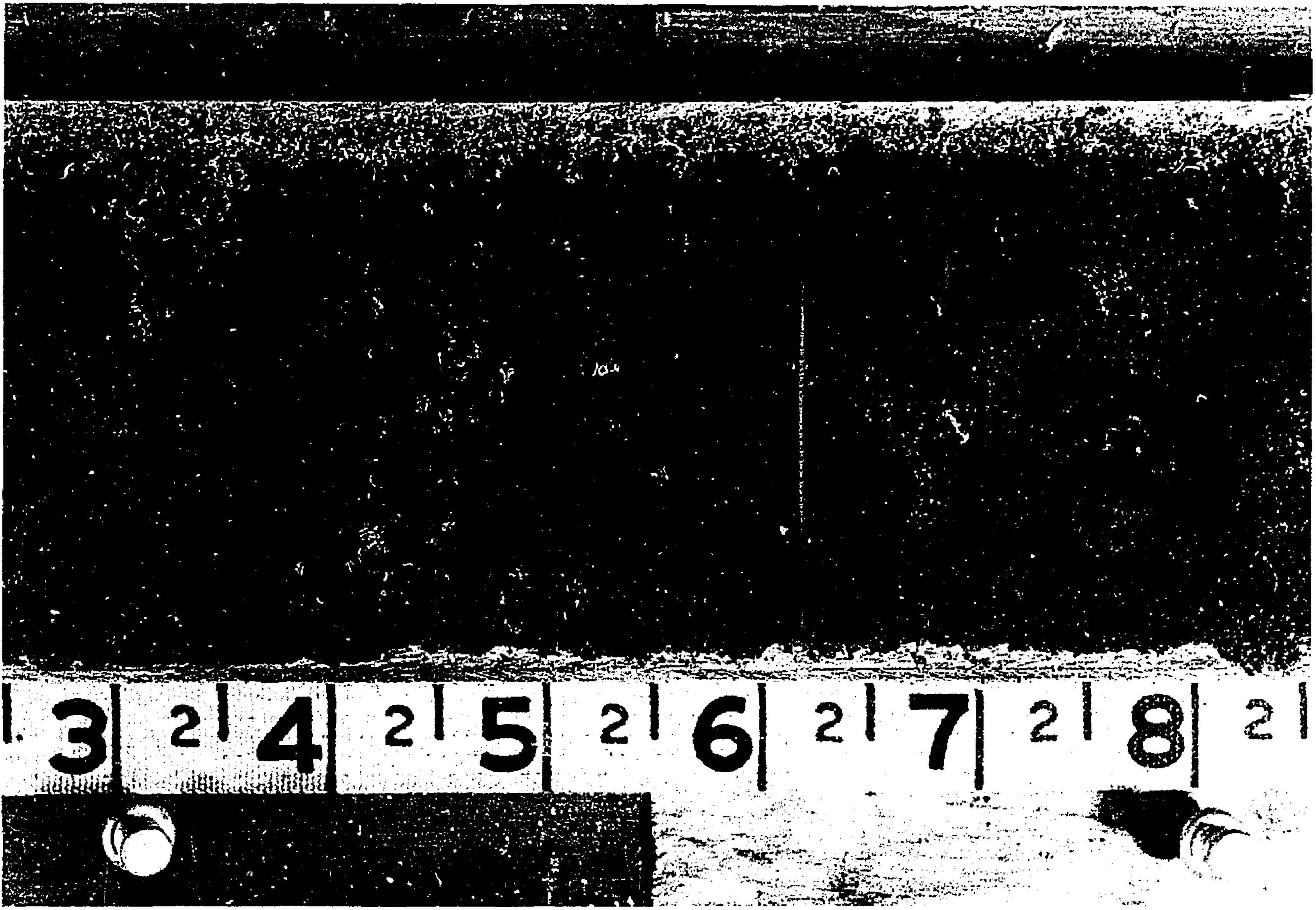
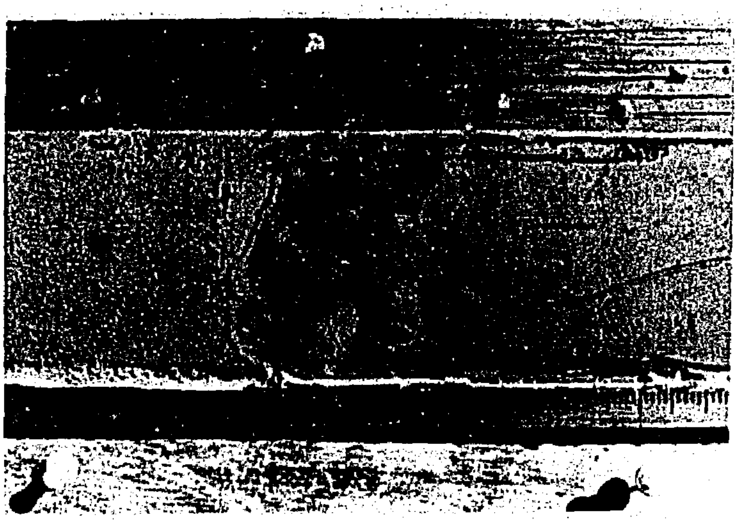
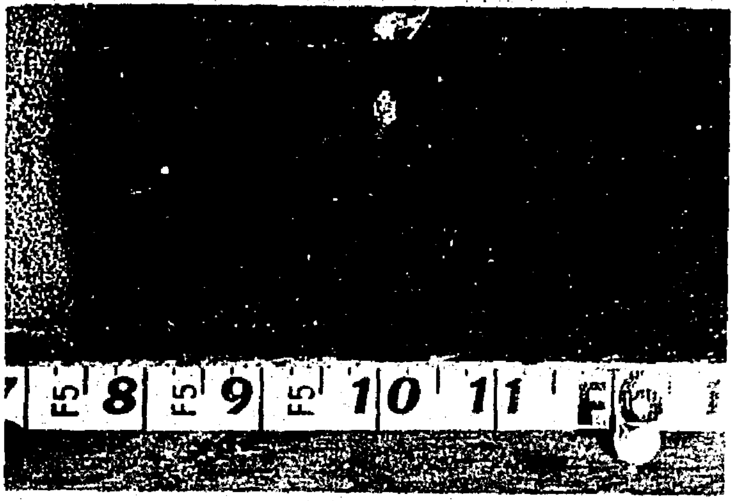

3
2
4
2
5
2
6
2
7
2
8
2

Figure 15. Sharp but conformable contacts between Pleistocene foreshore sands and backbarrier muds (left), Holocene foreshore sands and backbarrier muds (center), and Holocene nearshore sands and backbarrier muds (right). These contacts are the ravinement surface associated with the late Pleistocene (left) and Holocene (center, right) marine transgressions. In the center photograph note the muddy texture and shell debris (mud snails, oysters) of the tidal flat environment.




F5 8 F5 9 F5 10 11

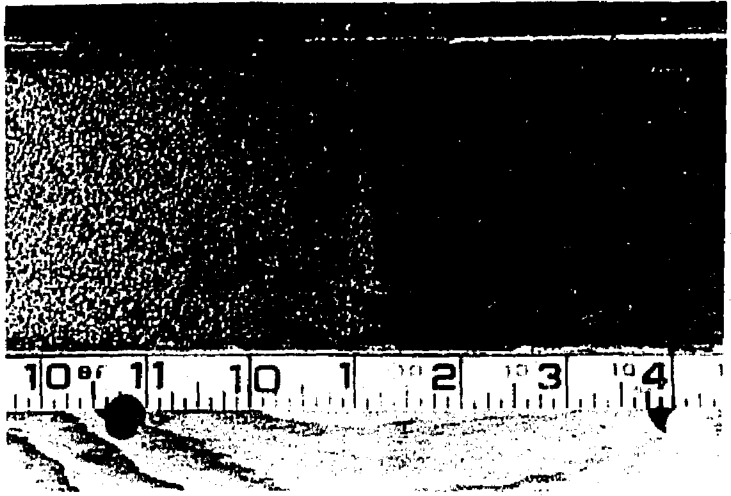
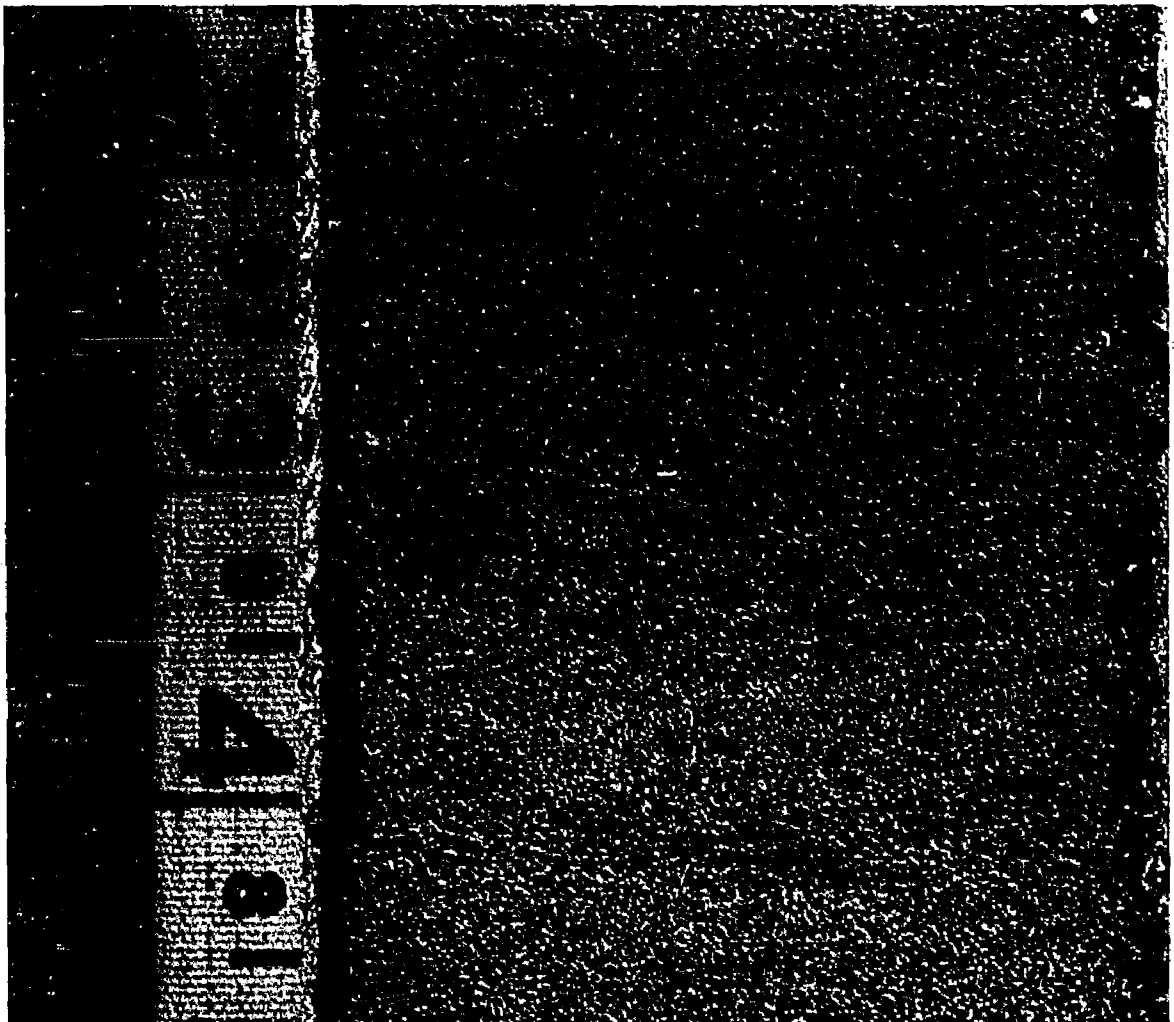

10 11 10 1 2 3 4

Figure 16. Located along the western foreshore of Mockhorn Island, adjacent to Magothy Bay, are tree stumps. These trees were killed due to salt-water inundation from the Holocene rise in sea level. The Holocene erosion of Mockhorn Island may also be recognized from the scarp (at right).

Figure 17. Mainland Pleistocene beach sands found below mainland fringing Holocene pocket beaches and marshes. Note the horizontal heavy mineral bedding.


4
5
6

A beach interpretation is based on a tan to light-grey, fine, well-sorted, and horizontally heavy mineral bedded sand (Cores MC-2 to 4, CL-1, 7-9, Appendix 1). Coarser sands and pebbles are below the beach sands. Ten samples analyzed show a range of means between -0.48 ϕ and 2.60 ϕ with some coarser sands exhibiting standard deviations over 1.50 ϕ (Table 3). The upper sands and locally present pebbles reflect the contact between Holocene sediments. The lower coarser sands penetrated may represent the contact to the lower section of the Wachapreague Formation.

Landward and seaward of Mockhorn Island are subsurface Pleistocene sands that show much more textural variety. These sands are interpreted as the original Pleistocene shoreface of Mockhorn Island, although the former foreshore of an earlier Mockhorn Island that rapidly retrograded or regressive littoral sands deposited with a falling sea after emplacement of Mockhorn Island are other possibilities. Mean grain sizes of individual samples range from 1.08 0 to 3.03 ϕ with a total sample mean of 2.10 ϕ and standard deviation of 0.64 ϕ (Table 3). Physical sedimentary structures include graded and thin planar beds from the coarser and finer deposits, respectively. These sediments lie below Holocene backbarrier deposits. The Pleistocene/Holocene contact is usually gradational (Figure 18). However, a sharp upper contact with a Holocene transgressive lag is found locally (Figure 19). The depth below MSL to the surface of these sands depends upon the amount of erosion since emplacement and depth of original emplacement. The irregular Pleistocene surface seaward of Mockhorn Island is generally seen in

Figure 18. Photomosaic of core 6-7 taken from the backbarrier environment approximately two km seaward of Mockhorn Island. Holocene backbarrier deposits are shown above Pleistocene sands. The contact between the two units, at approximately six meters, is gradational. The Pleistocene sands are fine grained, well sorted, and interpreted as a foreshore or nearshore deposit.

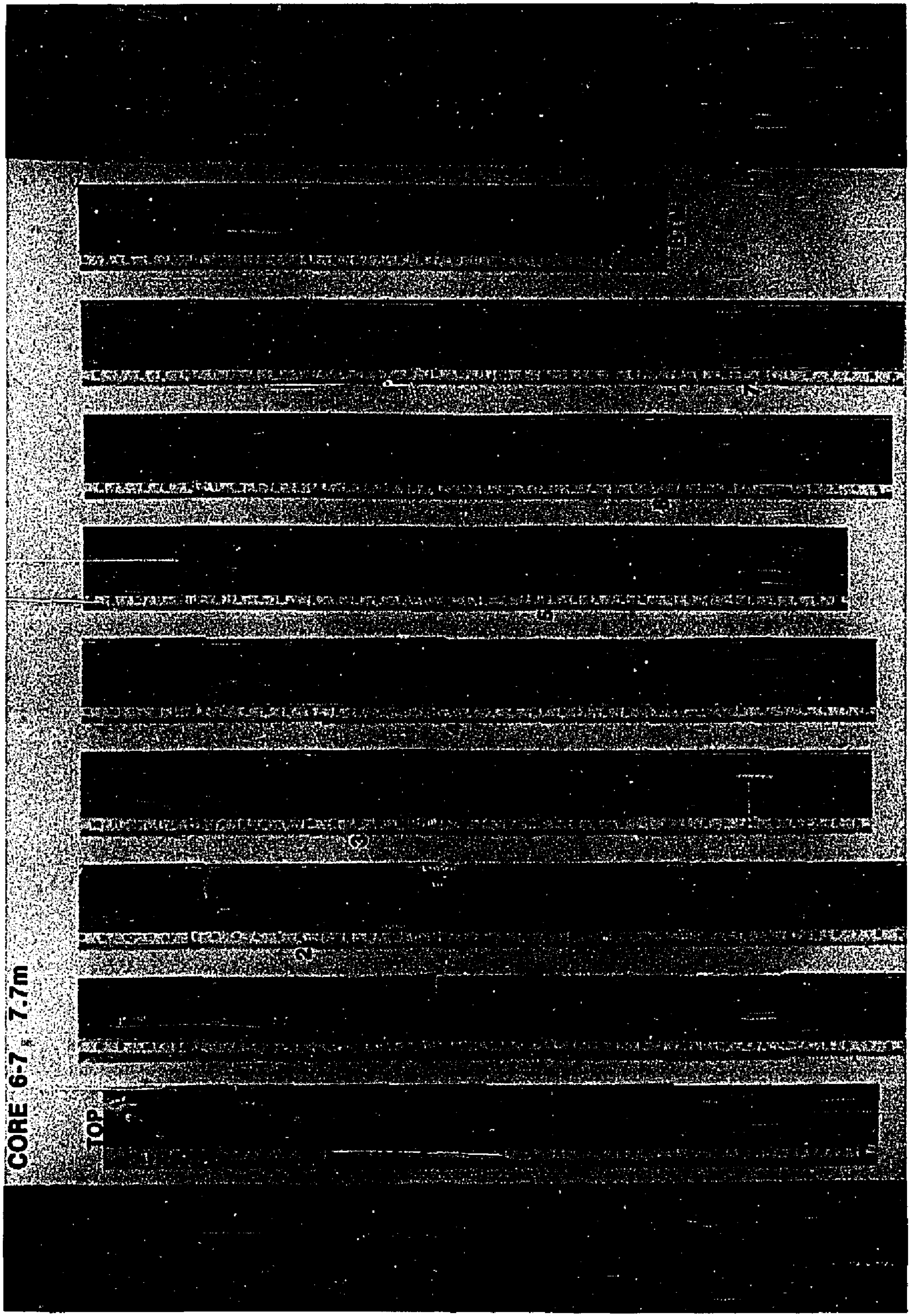
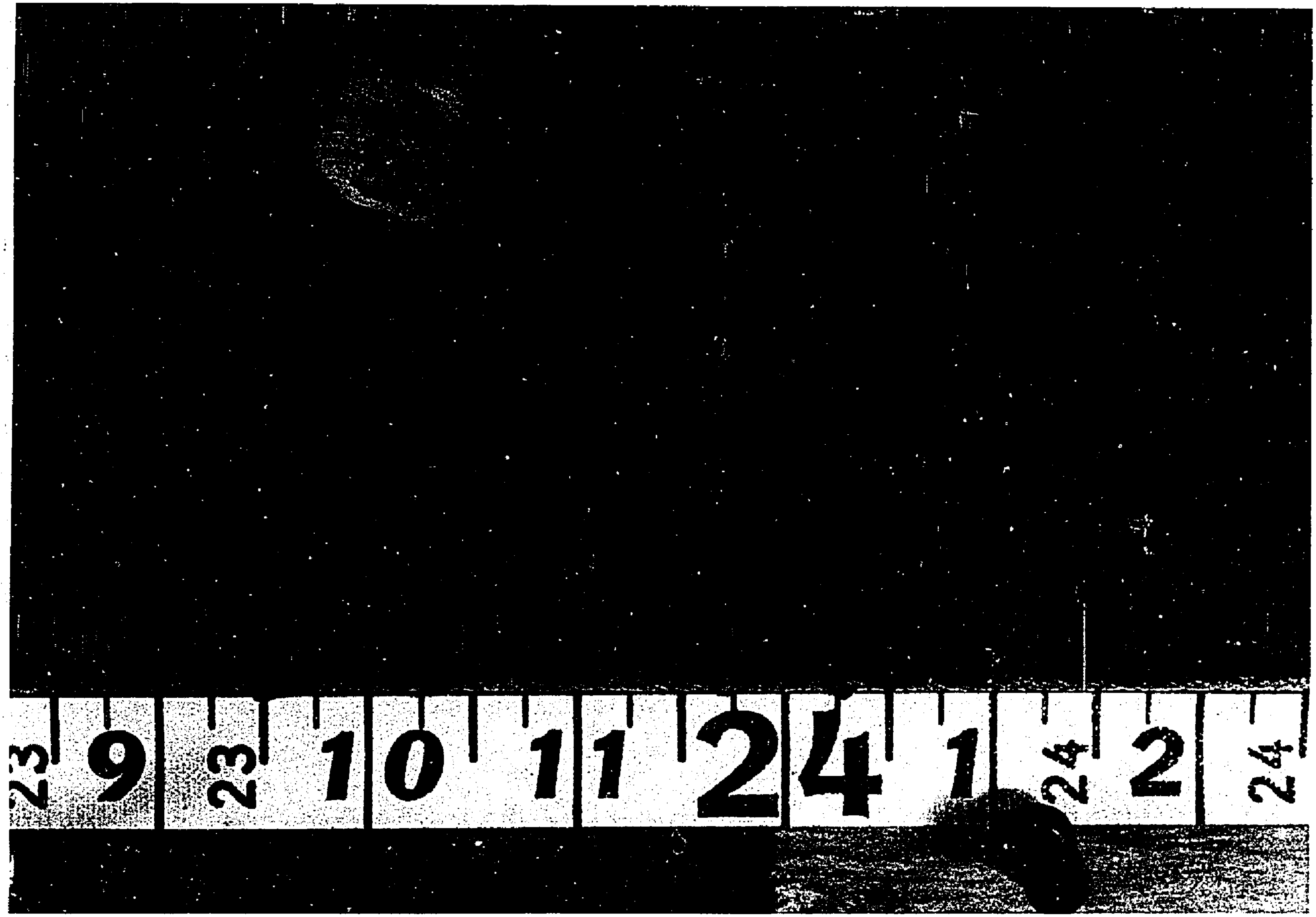

CORE 6-7 7.7m
TOP

Figure 19. Shells and pebbles in core 7-5 are from a transgressive lag deposit. This deposit reflects the initial inundation of the Holocene marine transgression. Pleistocene and Holocene sediments lie below and above the lag, respectively. This sharp contact between Pleistocene and Holocene deposits is not always seen. Often the contact is gradational.


23
9
23
10
11
24
1
24
2
24

the seismic record of Figure 10; this irregularity is included in the cross-sections (introduced later).

Several sand bodies are found in the mud facies below the barrier sands. The stratigraphic position, gradational contacts to the mud, and rooting of these sands indicate a backbarrier shoal origin, possibly a flood tidal delta. Core M-8 (Figure 20) exhibits this environmental interpretation. Planar bedded, medium to fine grained sands ($\bar{X} = 2.50\ \phi$) containing roots at top and overlain by peat first, then lagoonal mud, and finally the barrier sands; below the sand are more lagoonal muds.

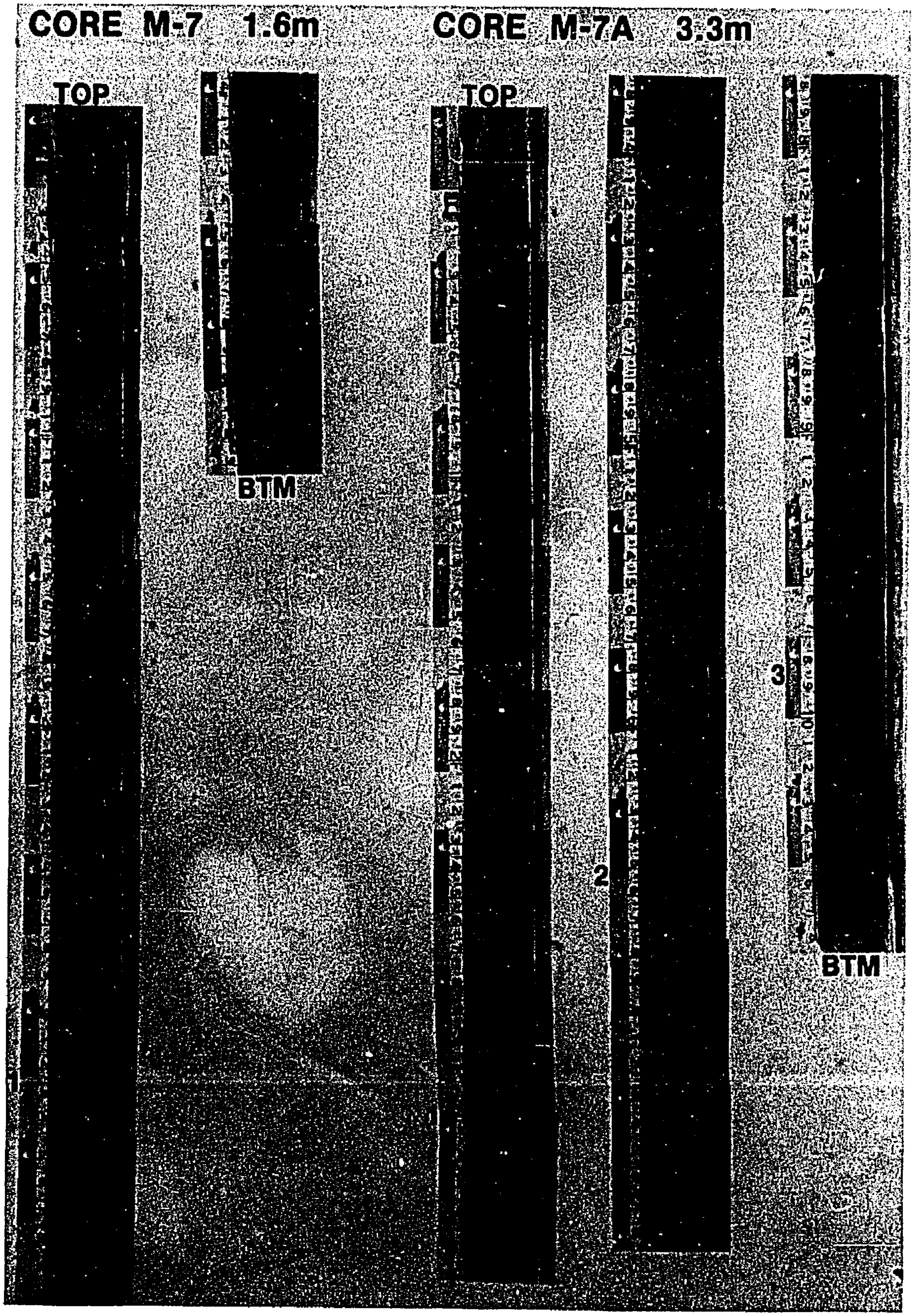
Pleistocene Mud Facies (Lagoon, Marsh)

Fourteen vibracores penetrated the Mockhorn Island barrier sands into a mostly clay-silt deposit (Table 16). This mud is found only below Mockhorn Island and is generally compacted and includes peat and organic-rich horizons (Figures 20, 21). It is at least 2.5 m thick; the lower contact was not penetrated. Sand/silt/clay percentages of seventeen samples vary little and show a respective distribution of 20%/44%/36% with a mean sand fraction of 2.68 ϕ and a mean standard deviation of 0.80 ϕ (Table 3). Two samples taken immediately above interbedded sand bodies are coarser. As mentioned previously, the contact with the Pleistocene sand facies is sharp but conformable (Figure 15). The mud often contains much plant debris and is sometimes mottled, possibly due to oxidation; lenticular sand beds are present locally (Figure 20). Mica appears very abundant in most of

Figure 20. Photomosaic of Pleistocene core M-8 from Mockhorn Island (see Figure 6 for location). The transgressive nature of Mockhorn Island is seen in this core. Beach sands overlie backbarrier deposits that show lenticular bedding, and include interbedded peaty clays, and a fine sand horizon interpreted as a flood tidal delta shoal.


CORE M-8 4.9m
TOP
2
3
4

Figure 21. Photomosaic of Pleistocene cores M-7 and M-7A from Mockhorn Island. The medium sands of Mockhorn Island are shown above backbarrier deposits. Included in the backbarrier deposits are peaty clays (at 250 cm) that have been C-14 dated.


CORE M-7 1.6m
CORE M-7A 3.3m
TOP
BTM
TOP
BTM
1
2
3

this facies, one of two samples analyzed supports this observation (Table 12). Glauconite is also present (Table 12).

Peats are characterized by their brown or black color, stratigraphic position, relatively large amount of organic matter, in one case 37.1 % (Table 4), and the presence of rootlets (Figures 20, 21). Several samples did not meet all of these criteria but contain relatively more organic matter and are brown or black in color; they are called organic-rich muds. Other samples from this mud facies contain between 5 and 10 % organic matter which is comparable to Holocene samples from a similar environment (Table 4).

Few fauna are found within the mud facies. No macrofauna is seen but in three samples both calcareous and agglutinated foraminifers are present (Table 6). Furthermore, unidentified dinoflagellates were found during the pollen extraction. However, no ostracodes were found in the one sample analyzed (Table 7). Most microfossils, if originally present, may have been leached following deposition.

A marginal marine lagoonal environment is interpreted for this facies. This conclusion is based upon the stratigraphic relationship with the sand facies, the textural characteristics of the mud, bedforms, and the few but supportive microfaunal assemblages. Peat and possibly organic-rich muds are believed to be the remnants of marshes.

Peats and organic-rich muds are C-14 dated (Table 14). These dates, and pollen assemblages (discussed later) separated from the muds, support a mid-Wisconsinan marine transgression. A more detailed explanation is presented later.

Holocene Barrier Island Deposits

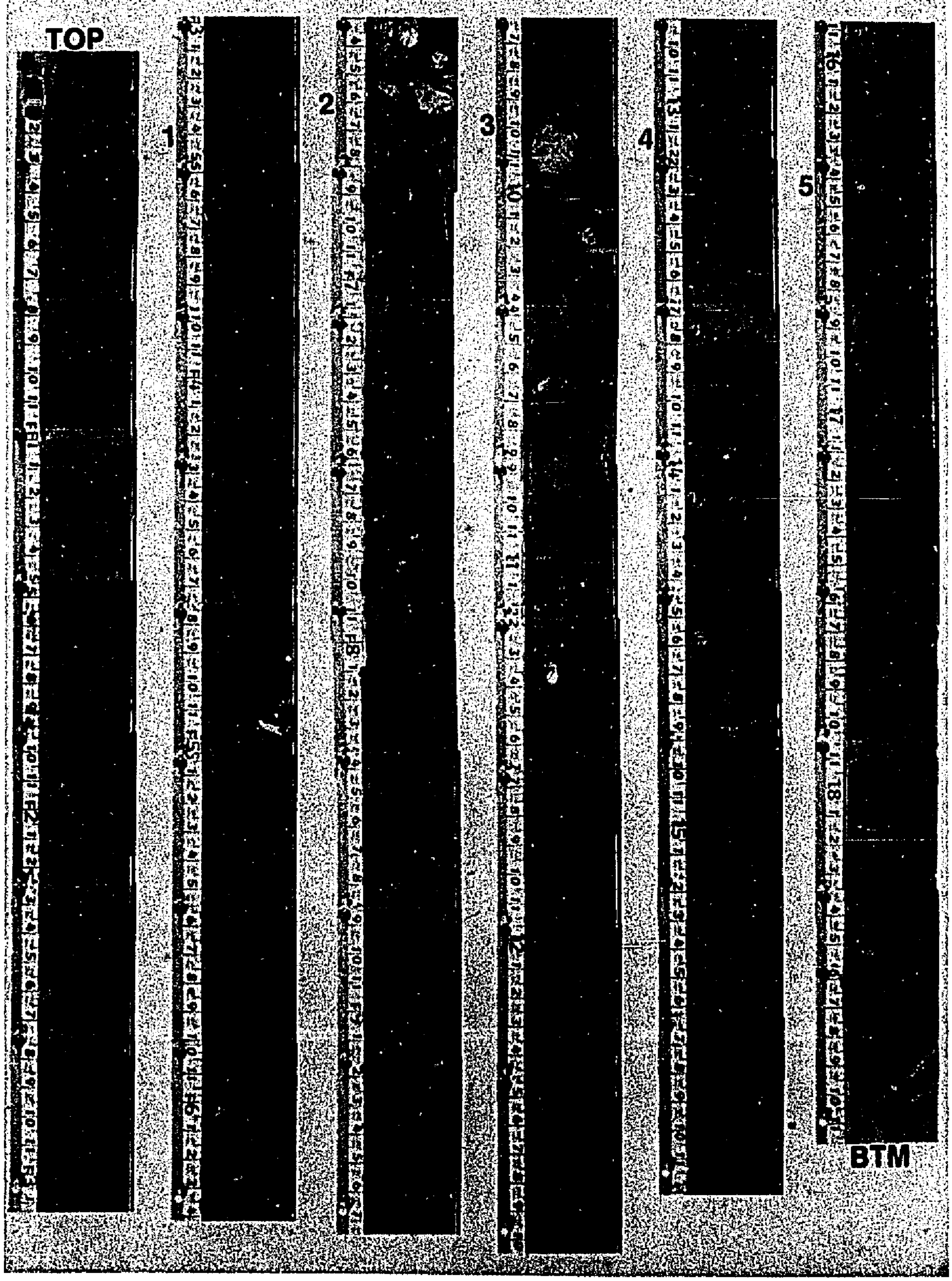
Barrier Depositional Environments

1. Barrier Beach and Washover: Foreshore, backshore and washover fans are grouped together because all are only surficially found on Smith Island and are mostly the product of swash and surf zone processes. This depositional environment is characterized by a texturally and mineralogically uniform, fine grained, well sorted orthoquartzitic sand (Figure 22). Mean grain size/standard deviation of the foreshore and washover sands are 2.30/0.49 ϕ and 2.39/0.53 ϕ, respectively. Upper foreshore and backshore sand thickness is approximately 1.0 to 2.5 m. The thin Holocene barrier island reflects the paucity of available sand. Low-angle to horizontal planar beds dominate the deposit internally. Exhumed backbarrier shells of oysters (*Crassostrea virginica*) and quahogs (*Mercenaria mercenaria*) along with Atlantic surf clams (*Spisula solidissima*), and whelks (*Busycon canaliculatum*) are common on the surface. The contact with the backbarrier muds below the sands is sharp but conformable (Figure 15).

One washover sample indicates relatively abundant calcareous foraminifers collect in this environment (Table 6). A heavy mineral assemblage of dominantly hornblende, garnet, and epidote occurs in the surface samples from Smith Island (Tables 8, 9, and 13). A weight percent of heavy minerals and mica from this environment is approximately 2.0 % (Table 13). Reflecting the high energy of the beach environment, only 1.0 to 2.9 % of the total number of heavy

Figure 22. Photomosaic of core 7-1A from the Smith Island foreshore (see Figure 6 for location). The top 70 cm are fine grained, well sorted, Holocene foreshore sands. Below the sharp contact are bioturbated tidal flat deposits which grade into open lagoon sediments between a range of 350 and 425 cm below MSL.

CORE 7-1A SMITH ISLAND FORESHORE 5.8m



mineral and mica grains is mica (Tables 8 and 13). Glauconite is as common as the most common heavy minerals (Tables 8, 12, and 13).

2. Shoreface: Shoreface sands are found seaward of Smith Island in cores 6A through 6E but the entire depositional environment is only seen in cores 6D and 6E (Figure 23). These cores penetrate a shoreface deposit 0.70 to 0.95 m thick. Sand/silt/clay percentages are 89/07/04 with a mean sand fraction of 2.90 ϕ and mean standard deviation of 0.25 ϕ. A trend of less mud and slightly coarser sand is identified in a landward direction. Sedimentary structures are not abundant but include some planar horizontal heavy mineral beds and a few round burrows. Small shell fragments and mica are locally present. Like the beach sands, the contact to the backbarrier deposits below the shoreface is sharp but conformable (Figure 15), i.e., erosion has taken place but no significant break in time for subsequent deposition has occurred.

Backbarrier Depositional Environments

1. Holocene Salt Marsh: Landward of, and usually beneath, Smith Island are organic-rich muds (Figure 24). Generally 0.5 to 1.0 m thick, they represent the entire accumulation of late Holocene marsh sedimentation. Marshes principally exist as both large and small backbarrier islands locally encroaching upon adjacent tidal flats (Figure 25). Marshes also fringe Mockhorn Island, the landward edge of Smith Island, and along the mainland shoreline west of Magothy Bay.

The marsh environment supports a relatively large assemblage of

Figure 23. Photomosaic of cores 6D and 6E from the nearshore of Smith Island. The fine sands of the nearshore are less than a meter thick. Below these sands are backbarrier muds. The contact is erosional and constitutes a ravinement surface.

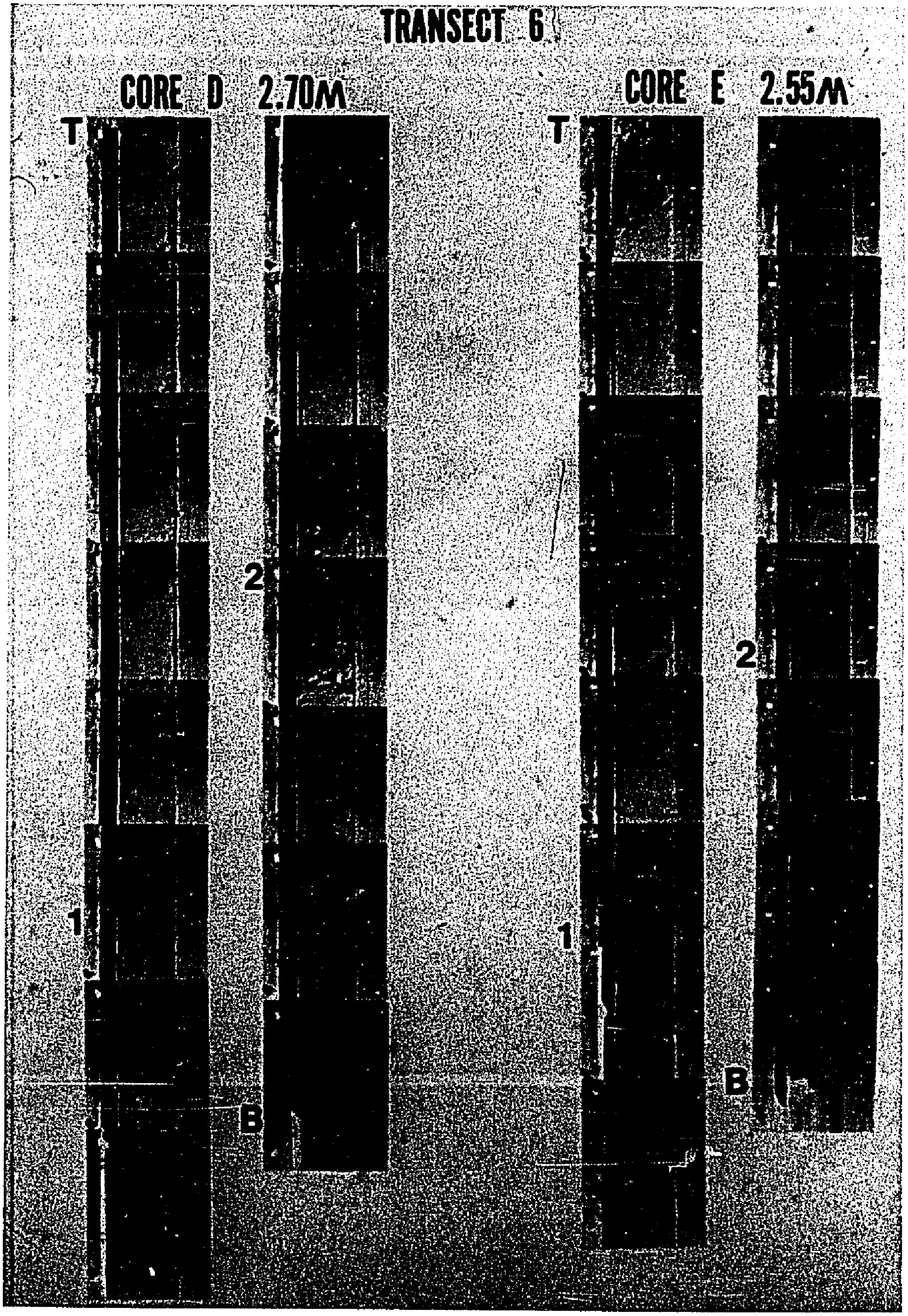

TRANSECT 6
CORE D 2.70M
CORE E 2.55M
T
T
2
2
1
1
B
B

Figure 24. Organic-rich muds, normally found at or near the surface of the backbarrier environment are shown. The vegetation is usually *Spartina alterniflora.*

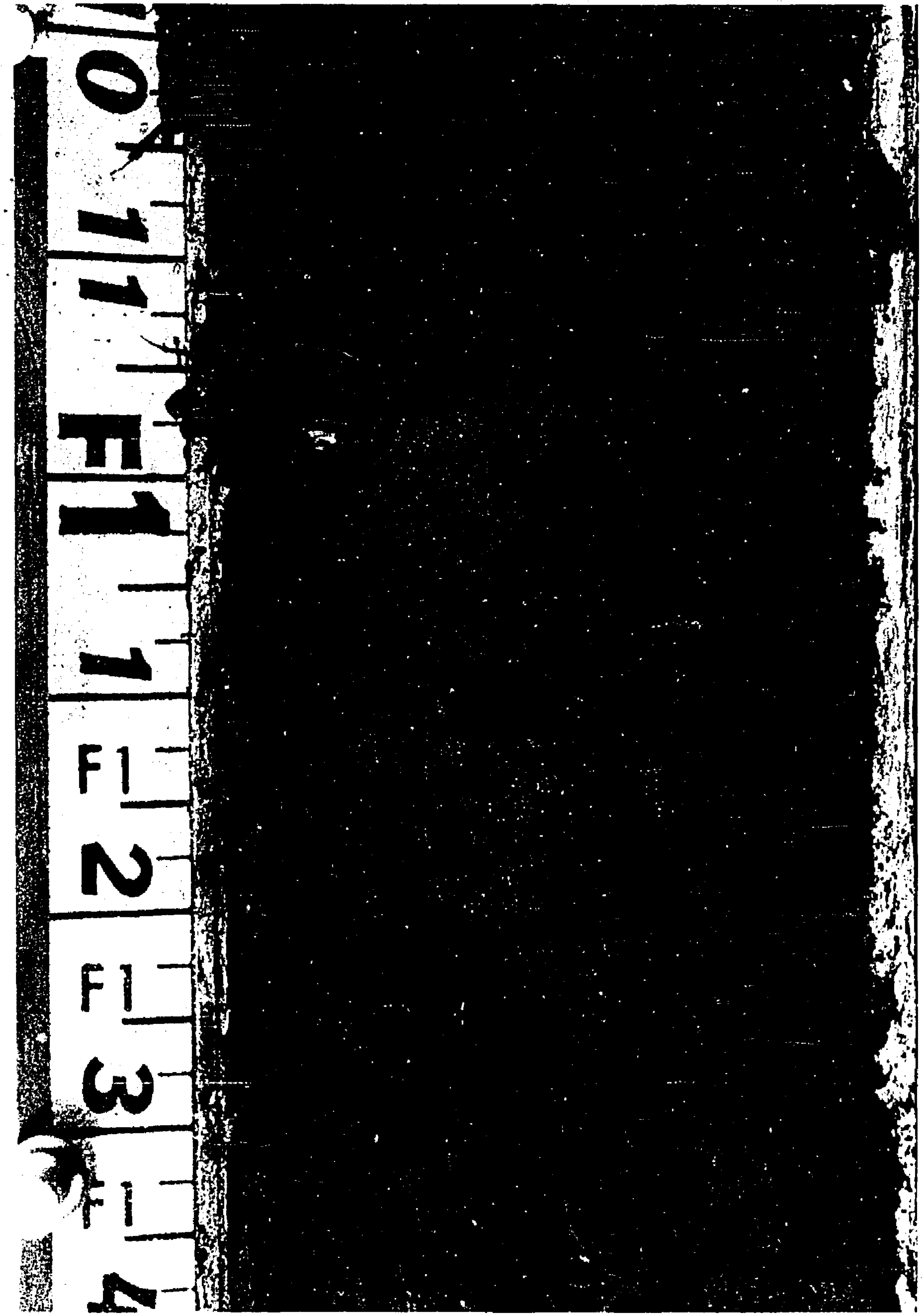
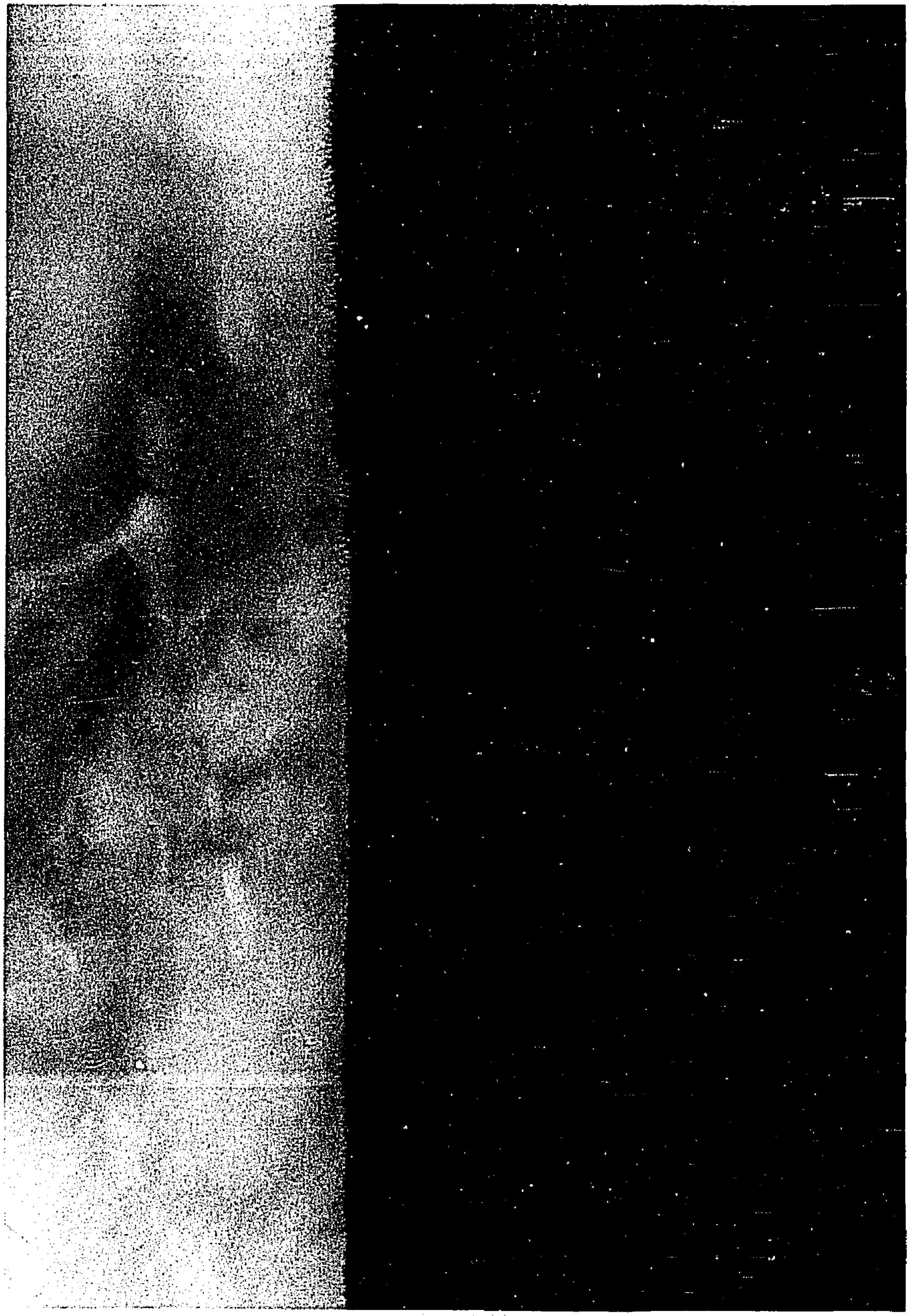

0
1
F1
2
F1
3
4

Figure 25. Holocene salt marshes are shown encroaching upon adjacent muddy tidal flats in the backbarrier environment. The transition from tidal flat to marsh, thus further infilling and restricting the backbarrier region, is demonstrated.

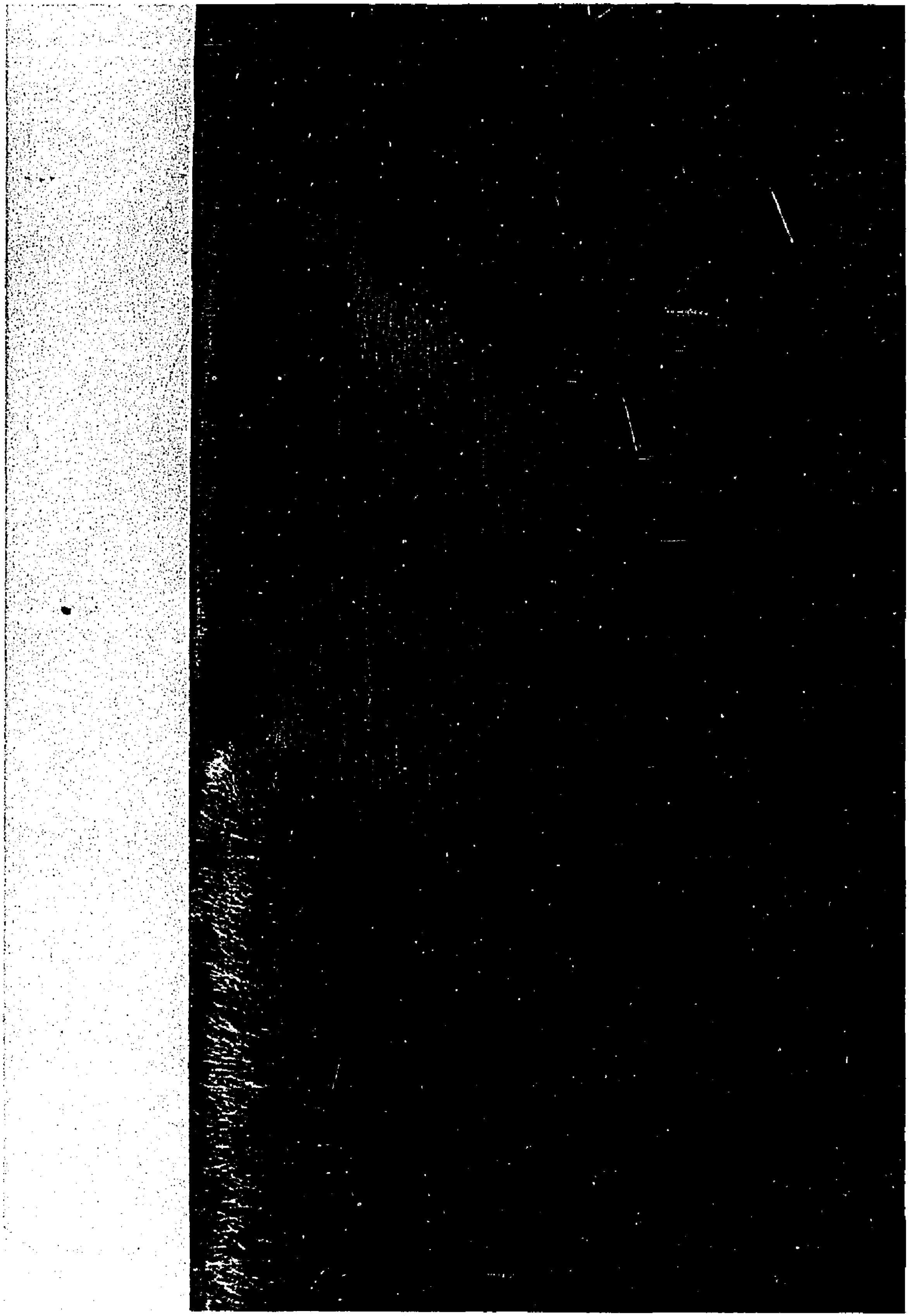


agglutinated foraminifera (Table 6) and is heavily rooted at the surface. A wide range of values for total organic matter by weight are found with some samples over 20% (Table 4). The fraction of organic matter averages 13% in the upper 75 cm but decreases towards the lower gradational contact (Table 4). Grain size measurements on 19 marsh samples were completed; 13 from mostly muddy marsh islands and 6 from sandy marshes that developed atop backbarrier beaches or Pleistocene sands (Table 3). Muddy marsh sediments contain about 27% sand, 55% silt and 18% clay with a mean sand fraction and standard deviation of 2.66 ϕ and 0.85 ϕ, respectively and coarsen adjacent to Smith Island. Sandy marsh deposits have a sand/silt/clay percentage of 75/15/10. The mean sand fraction of 1.65 ϕ and mean standard deviation 0.76 ϕ reflect the Pleistocene sand presence.

Surfaces of the marsh are nearly horizontal with numerous tidal creeks and channels bisecting them. Creek channels usually exhibit a steep, eroding bank and an accreting bank with colonizing *Spartina alterniflora* (Figure 26). Marsh Island biota include the marsh periwinkel (*Littorina irrorata*) and intertidal plants *Spartina alterniflora*, *Salicornia virginica* and less often *Distichlis spicata*. The latter two grow at elevations near mean high water (MHW). Low and high marsh plants are found within the fringing marshes. *Spartina patens* and *Borrichia frutescens* are well established.

2. Tidal Flat: The tidal flat is found usually adjacent to and below the topographically higher marshes. It is a typically intertidal deposit but, in this study, sediments described herein may also be

Figure 26. A backbarrier tidal creek exhibiting a steep eroding bank (right) and an accreting bank with colonizing salt marsh is shown. The creek is apparently migrating to the right (south).



found in the upper subtidal. The upper contact is gradational being characterized by the rooted and finer texture of the marsh sediment. The lower contact is also gradational and most often a coarser grained mixed or sand flat (open lagoon). Thickness of this deposit is as great as 3.0 m but averages around 1.5 to 2.0 m. It is characterized by a muddy texture, much bioturbation, and an abundance of oysters.

Like salt marshes, tidal flats may form over Pleistocene sands, reworking these sands in the process, and thus be coarser than the typically more muddy tidal flats (Table 3). Sandy tidal flats are most common adjacent to Mockhorn Island. The textural distribution of the more common finer-grained tidal flats averages about 40% sand, 40% silt and 20% clay. Sandy tidal flats exhibit a sand/silt/clay percentage of 82/10/8. Mean grain size/standard deviation for the finer and coarser tidal flat deposits are 3.04 0/0.59 ϕ and 1.78 0/0.67 ϕ, respectively.

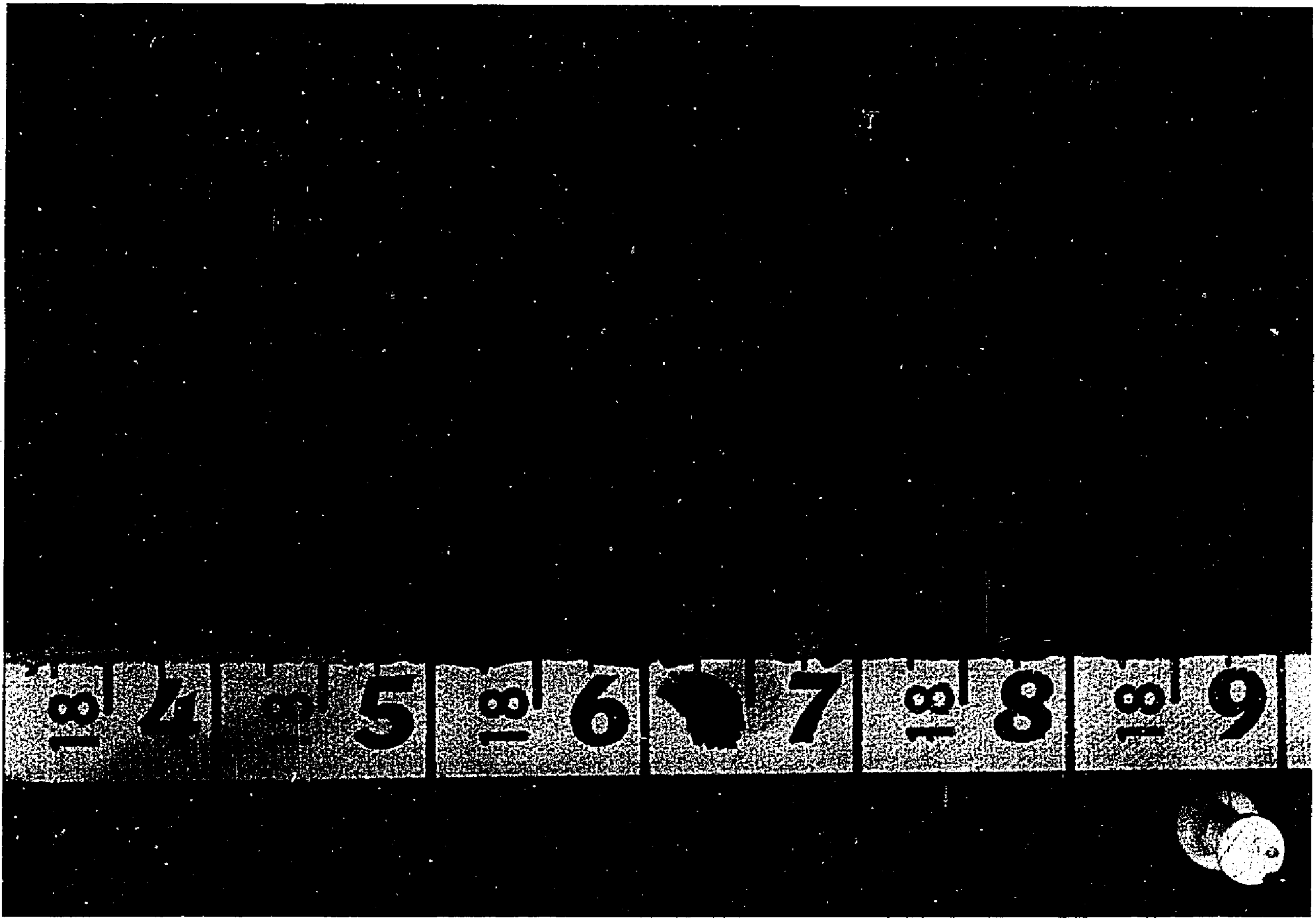
Calcareous foraminifera are common microfossils in the tidal flats (Table 6). Mica make up between 16 and 20 % of the non-silica component of the tidal flat sediment (Table 13) and in one sample equals 4.4 % of the entire 2 to 3 ϕ size fraction (Table 12). Although most heavy minerals are hornblende, garnet, and epidote the suite is less dominant than that found on the barrier beach. Many other heavy minerals show greater percentages (Tables 9 and 13). However, compared to the barrier beach, less heavy minerals are present (Table 13).

The deposit is extensively burrowed, thus physical sedimentary structures are not readily preserved; few are seen even with x-radiographs. Mud snails (*I. obsoleta*) are abundant in the muddy deposits (Figure 15). Oyster shells *(Crassostrea virginica)* in layers up to 2 m thick, but more often 0.3 to 0.5 m thick, are found in cores that penetrated this depositional environment. Similar to those found in South Carolina (Ruby, 1981), oyster bars in Virginia are found in a zone near the marsh-tidal flat contact. These oyster communities measure a few meters across but may be several tens of meters long.

3. Open (High Energy) Lagoon: This environment is best characterized by 1) muddy sands dominated by physical sedimentary structures such as flaser, wavy, lenticular and coarsely and thinly interlayered sand-mud bedding (Figure 27) or 2) a fine to very fine grained slightly bioturbated sand (Table 15). The fine sand member often grades into overtopping muddy sands. Bedding results from an interplay of high current velocity bedload transport of sand and low current or slack water deposition of suspended sediment. The sediment fines upwards with increasing bioturbation. Sediments from this environment usually range from 1.0 to 5.0 m thick and average about 2.5 m. Characteristics of grain size, sedimentary structures and species diversity described herein provide evidence for deposition in a relatively high energy backbarrier environment.

Textural analyses of muddy sand samples taken perpendicular to bedding planes indicate a composition of approximately 70% sand-size material, 20% silt and 10% clay. A mean grain size/standard deviation of the sand fraction from 15 samples are $2.85\ \phi/0.53\ \phi$.

Figure 27. Open (high energy) lagoonal sediments exhibiting lenticular and thinly interlayered sand-mud bedding are shown.


18 4
18 5
18 6
7
18 8
18 9

The fine sand member of this deposit often appears as a sand flat, containing little if any mud, and has a mean grain size of 2.88 0 and a standard deviation of 0.43 ϕ (7 samples). The grain size of these sands are similar to Smith rather than Mockhorn Island and thereby indicate a Holocene source. Magothy Bay is a modern open lagoon environment with a much coarser mean grain size of 1.74 ϕ (5 samples) (Table 3) from reworking of Mockhorn Island sands.

Similarly other researchers have described open or high energy lagoons. The high-energy lagoon of Ruby (1981) is much like the environment characterized above. On Virginia's Eastern Shore Coastal Plain, Mixon and Powers (1985) describe a massive to faintly crossbedded, slightly clayey and silty sand that may represent deposition in an open bay. The description of the muddy sand member is similar to the mixed flat deposit of Reineck and Singh (1980). They define mixed flats as those zones where sediments are deposited in transition between muddy intertidal flats near the high waterline and sandy intertidal flats near the low waterline. Similar sedimentary structures and sediment type may also be found in the subtidal environment (Reineck and Singh 1980, Figure 512). Therefore the exact location of this deposit with respect to sea level is not well defined. However, boxcores taken in 90 to 150 cm (MSL) of water in a moderately open backbarrier environment just seaward of the southern tip of Mockhorn Island (Figure 2) penetrated sediments described above (Table 2). Thus the open lagoon, of this study, is not intertidal but reflects a shallow subtidal environment. Sediments from the open lagoon depositional environment, so common at depth, probably aggraded in a vast subtidal zone at higher energy levels. Included in this depositional environment are those sediments deposited as active channel fill.

Except for the dwarf clam (*Mulinia lateralis*), few organisms are found in the fine sand member. These sands are also barren of foraminifers; probably a reflection of either high wave or current energy. Oyster shells are found locally in the muddy sand member. Calcareous foraminifers and ostracodes are also present there (Tables 6 and 7). Organic matter ranges from 3 to 8 % and 1 to 2 % for the muddy sand and fine sand members, respectively. Heavy minerals are not very abundant (Table 13), of those present, the hornblende/ garnet/epidote assemblage is most common (Tables 8 and 12). The muddy sands contain much chlorite while the fine sands are enriched in staurolite (Tables 9 and 13). Mica and glauconite are present (Table 12), the former in lesser numbers than other backbarrier deposits due to the higher wave and tidal current energy.

4. Sheltered (Low Energy) Lagoon: A subaqueous mostly muddy deposit from a sheltered lagoon environment is recognized in the Holocene stratigraphic section. The sediment is generally massive, moderately bioturbated and fine grained with an average sand/ silt/clay percent of 20, 48 and 32, respectively. The sand fraction is often too small to analyze with the rapid sediment analyzer (Table 3). Some sand laminae and shell material are recognized with X-radiographs. Plant remains, both as large solitary pieces and allochthonous plant detritus on bedding planes, are common. Calcareous foraminifers

(Table 6), two species of ostracodes (Table 7), glauconite, and mica (Table 12) are present. The majority of this deposit is believed to be deposited from suspension. Flow velocities are, in most cases, probably not great enough to produce bedforms. Sand stringers are interpreted to have been deposited during storm events.

Sediment of this type is not present in all cores but can be as great as 3.0 m thick. It may accumulate as inactive channel fill or in sheltered backbarrier bays. Locally, this deposit is present at the basal Holocene, probably in topographic lows of the Pleistocene surface.

5. Transgressive Lag: The transgressive lag is a deposit that forms on an erosional surface and is the product of a marine transgression. Transgressive lag deposits are described by Swift (1975, 1976) as the product of shoreline retreat along retrograding coastlines (Moslow, 1980). In addition, rising lagoonal waters inundate pre-Holocene features and may cause deposition of a surficial sand and/or shell lag landward of the Holocene barrier island. Therefore, transgressive lag deposits are discontinuous but should be present locally between pre-Holocene and backbarrier Holocene deposits.

Transgressive lag deposits are 0.2 to 0.5 m thick and are best preserved in cores of transect B-B′ (Figure 6, Appendix 1). They are mostly coarse sand to gravel (Table 3); shell material is also present in the lag of core 7-5 (Figure 19). This shell material is not in place and thus is not a reliable material for carbon-14 dating.

6. Backbarrier Beach: Backbarrier sand beaches are located as part of the eastern or western (mainland) shore of Magothy Bay (Figure 2). The former are mostly found in the northern part of the study area where Mockhorn Island is separated from Magothy Bay by Holocene marsh. These beaches rest upon the Holocene marsh and are apparently migrating east toward Mockhorn Island in response to sea-level rise. Backbarrier beaches fringing the mainland are about 0.5 m thick and rest upon either Holocene tidal flat sediments approximately 1.5 m thick or an older soil horizon; below this are Pleistocene sands (e.g. core 6-6, Appendix I).

Sedimentary structures are rare in beaches on the eastern shore of Magothy Bay. Mainland backbarrier beaches sometimes exhibit horizontal planar bedding, however, marsh growth usually disturbs this. Microfauna and heavy minerals assemblages are not included because few samples have been analyzed. Half shells of mollusks are found on the surface.

Backbarrier beaches on the mainland side of large backbarrier bays have previously been identified by Kraft (1971). Backbarrier beaches from this study are composed primarily of reworked Pleistocene sands with an average grain size and standard deviation of 1.50 ϕ and 0.69 ϕ, respectively (5 samples) (Table 3). Marshes are growing aside, and, in some places, encroaching upon the backbarrier beaches.

Summary

The stratigraphic sequence of sedimentary units from bottom (oldest) to top (youngest) are the Yorktown Formation, the lower unit of the Wachapreague Formation, latest Pleistocene barrier island deposits of the Mockhorn formation, and Holocene barrier island deposits. The latter two units are sampled in this study. From the descriptions given above, distinct facies and depositional environments are interpreted from these two units. The stratigraphic position of these deposits is shown in Figure 9 and described in Table 15.

Depending upon the locality, the Holocene barrier deposits are generally capped either by shoreface over backbarrier deposits, barrier beach over marsh, or marsh over tidal flat. Below these deposits backbarrier sediments usually coarsen downward as the environment becomes more active. An exception are sheltered (low energy) lagoonal deposits formed in inactive channels, sheltered backbarrier bays, or topographic lows of the Pleistocene surface. The contact between Holocene and, stratigraphically lower, latest Pleistocene deposits (Mockhorn formation) may be marked by a distinctive transgressive lag but in most places the contact is subtle. For example, mainland Holocene beach and marsh grade into Pleistocene sands. Some reworked Pleistocene pebbles are found with the lower Holocene sediments and help distinguish the contact. The latest Pleistocene deposits are best recognized on and below Mockhorn Island. These deposits are interpreted as barrier beach over lagoon.

Away from Mockhorn Island, latest Pleistocene sands are buried by Holocene backbarrier sediments.

RESULTS OF SAMPLE ANALYSES

Microfauna and Microflora

Foraminifera

Specific foraminifers are indicative of the environment of deposition. The foraminiferal species occurring in barrier and backbarrier core samples are listed in Table 5. The species present and the relatively low species diversity are characteristic of a marginal marine environment. They are thus consistent with the environment in which they are found. There are no exotic or extinct species which might serve as natural tracers. This suggests that most of the backbarrier sediments penetrated by the cores were probably deposited under relatively uniform environmental conditions.

Two distinct assemblages are present. The most common is the calcareous assemblage which occurs in subaqueous fine sands and sandy muds. The other is an agglutinated assemblage which is characteristic of a lower salinity. The latter assemblage is found in only several samples, almost all of which are from surface or near surface marsh sediments (Table 6). Most Pleistocene sediments, and open lagoon Holocene sediments that are particularly sandy, contain no foraminifera. This is attributed to: 1) the depositional environment being unsuitable for adaptation or 2) destruction of the tests by leaching.

Three Pleistocene sand samples from Mockhorn Island and three from the underlying mud facies contain mostly calcareous foraminifera (Table 6). However, the foraminifers found in the sand samples may be from subsequent Holocene overwash. Despite the limited frequency of occurrence, the number and type of foraminifers in the Pleistocene muds (*Elphidium* sp.) are much like those found in Holocene backbarrier sediments. In addition, several cores (e.g., M-8) contain abundant dinoflagellate cysts that also portray marginal marine conditions. The similar foraminifers along with similarities in lithology and stratigraphic sequence indicate analogous environments of deposition, i.e, backbarrier.

Ostracodes

Ostracodes are also useful for characterizing depositional environments. However, only four samples were analyzed for abundance and identification and one, a Pleistocene sample, contained no ostracodes (Table 7). The other three samples are from core 6-1. Samples from 300 cm and 745 cm contain sparse assemblages; the former indicative of estuarine lagoonal environments, the latter possibly slightly more marine. The shallower sample is dominated by *Cyprideis mexicana*, a species indicative of brackish water lagoonal/tidal flat environments. Based on the lithology, these two samples are from tidal flat and sheltered lagoon environments, respectively. Thus the ostracodes found are consistent with the suggested environments of deposition.

The sample from 400 cm yielded a diverse assemblage that includes backbarrier and shallow marine species. This signifies a transitional region between lagoonal and inner sublittoral environments where death assemblages such as these commonly occur. An open lagoon depositional environment is interpreted for this sample. It's characterization as a more open, unrestricted, and subtidal environment is supported by the ostracodes of this sample.

Two relatively cryophilic, mild temperate species, *Bensonocythere mexicana* and *Loxoconcha sperata*, signify summer weather temperatures no higher than 25^{0}C , whereas more thermophilic species, *Cytherura forulata*, *Proteoconcha nelsonensis*, *Loxoconcha matagordensis*, *Leptocythere nikraveshae* indicate winter water temperatures above 5.0 to 7.5^{0}C. This temperature regime is quite similar to the local modern interglacial situation and indicates that modern average climatic temperatures had appeared by the time these sediments were deposited.

Pollen

Pollen assemblages provide climatic information from Pleistocene backbarrier sediments associated with Mockhorn Island. Pollen analysis of C-14 dated mid-Wisconsinan peaty clays and stratigraphically adjacent muddy samples are dominated by *Pinus* (25-50%), *Picea* (2-26%), Gramineae (4-34%), *Alnus* (1.5-6%), and *Betula* (trace-5%) (Figure 8). Among other major arboreal and nonarboreal taxa are *Quercus* (2-8%), Cyperaceae (2-12%), and Compositae (2-8%). *Sphagnum* dominates the wetland and aquatic taxa of most samples.

Close matches for those pollen assemblages from published modern surface spectra are not available. The closest analogues are from the mixed coniferous-hardwood forests of Michigan, Minnesota, and New England (Whitehead, 1981). However, the percentage of Picea in many samples (e.g., 6-5, M-8) (Figure 8) exceeds those of modern surface sampling from these areas. Whitehead (1981) notes that the lack of modern analogues probably reflects inadequate sampling of modern vegetation associations. Nevertheless, the possibility exists that comparable environments (i.e., large areas south of ice margins) to these assemblages no longer occur.

Correlatives of these assemblages among other mid-Wisconsinan fossil flora from the Middle Atlantic region are more clear. The closest affinities are from dated peaty sands of the Parsonburg Formation of the central Delmarva Peninsula (Sirkin et al., 1977). These spectra contain comparable percentages of Picea, Pinus, Betula, and Sphagnum. Mid-Wisconsinan spectra reported by Whitehead (1981) for Rockyhock Bay, North Carolina, are also very similar in the types and percentages represented. In addition, the undated upper section of the Wachapreague Formation shows a similar assemblage.

Size measurements of spruce and pine grains (Birks and Peglar, 1980) and indicator pollen taxa suggest the regional vegetation of the Mockhorn area between ca. 34,000 - 23,000 years B.P. appears to have been mainly a boreal assemblage represented by both white spruce (Picea glauca) and black spruce (Picea mariana), jack pine (Pinus banksiana), fir, with an understory of ericads, composites, dwarf birch (Betula cf. glandulosa), and such northern herbs as Thalictrum and Lycopodium annotium. However, while climatic conditions were probably cool and moist, the presence of a significant deciduous element (e.g., Quercus) in the arboreal spectra, suggests a more interstadial, rather than full-glacial, character to the regional climate. Whitehead (1981) has suggested that the chronologically-equivalent pollen assemblage zone from Rockyhock Bay, North Carolina, record an average temperature about 10^0 lower than present.

Extensive freshwater bogs and marshes dominated by Sphagnum and sedges and perhaps fringed by ericads, alder, and other shrubs appear to have characterized mica of the area prior to about 29,000 years B.P. Locally, emergent aquatics such Potamogeton and Typha also occurred. After ca. 29,000 years B.P., the decline of these taxa in stratigraphically younger backbarrier samples in several cores (e.g., M-8, 6-5), and the rise of Gramineae imply replacement of these bogs and fresh marshes by grassy (probably Spartina spp.), higher salinity marshes. This shift to higher salinity conditions is corroborated by the simultaneous appearance in these samples of dinoflagellate cysts. Although dinoflagellates are not strictly marine in occurrence, their presence in pollen samples from modern fresh and low brackish marshes of the nearby Chesapeake Bay is rare (M.S. Kearney, written communication).

Mineralogy

Possible variations in source and transport properties of sediment from the barrier island complex may be examined using mineralogical analyses. In addition, the environment of deposition, in some cases, may be better defined. For example, well rounded heavy minerals from Mockhorn Island beach sands indicate a wave dominated environment.

Smith Island barrier beach sands exhibit a primary hornblende/garnet/epidote assemblage of heavy minerals (Tables 8, 13). Frequency differences in the barrier samples are very likely related to transport and depositional factors. Multiple samples show that relatively large changes in distribution of mineral species can occur in samples a few meters apart. As expected, heavy minerals are relatively abundant in the barrier beach environment and coexist with quartz grains of similar size (Table 13).

Creek and backbarrier samples show a mostly similar dominant mineral assemblage (Tables 9, 10, 13). The weight percentages of heavy minerals from creeks are much greater then in beach or backbarrier environments. Garnet is especially large. Apparently, few of these minerals are deposited in the backbarrier region as samples in this environment show a low frequency of heavy minerals; garnet is also reduced. Chlorite, however is relatively abundant.

Differences in heavy mineral frequencies from backbarrier samples are found between the very fine to fine sands and the fine, medium and coarse sands (Table 9). The generally higher hornblende and lower garnet content of the finer grained samples is probably related to the lower energy transport conditions in this environment and not necessarily to source differences.

The primary heavy minerals are ubiquitous in all samples. No sudden appearances of a mineral with a high frequency or disappearance of hornblende, garnet, or epidote was seen. To determine if heavy mineral frequencies are controlled by the environment of deposition or a change in source area, Johnston (1985) analyzed samples from cores 7-1A and 9-1A (Table 13) using contingency tables based on chi square distribution. Heavy mineral frequencies were found independent of location. This supports an interpretation that these frequencies are controlled by the environment of deposition and not a change in source area.

Glauconite pellets are rare or missing in creeks draining the mainland (Table 11). It is relatively abundant on Smith Island and in the backbarrier sediments (Tables 8, 12). These pellets are similar to quartz in specific gravity and are thus apt to be transported with quartz grains of equivalent size. It is unlikely that the bulk of the glauconite in barrier and backbarrier deposits are derived from erosion of the mainland surficial deposits. The most likely source are offshore sediments either carried southward along the Delmarva coast or drifted shoreward from shelf deposits.

Mica is indicative of low energy conditions and is found primarily in the backbarrier sediments (Tables 8, 12). Mica is very easily transported and its absence in fine to medium sands from the barrier beach and some open lagoons (Tables 8, 12) may be attributed to hydraulic factors. However, seaward draining creeks from the mainland have fine grained beds but do not contain very much mica (Table 11). The source of mica must therefore be from reworked Pleistocene sediments from the Mockhorn Island barrier (Table 12) and offshore.

Sediment Size

Most environments of deposition are characterized by specific textural parameters. However, the pre-existing topography and sediment type may dictate the grain size of a specific environment. For example, Holocene marsh and tidal flat deposits are characterized by a dominance of mud over sand except where these deposits lie above sandy environments (Table 3).

Pleistocene and Holocene sand deposits often can be distinguished by their mean grain size. Smith Island beach sands are approximately 2.30 ϕ and the associated washover sands slightly finer (Table 3). Backbarrier beaches and the Pleistocene barrier are composed of medium grained sands that are about one half phi size larger. Sand fractions from Holocene backbarrier environments are generally in the fine sand range except when adjacent to the coarser sands mentioned above.

Backbarrier environments generally exhibit a fining upward trend. Sandy open lagoon deposits grade into mixed sand and mud tidal flats and are capped by mostly muddy marshes. A finer grained sheltered lagoon deposit is included in some cores but is interpreted as a locally encountered environment.

Based upon grain size measurements, mainland shore sediments (cores 6-6, 7-9, 8-7, 9-6, C1-1) are more difficult to characterize. Most samples are relatively coarse grained (Table 3). Some deposits are interpreted as Pleistocene environments (Pleistocene sand facies, and some as Holocene environments (marsh, backbarrier beach) that contain recently reworked Pleistocene sediments.

Percent Total Organic Matter

The percentage of organic matter from core samples was measured to 1) determine trends in deposition of Holocene organic matter and 2) compare Pleistocene and Holocene environments believed to be analogous. As expected samples with noticeable organic matter show high percentages (Table 4). Twenty-three muddy Holocene samples incorporated with marsh vegetation contain an average of 12.3 % organic carbon. The percentage is greater near the surface and lessens as marsh vegetation becomes less abundant with depth. This data indicates marshes are more abundant today then in the past or organic matter is consumed by oxidation with time.

Multiple samples from Holocene cores show a trend of less organic matter with depth (Table 4) (Figure 28). This pattern parallels the fining upward sequence seen in many cases. Very little organic matter is present in deeper samples from environments that are composed of mostly fine sand.

The Pleistocene mud facies is compared to the Holocene backbarrier environments to help recognize any differences or

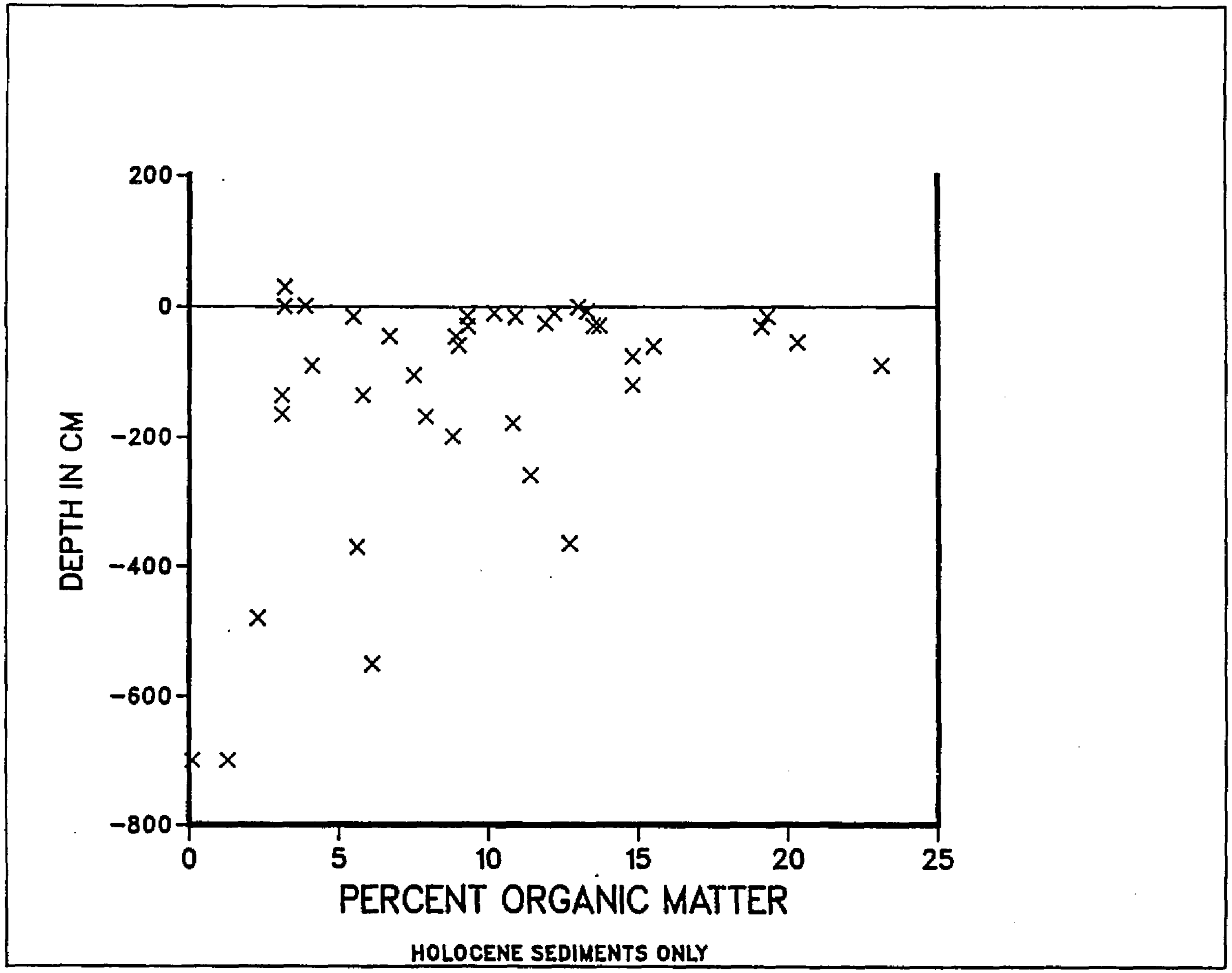


Figure 28. The percentage of organic matter by depth is shown above. As expected, a trend of more organic matter closer to the surface is observed.

similarities between the two. The following indicates a mostly similar percentage of total organic matter and thus a possibly analogous depositional environment. Pleistocene and Holocene muds contain 7.4 and 8.2 % organic carbon, respectively. Three Pleistocene samples of mud and macroscopic vegetation contain an average of 10.3 % organic matter; a percentage much like that found above from Holocene samples of similar composition. Six samples of peaty clay from the Pleistocene mud facies are believed to be compacted salt marsh and range from 37.1 to 7.0 % organic carbon. Under the microscope these samples exhibit a dense mass of vegetation.

Radiocarbon Age Dating

Two groups of C-14 dates are recognized in Table 14. They are categorized by age and include 1) 10 Pleistocene dates from eight samples and 2) 16 Holocene dates. Pleistocene dates range in age from 23,340 to 33,940 years B.P. (Table 14). The materials dated are organic-rich sediments, most of which are considered peats, from the Pleistocene mud facies located below Mockhorn Island. They are from a marsh or shallow lagoonal environment and thus indicate the approximate position of sea level. These dates are taken from samples found in eight cores that trend north-south for approximately 4.5 km. Sample depth ranges from 4.55 to 2.50 m below MSL.

All of the Pleistocene dates are mid-Wisconsinan in age and, as such, approach the limit of the Carbon-14 method. As previously described by other researchers, dates of this age have been called contaminated or isotopically dead. However, the number of dates, their relatively close proximity both laterally and vertically, and their presence in one deposit lends support for their credibility.

The error bars of replicate samples do not overlap (Table 14). In addition, there is an approximate 10,600 year range between the oldest and youngest dates. These facts give reason for closer scrutiny of the dates. However, isotopically old organic materials, such as these, date imprecisely because of minor age differences within the dated horizons (M. Tamers, Beta Analytic, Inc., personal communication). The dates point to a deposit much older than Holocene and much younger than Sangamonian. A mid-Wisconsinan sea level near today's position is shown on an abridged late Quaternary sea-level curve in Figure 29. Rather than an exact date for the highstand, Figure 29 illustrates a 10,600 year time span during which relative sea level rose to near-present levels once.

Many of the Holocene dates are from marsh grasses and oyster shells. These materials may be used as sea-level indicators as they are found in the intertidal and shallow subtidal, respectively. These dates are included in the sea-level curve of Finkelstein and Ferland (in press) for the Virginia barrier island system (Figure 30). Little new sea-level information for the Holocene is provided by these dates as the dated materials are all young and mostly from relatively shallow depths. Some of these materials may have undergone post-depositional displacement. For example, an older marsh sediment sample is found stratigraphically above a younger shell in core 7-1 (Table 14). The shell is believed to be in place; similar ages and

Figure 29. A proposed late Quaternary sea-level curve from approximately 40,000 years B.P. to the present is shown. Note the proposed sea-level highstand at about 28,000 years B.P.

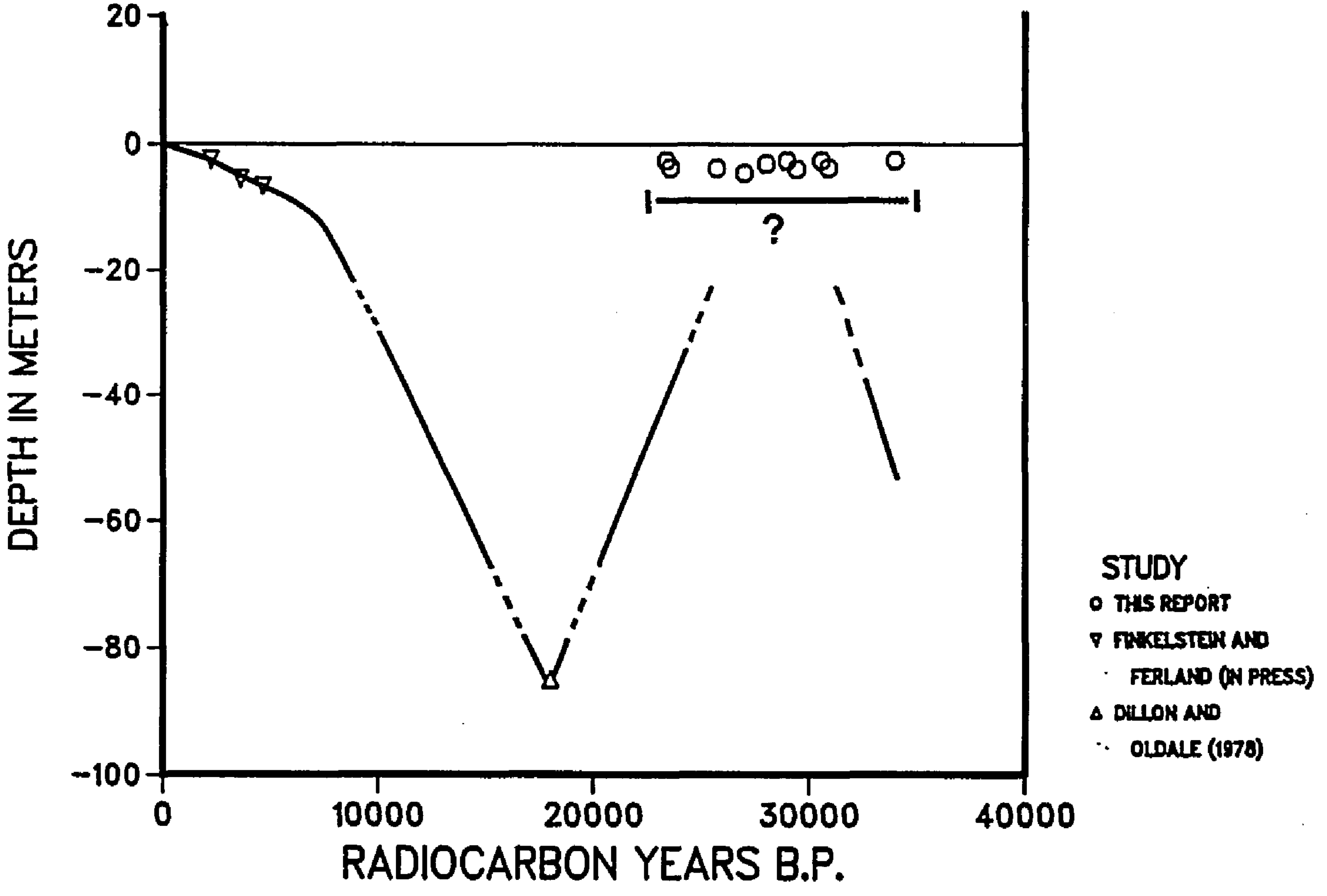
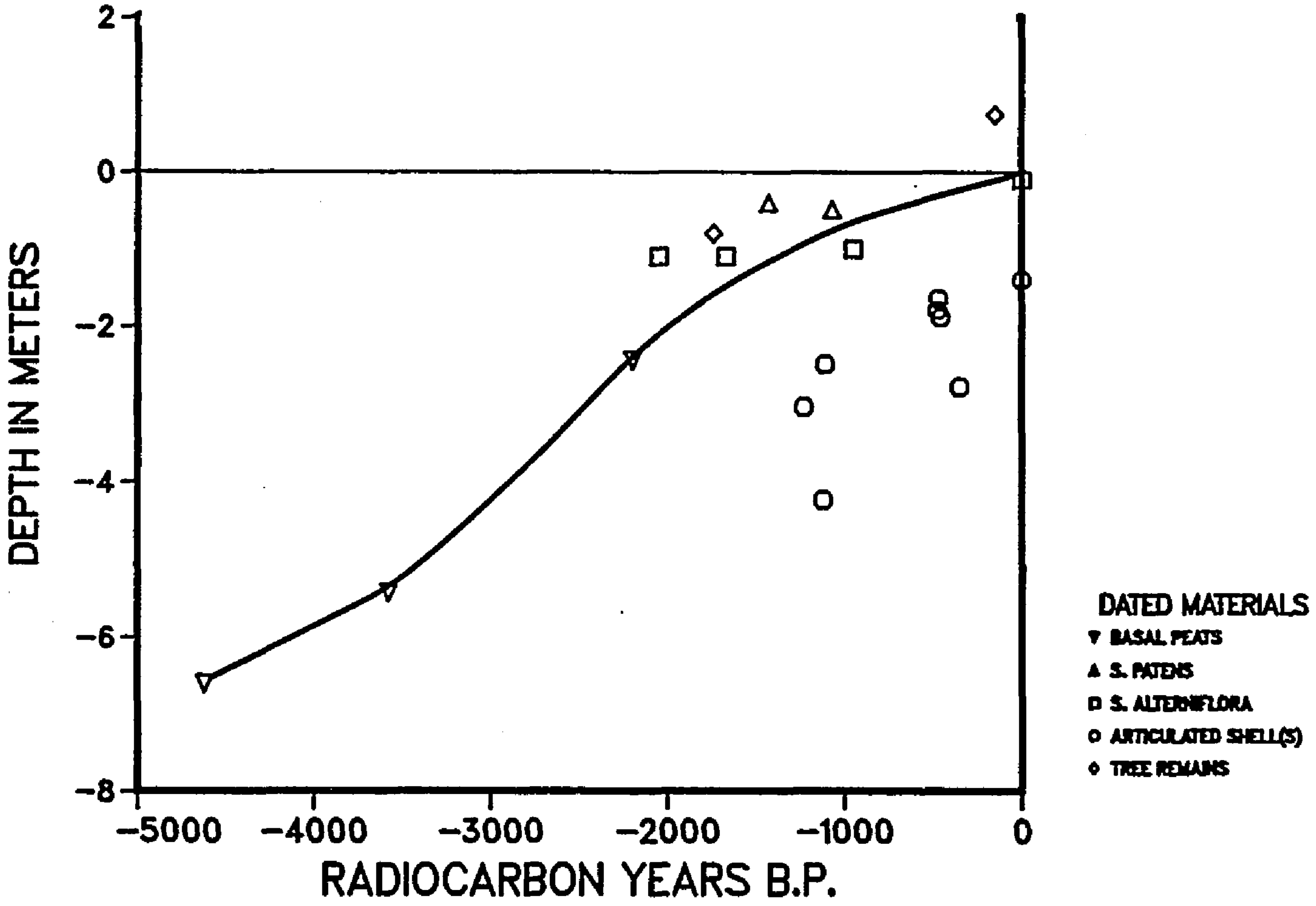

20
0
-20
-40
-60
-80
-100
DEPTH IN METERS
0
10000
20000
30000
40000
RADIOCARBON YEARS B.P.
?
STUDY
○ THIS REPORT
▽ FINKELSTEIN AND FERLAND (IN PRESS)
△ DILLON AND OLDALE (1978)

Figure 30. A sea level curve for the study since approximately 5,000 years B.P. The basal peats and sea-level curve (solid line) are from Finkelstein and Ferland (in press). Dated materials from this study are shown above and below this line.


DEPTH IN METERS
2
0
-2
-4
-6
-8
-5000
-4000
-3000
-2000
-1000
0
RADIOCARBON YEARS B.P.
DATED MATERIALS
▼ BASAL PEATS
▲ S. PATENS
□ S. ALTERNIFLORA
○ ARTICULATED SHELL(S)
◇ TREE REMAINS

positions are found from dated shells in cores 7-1A and 7-7 (Table 14).

STRATIGRAPHY

Introduction

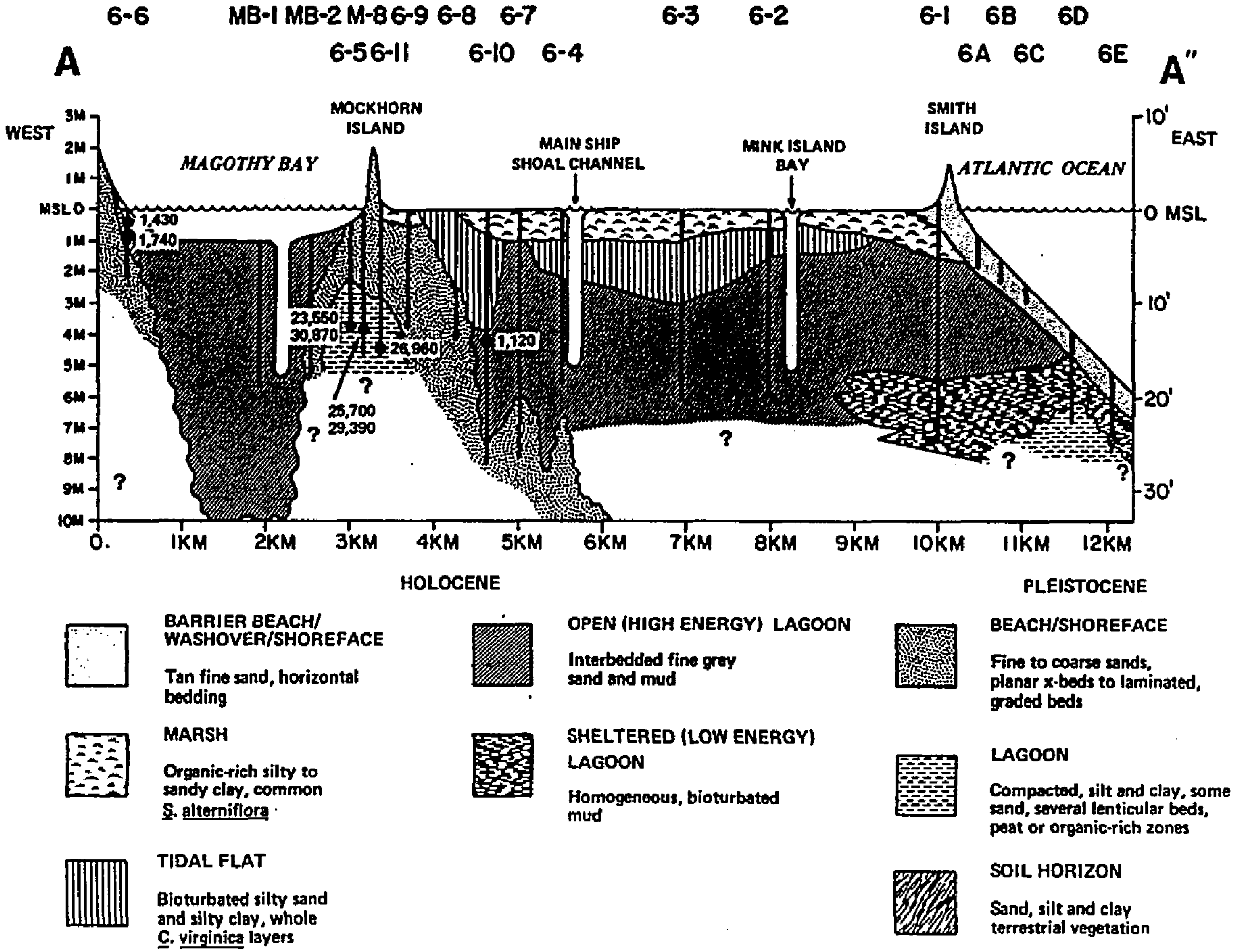
Two survey lines were established shore-normal to Smith and Mockhorn Islands and across the associated nearshore and backbarrier environments to the mainland. Vibracores and subbottom records taken along these transects, A-A" and B-B´, provide cross-sections of the region to a depth of approximately 10 m (Figures 31, 32). These and two other cross-sections (A-A´, C-C´) also describe the stratigraphy of Mockhorn Island and the relationship between the Pleistocene and Holocene units (Figures 33, 34). In addition, two cross-sections (D-D´, D-D") were constructed to examine the infilling of an ephemeral inlet (Figures 35, 36) and one cross-section (E-E´) was drawn to determine the relationship between Pleistocene and fringing Holocene mainland sediments (Figure 37).

Controls of Barrier Stratigraphy

Fluctuations in sea-level, variations in sediment supply, tectonic setting, and the pre-existing topography are the principal factors that determine the stratigraphic nature of any barrier depositional system. In addition, wave and/or tidal processes result in the deposition of sediments from distinctive sedimentary

Figure 31. Smith-Mockhorn Island shore-normal transect A-A". This cross-section extends from the nearshore zone of Smith Island to the mainland shoreline. Note the thin nearshore sands and the generally fining upward backbarrier sequence. Mockhorn Island sands are much thicker than those of Smith Island and may be preserved. C-14 dates below Mockhorn Island argue for a mid-Wisconsinan emplacement of Mockhorn Island.

SMITH-MOCKHORN ISLAND TRANSECT A-A'



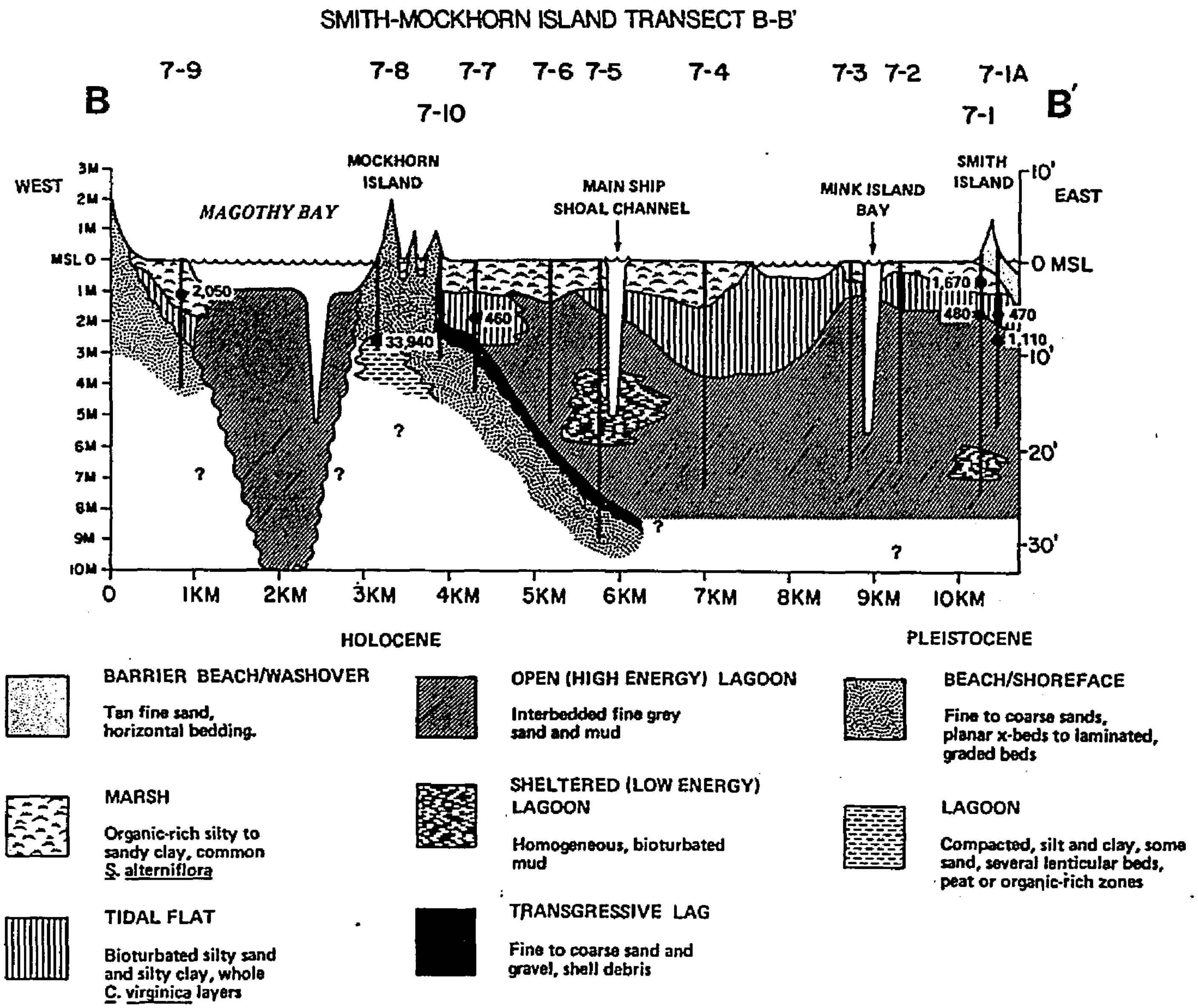


Figure 32. Smith-Mockhorn Island transect B-B' showing the surface and subsurface Holocene and upper Pleistocene geology.

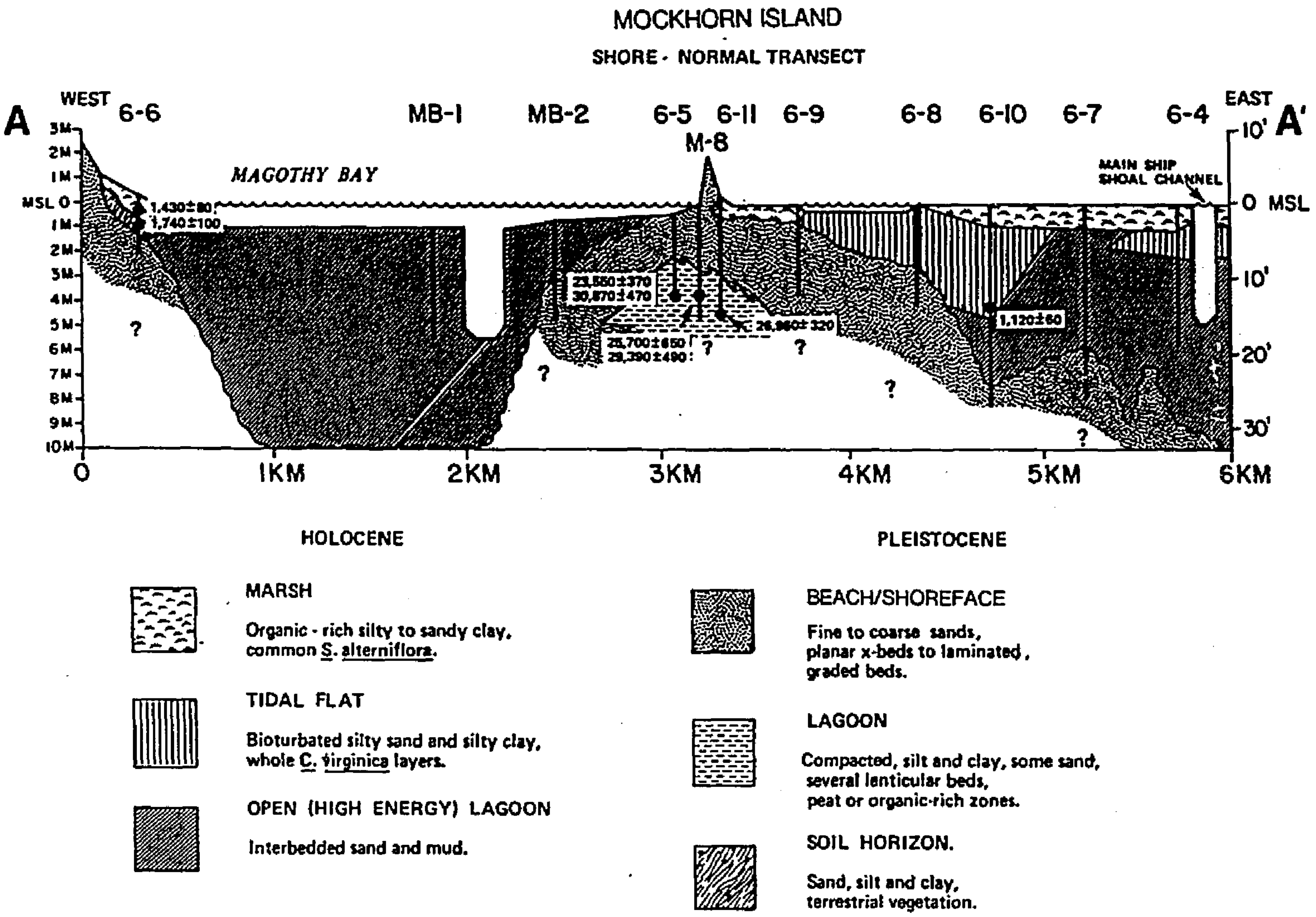


Figure 33. Shore-normal Mockhorn Island transect A-A'. This transect extends from the mainland shoreline to the center of the backbarrier environment. The relationship between Holocene and Pleistocene sediments is readily apparent.

Figure 34. Shore-parallel Mockhorn Island transect C-C′. The stratigraphic sequence of sediments below Mockhorn Island can be seen from this cross-section. Beach sands sit above backbarrier sediments and locally present sand shoals. Note the mid-Wisconsinan ages for the dated backbarrier organic materials.

MOCKHORN ISLAND

SHORE - PARALLEL TRANSECT

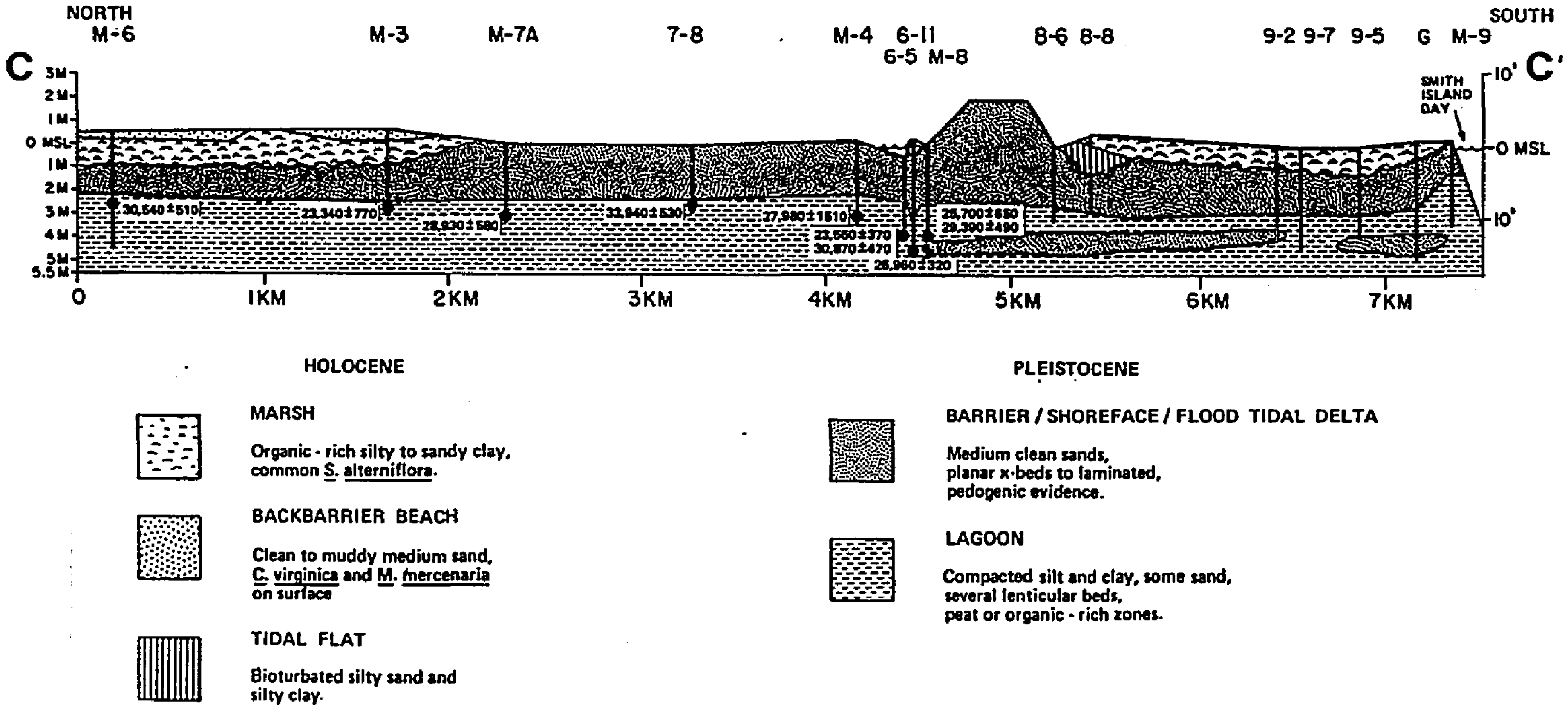


Figure 35. Bungalow Inlet shore-parallel transect D-D′. This cross-section shows the inlet fill sediments associated with Bungalow Inlet. The thinness of these sediments attests to Bungalow Inlet being a shallow inlet. Below are backbarrier deposits separated by an erosional contact.

Figure 36. Bungalow Inlet shore-normal transect D-D". Along with inlet fill sediments are two presently preserved washover events.

BUNGALOW INLET

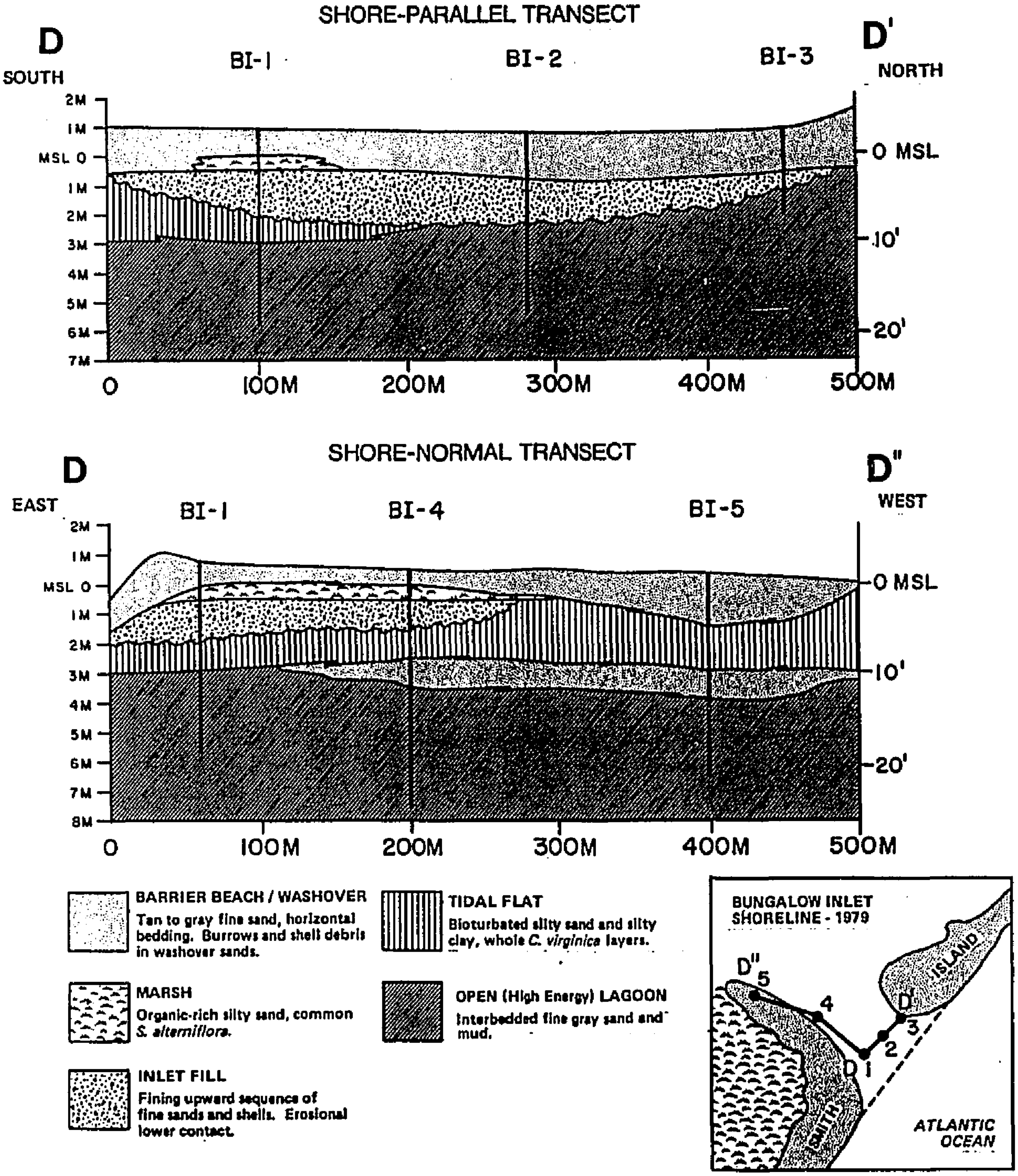
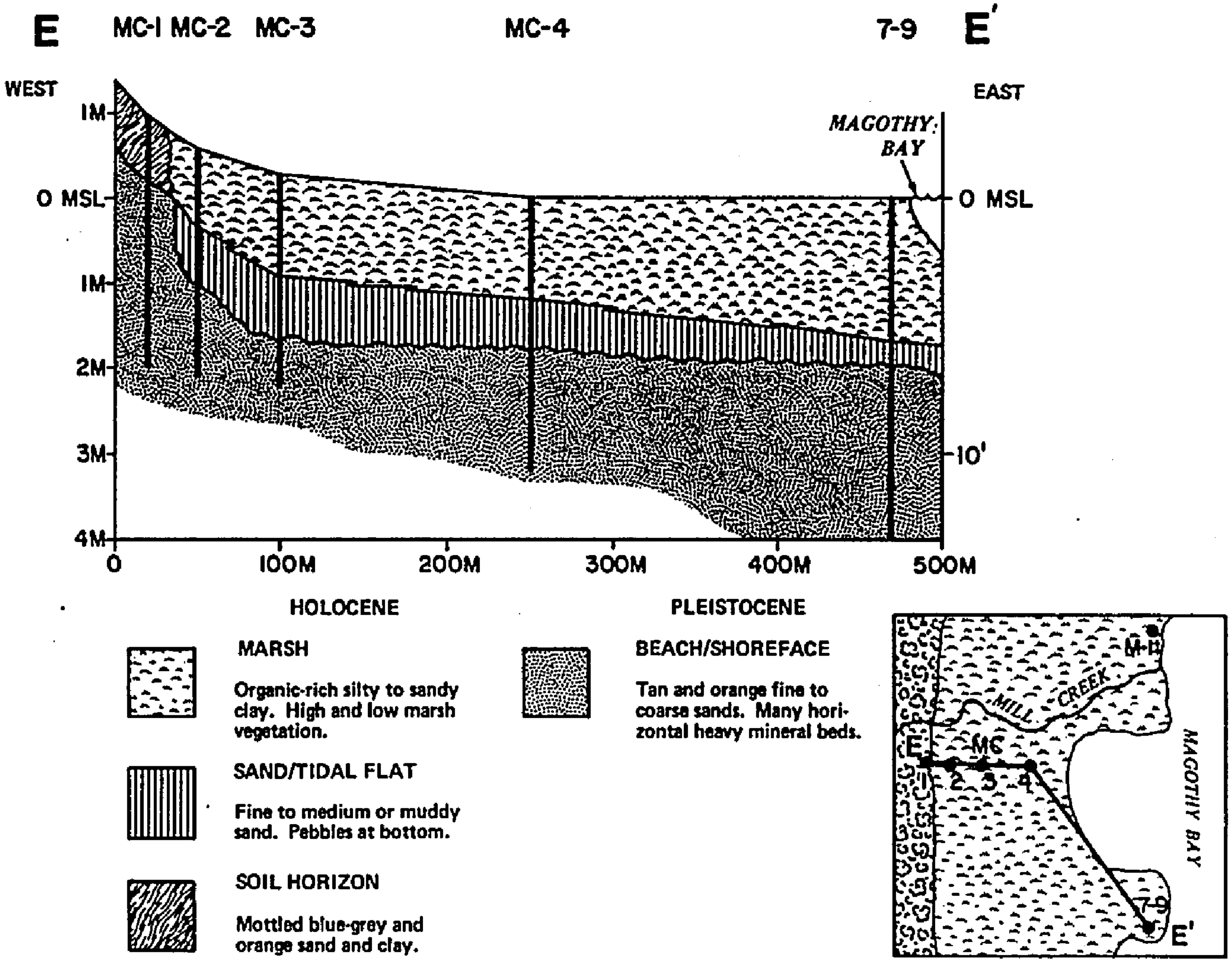


Figure 37. Transect E-E′ includes those cores taken adjacent to Mill Creek. This cross-section shows the relationship between Holocene and Pleistocene environments. The ravinement surface between Holocene and Pleistocene sediments is steep at the mainland shoreline but otherwise gentle.

MILL CREEK TRANSECT



environments of variable preservational potential (e.g. inlet deposits, tidal deltas, washover fans). The relative importance of these controlling factors can vary greatly from one barrier shoreline to the next (Moslow, 1980). Nevertheless, the ultimate preserved stratigraphic sequence and facies pattern is controlled by the rate of net deposition/erosion and its interaction with relative sea-level change through time (Fisher, 1961; Curray, 1964). For example, an increasing sediment supply with a stable or even slowly rising relative sea level results in seaward progradation of the barrier, i.e., a marine regression. The early to mid Holocene eustatic and late Holocene relative rise in sea level (Figure 30) along with an insufficient sediment supply has resulted in a marine transgression and landward retreat of the Virginia barrier islands. Thus, the Smith Island barrier system exhibits a transgressive stratigraphic sequence.

Similar factors determine the facies relationships of older barrier deposits. Previous late Pleistocene marine transgressions are recognized from transgressive barrier sequences from the Delaware (Demarest et al., 1981) and southeastern Virginia coastal plain (Peebles, 1984). Likewise, Mockhorn Island exhibits a transgressive barrier stratigraphy. While sediment availability and sea-level rise may interact to determine the nature of an individual barrier system, the relative position and facies relationship between Holocene and late Pleistocene barriers may be a function of neotectonism. Post-depositional movement, occurring along passive margins, is a mechanism for vertically repositioning Pleistocene barrier systems. Therefore this displacement partially controls the resulting preservation of vertical sequences and facies patterns after a subsequent (Holocene) marine transgression.

Pleistocene Stratigraphy

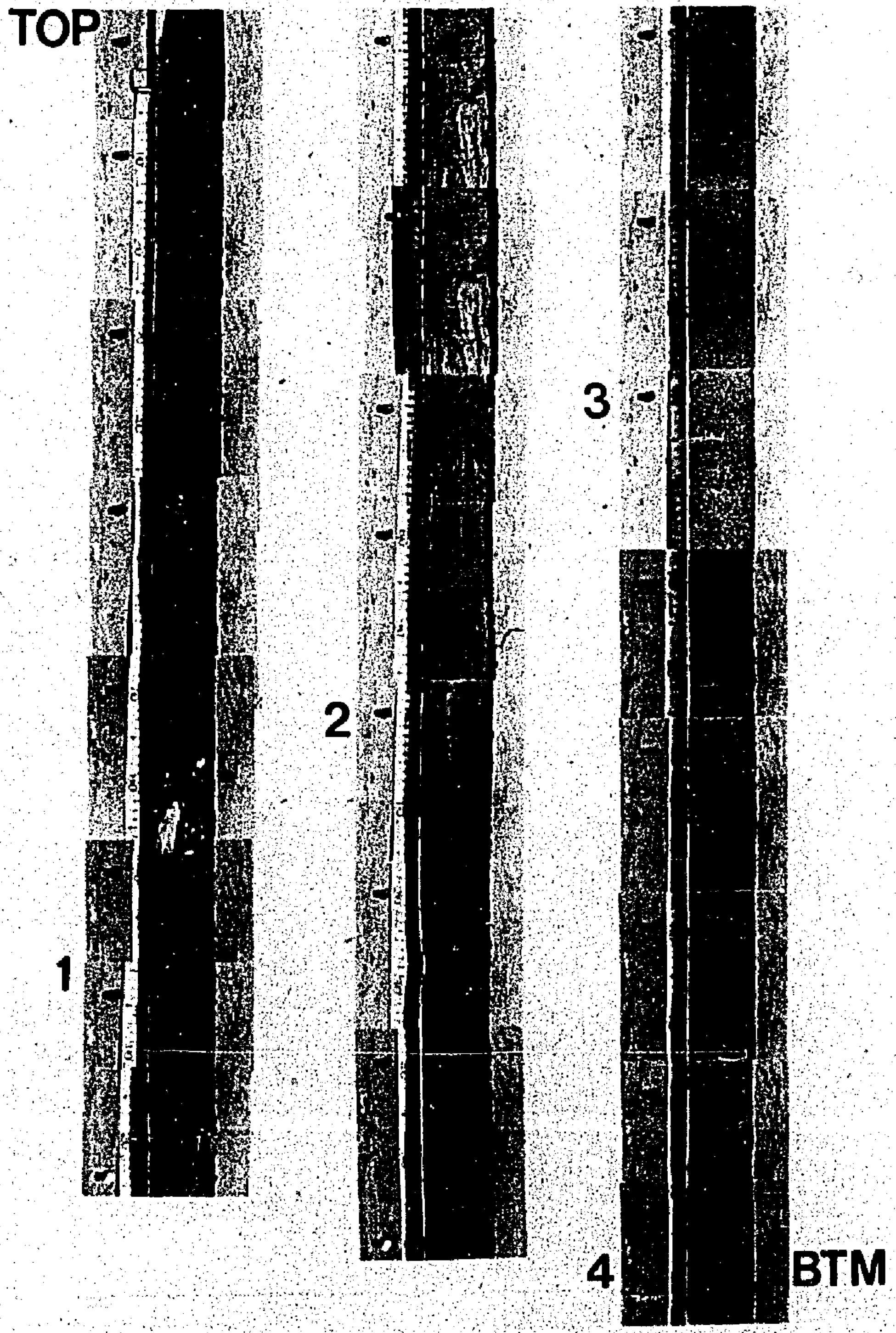
Mockhorn Island

The stratigraphic relations between the Holocene backbarrier and Pleistocene barrier sediments are shown in transects A-A′ A-A", B-B′, and C-C′ (Figures 31-34). Mockhorn Island is composed of Pleistocene sand but Holocene marsh and tidal flat encroach onto the island, particularly on its eastern shore (Figure 5). Just east of Mockhorn Island and surrounded by Holocene marshes (mostly *S. alterniflora*) are mounds, approximately 5 to 10 m long and 2 to 5 m wide, composed of coarse sand and supporting high marsh vegetation (Figure 32). These features may owe their origin to a marine regression following the emplacement of Mockhorn Island.

The vibracore and seismic subbottom data show that Mockhorn Island is part of a continuous sand sheet, at least 3.5 m thick, extending over four km (Figure 33). These sands gradually dip seaward beneath conformably and disconformably overlying modern backbarrier tidal flat, lagoon, and marsh deposits. The Pleistocene surface is partially scoured, presumably by fluvial processes during marine lowstand (Figure 20). Toward the mainland, they are overlain by a sequence of open lagoon sandy deposits (Figure 38). Pleistocene lagoonal sediments lie disconformably below Holocene backbarrier sediments in nearshore cores 6D and 6E of transect A-A" at 6.3 and 7.5

Figure 38. Photomosaic of core MB-2 from Magothy Bay (see Figure 6 for location). The infilling of Magothy Bay is recognized from the bioturbated Holocene mud and sand in the upper 250 cm. Below these muds are Pleistocene sands associated with Mockhorn Island.

MAGOTHY BAY 2 4.0M



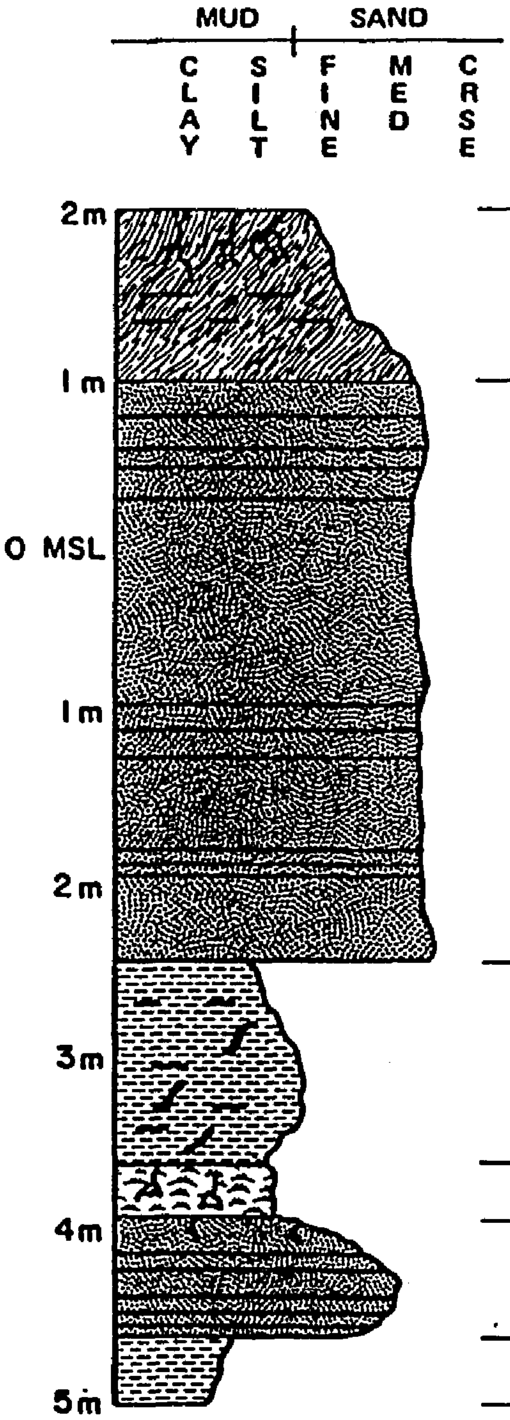
m, respectively (Figure 31). This is a puzzling occurrence as Pleistocene sands, normally stratigraphically above the lagoonal sediments, are found landward and below these muds (Figure 31). Possibly, a topographically high Pleistocene nearshore shoal provided a sheltered region for fine-grained sediment deposition.

Sedimentologic analyses reveal that the Mockhorn Island sands are coarser than that of Smith Island, with interspersed heavy mineral laminae between planar, mostly horizontal beds. In several cores from the island, a truncated paleosol can be found below more recently reworked foreshore sands.

The transgressive stratigraphic sequence from Mockhorn Island is shown in Figure 39. The Mockhorn barrier sands conformably overlie a clayey silt with intercalated peaty clays and scattered shoal-like lenticular sand bodies that probably represent flood tidal deltas. The vegetation of the delta sands, recognized in Core M-8 as marsh sediments, gradationally overlie these sands. The relatively homogeneous grain size distribution of muddy samples, the characteristic bedforms, and the occurrence of both calcareous (e.g. Elphidium sp.) and agglutinated foraminifera compare favorably to backbarrier Holocene sediments of the area. Contacts between sand bodies, lagoonal muds, and peaty clays are all gradational. The contact from the mud to the Mockhorn barrier sands is sharp but conformable and is much like the contact between Smith Island beach sands and its associated underlying backbarrier muds (Figure 15).

Figure 39. The stratigraphic sequence of sediments and associated environments is shown from Mockhorn Island. Cedar, loblolly pine trees and a soil horizon are found at the center of the island. They overlie a clean medium sand that outcrops on the beach. Below are lagoonal muds and interbedded peaty clay deposits. A transgressive stratigraphic sequence is recognized.

MOCKHORN ISLAND
STRATIGRAPHIC SEQUENCE



ENVIRONMENT	DESCRIPTION
SOIL HORIZON	Dark organic-rich soil grading downward into medium sand. Cedar and loblolly pine trees at surface.
FORESHORE	Medium clean sand. Several small burrows, heavy mineral laminations.
LAGOON	Compacted clay, silt, and scattered interbedded sand. Some bioturbation, Decayed shells found rarely.
MARSH	Brown, black; rooted
FLOOD TIDAL DELTA	Clean medium to fine sand, grades upward into sand with roots. Planar bedded.
LAGOON	Dense compacted clay and silt, some sand.

Mainland Shoreline

The Pleistocene stratigraphy of sediments adjacent and below the mainland shoreline is determined from the Mill Creek core (Core T-16) of Mixon (1985) and vibracores from this study (Cores MC 1-4, 6-6, 7-9, 8-7, 9-6), recovered from within the approximate 500 m mainland fringing Holocene marsh (Figure 6). Stratigraphic information of this type provides (1) clarification of the relationship and contact characteristics between the mainland fringing Holocene marsh and backbarrier beach, and the Pleistocene sediments; (2) the possible evidence of a Pleistocene backbarrier beach deposit correlative to the Mockhorn Island barrier; and (3) a determination of the stratigraphic position of the upper Pleistocene sediments, i.e., an indication of whether they are part of the Wachapreague Formation or some other unit.

Mixon's (1985) Mill Creek core is shown in Figure 12. The Yorktown Formation is unconformably overlain by the Wachapreague Formation with the latter unit extending from at least 3.9 to 10.0 m below MSL. A progressive change from warm-temperate climatic conditions in earliest Wachapreague time to cool- or cold-temperate conditions in middle and late Wachapreague time is recognized based on pollen assemblages (Mixon, 1985). Sediments from the Wachapreague Formation in this core differ from the Type Section at Wachapreague, Virginia in that a fine grained lithic unit is not found below a coarse grained lithic unit. Instead, a sequence of medium to coarse clayey sand with pebbles is observed at the base fining upward to fine sand, clay, and silt at the -3.9 m surface. An unconformity is drawn at -3.9 m but the surface of the Wachapreague Formation is not clearly identified (Figure 12). Coarse sands and pebbles lie above -3.9 m.

As shown in Transect E-E′ (Figure 37), the Mill Creek cores of this study (MC 1-4), particularly MC-4 (Figure 12), penetrate through the Holocene and into the Pleistocene sediments below. The Holocene sediments are marsh muds or sands underlain by mud and sand. These sediments represent mainland fringing marshes or backbarrier beaches over a tidal flat environment. The Holocene-Pleistocene contact is subtle with some pebbles above and locally iron stained sands below the contact. The pebbles are reworked Pleistocene material re-deposited during the initial inundation of the backbarrier region from the Holocene marine transgression. They represent a thin transgressive lag deposit. At MC-4 the Holocene-Pleistocene contact is at 1.8 m below MSL and at Core CL-1 and 7-9 it is approximately 2.0 m. These upper Pleistocene sands are composed of sand and pebbles which grade upward into fine sand with many heavy mineral beds (Figures 37, 12). The fine sands between 1.0 and 2.0 m thick are interpreted as a beach deposit. Similar sands of this type are found as the upper Pleistocene deposits in cores CL-1, 6-6, 7-9 and 8-7, Appendix 1).

The recognition of the Pleistocene/Holocene contact provides for a revised stratigraphy that differs from that of Mixon (1985). The upper Pleistocene sands are interpreted as a mainland beach deposit correlative to the Mockhorn Island barrier. This conclusion is based on the texture and bedforms of these sands and the similar stratigraphic position of each deposit. Both lie stratigraphically below Holocene sediments.

The position of a contact below the coarser sands at -3.9 m MSL (Figure 12) would indicate that two Pleistocene units exist. These are the Wachapreague Formation below and unnamed Pleistocene sediments (Mockhorn formation) that correlate with Mockhorn Island above -3.9 m. Holocene sediments lie above the Mockhorn Formation. The data supporting this interpretation is not conclusive because Mixon's (1985) upper Wachapreague contact is not clearly demarcated (Figure 12). However, the presence of coarse sand and pebbles above -3.9 m and fine sand, silt, and clay below would indicate the presence of such a contact (Figure 12).

Holocene Stratigraphy

Barrier and Backbarrier

The rise in Holocene sea-level along with a low sediment supply has resulted in shoreface erosion of Smith Island and subsequent landward barrier migration. General facies relationships for a landward migrating (retrograding) barrier shoreline were hypothesized by Fischer (1961-Figure 3) and Swift (1976-Figure 10) and verified by Newman and Munsart (1968) and Kraft (1971), among others. More detail of the lateral and vertical distribution of depositional environments associated with a retreating barrier is shown in this study. The significance of these stratigraphic sequences is that they occur beneath a single barrier system that overlies an earlier transgressive shoreline deposit.

Most Holocene depositional environments change gradually in both the vertical and lateral direction. This is especially true for backbarrier environments: marshes, tidal flats, open lagoons, and sheltered lagoons. Cores display vertical trends in lithology and sedimentary structures that are representative of the backbarrier stratigraphy. The most pertinent trends are (1) an overall fining upward sequence of sediments from fine sand and/or muddy sand and (2) a dominance of biogenic sedimentary structures closer to the surface with a downward increase in physical sedimentary structures (Figures 22, 31, 32). This trend normally exists unless the locally encountered sheltered lagoonal environment is penetrated.

The dominant subsurface backbarrier environments are open lagoons and tidal flats (Figure 22). Tidal flats and marshes are most common today. Tidal flats are primarily intertidal and subject to lower current velocities and extensive bioturbation. Oysters are numerous within this environment. Open lagoons represent a subtidal environment subject to channelized tidal currents.

The Holocene backbarrier sediments overlie Pleistocene sands associated with Mockhorn Island and the mainland. Scattered transgressive lag deposits are encountered between these two units (Figure 19). Elsewhere the contact is subtle (Figure 18). A basal Holocene peat might be expected above the Pleistocene sediments, yet that is not found. The lack of a distinct transgressive discontinuity or a basal peat at the Pleistocene-Holocene contact diverges from the conceptual model of active transgression, i.e., the presence of an erosional backbarrier contact and/or a transitional peat from the initial backbarrier inundation of the sea. The backbarrier sediments surround Mockhorn Island with mostly surficial marshes and tidal flats on the seaward side and open lagoon sediments filling Magothy Bay (Figure 38).

Smith Island beach and washover sands exhibit abrupt yet conformable contacts to the backbarrier sediments normally found one to three meters below (Figures 15, 22). An erosional contact to backbarrier sediments is seen below nearshore sands of approximately one meter thickness (Figure 23). The abundant shells and coarse and poorly sorted sands that are characteristic of a transgressive lag deposit are not found. This contact is a transgressive discontinuity called a ravinement surface. Nearshore sands are deposited on top of this surface. This occurs as Smith Island retrogrades and surface and subsurface deposits are reworked in the shoreface. Some of this material is redeposited as washover, foreshore, or nearshore sands. The amount of reworking was found to be 64 m^3/yr per meter of shoreline from a net erosion/migration rate of 8.0 m/yr, a barrier height of 1.5 m (MSL), and a closure depth for active erosion at 6.5 m (MSL) (Finkelstein, 1986). The thinness of these sandy environments contrasts with the relatively thick backbarrier sediments. The nearshore sands could be removed by wave and tidal currents thereby leaving the backbarrier sediments at the water-sediment interface.

Washover sands are only found within one km of Smith Island. They are particularly common landward of ephemeral Smith Island inlets. Washover sediments, characterized by their texture, sorting, and shell content, are rarely identifiable in the backbarrier cores. This probably reflects the wide backbarrier region with numerous tidal channels that prevents widespread lateral deposition. Channels transport washover sediments, and those sands deposited on marshes and tidal flats may be reworked by bioturbation, which would conceal the overwash event.

The preceding discussion indicates that the Holocene sediments associated with the Smith Island barrier display a typically transgressive stratigraphy. However, the southern end of Smith Island has prograded alongshore and displays, in part, a regressive stratigraphy with well-developed beach ridges, although that area is currently retrograding. If preserved, both transgressive and regressive stratigraphic sequences could occur. This is not unusual; Moslow and Heron (1978) found both these sequences near Cape Lookout, North Carolina. Therefore, even in a retreating barrier system like Virginia, a regressive stratigraphic interpretation could be made on the basis of a local study. This illustrates the problem of using a "classical" barrier model (Fisk, 1959; Bernard et al., 1962; Kraft, 1971) that describes one type of barrier stratigraphy for environmental interpretation. The transgressive or regressive nature of a barrier is usually the result of very local variation in sediment supply (Ruby, 1981).

Bungalow Inlet

According to the 1979 USGS 1:24,000 topographic map of the Ship Shoal Inlet Quadrangle, Bungalow Inlet, a 500 m wide ephemeral Inlet 4.5 km south of Little Inlet (Figures 2, 40), was open. The 1980 NOAA nautical chart (#12224) shows it closed and it remains so today. It was also closed between 1855 and 1929 and then open until 1969 (1855 USCGS 1:400,000 nautical chart; 1943 USGS 1:24,000 topographic map of the Ship Shoal Inlet Quadrangle; 1946 US Army Topographic Command 1:250,000 topographic map; 1968 USGS 1:24,000 topographic map; 1969 USGS 1:250,000 topographic map; Rice et al., 1976). Because inlets often scour deeply into the subsurface and migrate, much of the inlet fill sediments may be preserved below the wave base of a transgressing sea. Along the Outer Banks of North Carolina, Moslow and Heron (1978) showed that much of the Holocene barrier section has been reworked by tidal inlet migration. To define the stratigraphic sequence of inlet sediments and to determine their preservational potential, several cores were drilled in and near the Bungalow Inlet site.

The position of five vibracores, BI 1-5, are shown in Figures 35 and 36; these are used to construct a shore-parallel transect D-D′ and a shore-normal transect D-D″. Transect D-D′ is composed of three cores: BI-1, BI-2, and BI-3. The inlet fill sequence is especially well preserved in BI-1 and BI-2. The inlet channel bottom is 2.0 and 2.5 m, respectively. It is only about 1.0 m in BI-3, which indicates that this core is taken from the inlet margin. In all these cores, much shell debris and intact shells of oysters, razor clams, and arks lie disconformably over muddy backbarrier sediments. This erosional

Figure 40. An aerial photograph of Smith Island highlighting the washover fan at the former location of Bungalow Inlet (at center) is shown.

contact is very distinct (Figure 41). The inlet fill sands, which are approximately 2 m thick, are medium to fine grained and tan colored. and contain a significant amount of shell debris. Conformably overlying these sands are tan fine grained foreshore sands with many heavy mineral beds. In BI-1, a 10 cm marsh deposit is found between the two sandy environments.

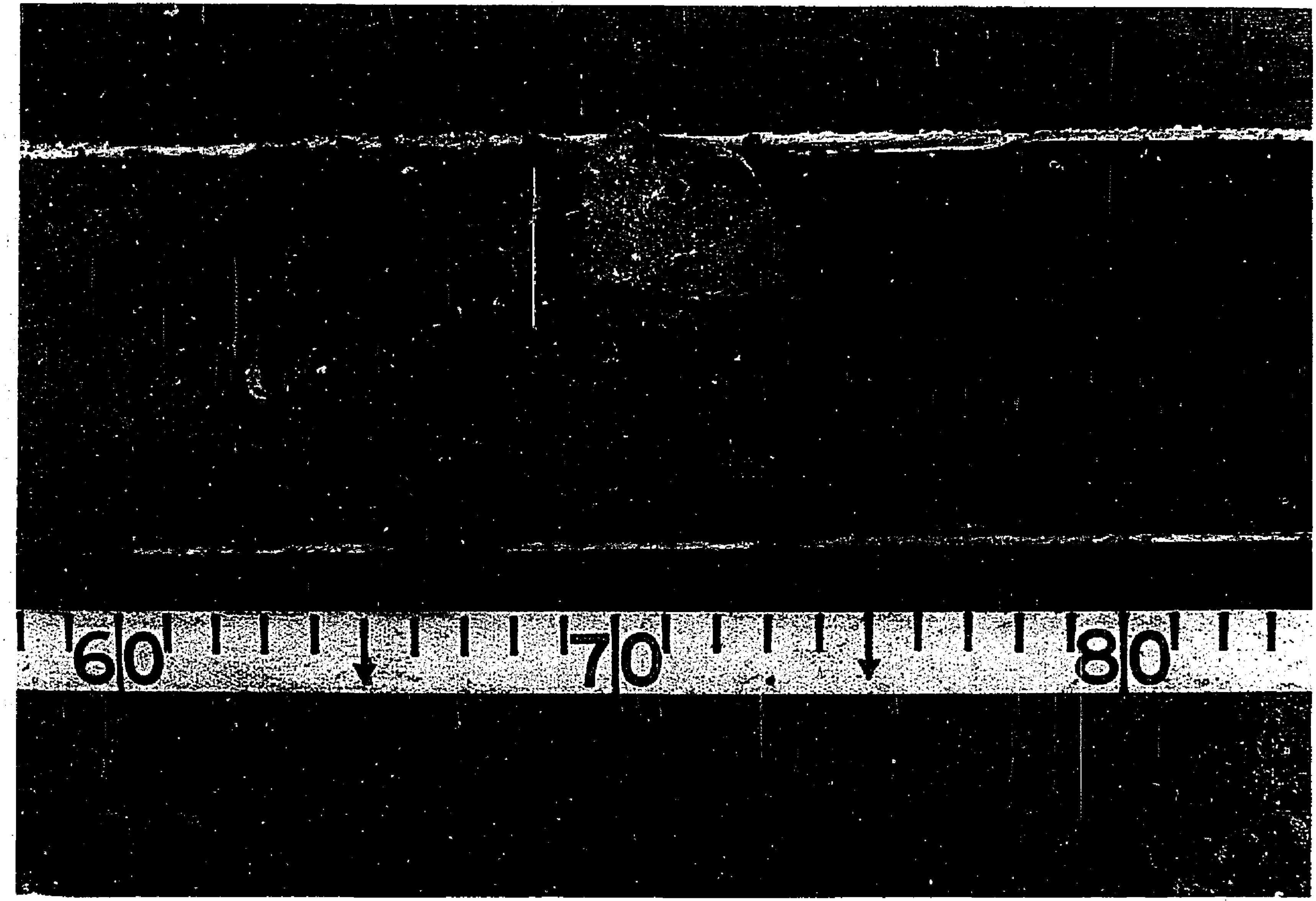
Three cores, BI-1, BI-4, and BI-5, extend along transect D-D" (Figure 36). The inlet fill deposits are encountered in BI-1 and 150 m landward in BI-4 but 150 m further west the southern inlet margin is penetrated. The thickness of the inlet fill sands decreases in a landward direction. However, a previous washover event is recognized in cores BI-4 and BI-5. These washover deposits are found conformably between typical tidal flat and open lagoon environments.

These cores and cross-sections indicate that Bungalow Inlet was a shallow channel no more than 2.5 m below MSL. Discussions with local fisherman support that conclusion. Previous openings of the inlet are not recognized in these cores; the last active period of channelization may have removed any older but shallower inlet fill deposits.

Summary

Transgressive Holocene and Pleistocene stratigraphic sequences are shown partially superposed on top of one another. Mockhorn Island is a relatively thin barrier island that overlies backbarrier sediments. Pleistocene sands associated with this barrier system

Figure 41. The erosional contact between ephemeral Bungalow Inlet fill (sand above) and backbarrier muds is shown from core BI-1.


60
70
80

extend under Holocene backbarrier sediments seaward and landward of Mockhorn Island. Upper Pleistocene sands found below mainland fringing Holocene sands and muds are lithologically and perhaps chronologically different from the underlying lower section of the Wachapreague formation. These Pleistocene sands (Mockhorn formation) may be the backbarrier beach correlative to the Mockhorn Island barrier. Pleistocene muds outcrop anomalously high in the stratigraphic column from cores recovered in the nearshore zone. A sheltered region behind a Pleistocene shoal may account for this.

The Holocene backbarrier sequence generally fines upward and is usually capped by marsh or tidal flat sediments. Smith Island barrier sands and its nearshore sediments are no greater than three and one meter thick, respectively. Ephemeral inlet fill deposits extend only 2.5 m below MSL. The basal Holocene deposit is locally a transgressive lag but more usually the Pleistocene contact is conformable.

DEPOSITIONAL HISTORY

Late Pleistocene

Sangamonian Interglaciation (125,000 to 70,000 years B.P.)

Sangamon deposition began landward of the study area with barrier, lagoonal, and nearshore sediments deposited to form the Nassawadox Formation (Mixon, 1985). Subsequently, another marine transgression truncated the Pliocene Yorktown Formation and, in part, the Nassawadox Formation. This resulted in deposition of the Wachapreague Formation (Mixon, 1985). North of the study area, beach ridges and narrow lagoons are designated as part of the Wachapreague Formation, indicating a later marine regression (Mixon, 1985). Although Uranium-isotope (128,00 years B.P) and amino-acid racemization (82,000 years B.P.) age estimates conflict, these dates along with the stratigraphy support a late Sangamonian age for the Wachapreague Formation (Mixon, 1985). These dates are from the lower section of the Wachapreague Formation as discussed earlier. Latest Pleistocene sediments of the Mockhorn formation and the stratigraphically equivalent upper section of the Wachapreague Formation overlie the lower section along the present mainland shoreline. These sediments are correlative with those of Mockhorn Island, both of which probably result from a late mid-Wisconsinan marine transgression, as discussed below.

Wisconsinan Glaciation (70,000 to 10,000 years B.P.)

The Wisconsinan glacial period began about 65,000 years B.P. and ended with the rapid warming of the Holocene about 10,000 years ago. The last interstadial event ended about 23,000 years B.P. and after this time the ice sheets seem to have expanded markedly with glacial maximum around 18,000 years B.P. (Goudie, 1979). Although other Wisconsinan interstadial events are recognized on late Pleistocene sea-level curves (Shackleton and Opdyke, 1973; Bloom et al., 1974; Chappell, 1974) (Figure 42), researchers have only discussed the possibility of sea level standing near its present position during mid-Wisconsinan time (40-25,000 years B.P.).

Mockhorn Island sands overlie backbarrier sediments, some of which are peaty clays, that have been dated between 34,000 and 23,000 years B.P. (Table 14). Dated materials are 2.5 to 4.5 m below MSL and are from a cool to cold marginal marine environment. This suggests that relative sea level was near today's level during this time period if isostatic adjustments are ignored. The transgressive Mockhorn barrier sequence points to an island that is clearly coeval with, or younger than, these dated sediments. These data contrast with the portrayal of lower sea levels during the mid-Wisconsinan. Bloom (1983) reports sea level between 38 and 42 m below present at the time Pleistocene sediments dated in this study were deposited. Possibilities that could account for this discrepancy are as follows:

1) Mockhorn Island might in fact be a Holocene barrier island. This conclusion is based on the possibility that Mockhorn Island was originally a part of the Holocene barrier island chain of Virginia and

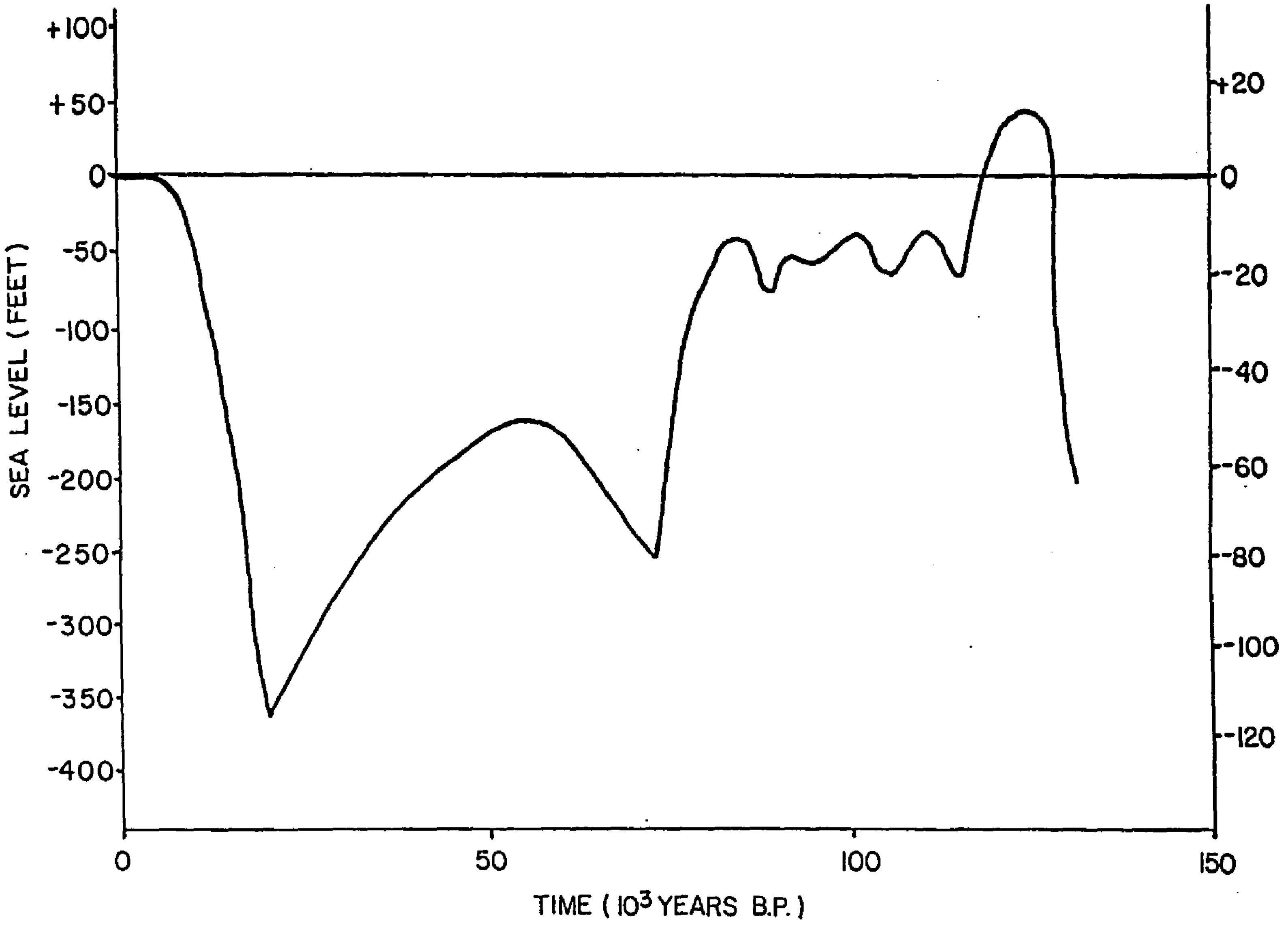


Figure 42. A late Quaternary sea-level curve from oxygen-isotope data is shown above. Note sea level well below today's level, especially during mid-Wisconsinan time, during the past 120,000 years (from Shackleton and Opdyke, 1973).

was subsequently overlapped by Smith Island. This type of barrier overlap has occurred during Holocene time; for example, Assateague Island extended to the south by spit progradation until it overlapped Chincoteague Island (Goettle, 1981). However, despite the similarity in height and sand thickness, Mockhorn and Smith Island exhibit many lithological differences. Mockhorn Island's larger and locally iron stained sands, its compacted and mostly dewatered backbarrier sediments, and the truncated paleosol below more recently reworked foreshore sands indicate that it is distinct from Smith Island and considerably older. An atlatl, or spearthrower ornament, was found on Mockhorn Island and dates somewhere between 3,000 and 5,000 years B.P (personal communication, K. Egloff, Virginia Division of Historic Landmarks). This points to human occupation on an island that has remained stationary. Holocene islands were further offshore at this time and have subsequently retrograded landward. Finally, the radiocarbon dates and pollen assemblages found below Mockhorn Island contradict the hypothesis that Mockhorn Island is Holocene.

2) Mockhorn Island is a result of a very late Sangamon or early Wisconsinan marine transgression. This conclusion would support most late Pleistocene sea-level curves previously mentioned if a slow tectonic uplift rate of 0.1 to 0.3 m per 1000 years is assumed. During oxygen-isotope stage 5a (Late Sangamon) or an early Wisconsinan interstadial, a hypothesized sea level of between -13 and -20 m is shown in eustatic studies by Mathews (1973), Bloom et al (1974), and Chappell (1974) and utilized in neotectonic studies of the Virginia region (Cronin, 1981). One of these relative highstands may have

produced the Mockhorn barrier complex with subsequent neotectonic uplift from -15 to -2 m (below present MSL) over approximately 65,000 to 82,000 years. These rates of uplift closely match those of Cronin (1981) for a similar time period and region.

A late Sangamon or early Wisconsinan time for deposition of the Mockhorn barrier complex would presume the ten mid-Wisconsinan C-14 dates are erroneous. Humic acids, organic decay products, and modern calcium carbonate may have been carried in the groundwater flow or downwards to respectively contaminate adjacent or underlying sediments. A calcium-carbonate shell of 100,000 years old would give an apparent C-14 date of 37,000 years if contaminated by only 1% modern $CaCO_3$ (Goudie, 1979). However, all modern carbonates were removed during sample pre-treatment and no shells were dated in this study. C-14 dates obtained in this study are in relatively close agreement; it would seem fortuitous that all samples were contaminated by almost the same amount of modern carbon. Moreover, the possibility of migration of organics downward through mostly impervious backbarrier clays is a hypothesis, not presently substantiated.

Pollen assemblages from below Mockhorn Island (Figure 8) could support an earlier than mid-Wisconsinan time of deposition. The cool to cold pollen spectra may correlate to colder climates that occurred either before or after oxygen-isotope stage 5a. A lag time may exist between the warming trend that produced a relatively higher sea-level and the Mockhorn barrier complex, and a change in vegetation, i.e., the pollen rain. This could cause pollen assemblages from colder climates to be found within a stratigraphic sequence that indicates warming and sea-level rise.

3) The Mockhorn barrier complex results from a mid-Wisconsinan sea-level highstand. The preceding discussion provides a reasonable explanation for an older age of the Mockhorn barrier complex. This possibility is certainly plausible. However, based upon the geomorphology, stratigraphy, C-14 dates, and paleontologic data, a mid-Wisconsinan age is most likely.

Mockhorn Island provides the first reliably dated stratigraphic and geomorphic evidence from a specific locality for a mid-Wisconsinan sea-level highstand along the middle Atlantic coast. The C-14 dates taken from positively identified backbarrier sediments below the barrier sands have been cross-verified with dated pollen assemblages. Pollen found with the C-14 dated sediments of this study are very similar to assemblages dated between approximately 24,000 to 31,000 year B.P. from the central Delmarva Peninsula (Sirkin et al., 1977) and from transgressive sands (Sinepuxent Formation) of presumed mid-Wisconsinan age in the northern Maryland coast (Owens and Denny, 1979). As mentioned earlier, most previous studies indicating a mid-Wisconsinan highstand lack paleoclimatic data, contain only a few reliable C-14 dates, and/or do not include a subaerial barrier facies.

The marine transgression that resulted in deposition of the Mockhorn barrier complex is part of the Farmdalian (Lake Michigan lobe) or Plum Point (Lakes Ontario-Erie lobe) Interstade. This interstadial period is dated between approximately 34,000 to 22,000 years B.P. (Table 1). There is little evidence for this phase in marine cores. It may not have been observed because of a sampling interval that was too wide or because of core disturbance by bioturbation.

Alternatively, it may be too small and local an event to be recorded in the oceanic record.

A Late Quaternary sea-level curve is shown in Figure 29. The ten C-14 dates of this study "cluster" at about 2 m below present sea level at approximately 28,000 years B.P. This curve is similar to those of Curray (1965), Milliman and Emery (1968), and in part, Dillon and Oldale (1978) (Figure 43), despite the fact that the mid-Wisconsinan portion of the curves of the first two are based on speculative data (Bloom, 1983).

Two explanations are possible for the present height of the mid-Wisconsinan Mockhorn barrier. The first is that eustatic sea level was much higher than previously reported during this time frame. The second is that neotectonic uplift has subsequently raised the barrier complex. The improbability of an eustatic sea-level rise during the Middle Wisconsin, when ice continuously occupied latitudes as far south as the St. Lawrence Lowland, remains an obvious, fundamental objection to an interstadial sea-level highstand. Pollen assemblages indicate average temperatures were at least 10^0 colder than present thereby prohibiting rapid glacial melting and a large rise in eustatic sea level. These points, however, do not eliminate the possibility that the apparent transgression that produced Mockhorn Island and perhaps other geomorphic features reported for the middle and southeastern Atlantic Coasts was the result of global geoidal or more local, regional isostatic adjustments. The East Coast continental margin may have risen since the end of the Pleistocene due to eustatic loading of the Atlantic Ocean basin (Walcott, 1972). Indeed, there is

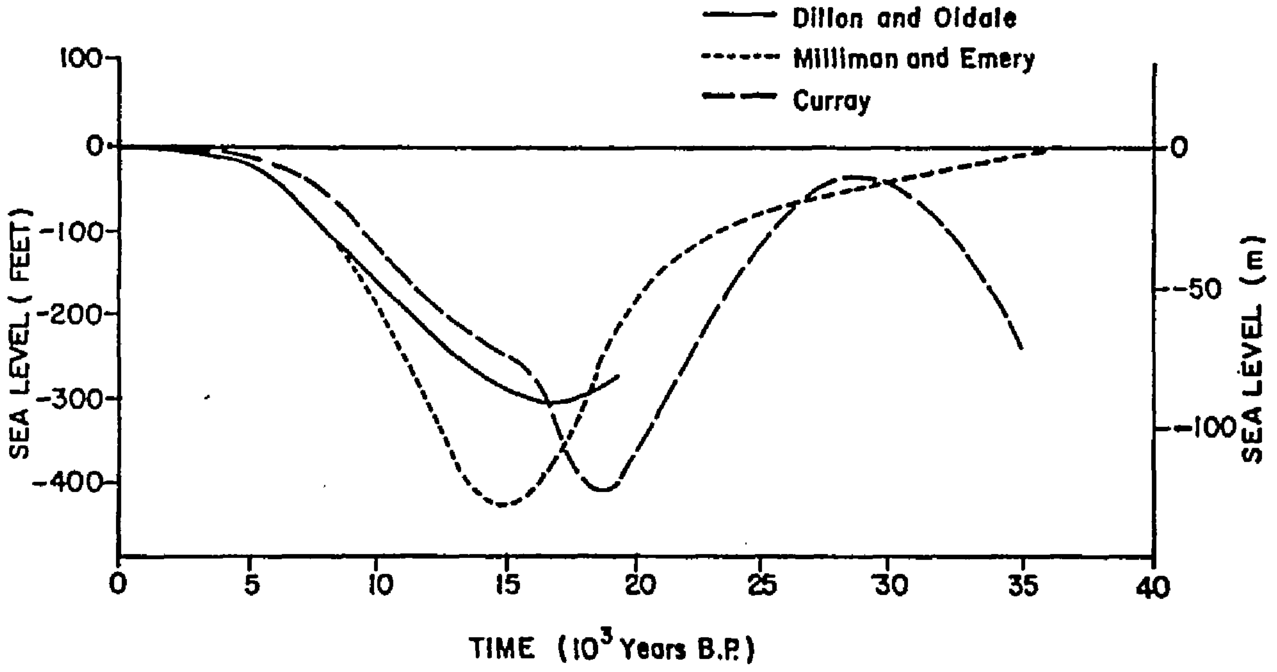


Figure 43. Late Quaternary sea-level curves reported by Curray (1965), Milliman and Emery (1968), and Dillon and Oldale (1978) (from Dillon and Oldale, 1978). The data indicating a mid-Wisconsinan sea-level highstand may be in error.

increasing evidence for considerable late Quaternary differential warping of continental shelves along the northern and middle Atlantic Coasts (Dillon and Oldale, 1978). The dilemma of a mid-Wisconsinan sea-level highstand thus becomes not so much a question of the ultimate validity of the evidence but of the rheological mechanisms that could have given rise to these phenomena. With this in mind, Pleistocene data points in the late Quaternary sea-level curve shown in Figure 29 probably include some tectonic uplift.

This neotectonic explanation is not without its problems. If the Bloom et al. (1974) sea level of -38 m at 30,000 years B.P is assumed correct, then Mockhorn Island would need 1.20 mm/yr uplift for 30,000 years to produce it's present height. What is troublesome about this uplift is that it is not readily seen in older late Pleistocene deposits. For example, Cronin et al. (1981) date a late Pleistocene ridge in the Virginia-North Carolina border area at 7.0 m above MSL at approximately 72,000 years B.P. If eustatic sea level was then -13 m (Bloom et al., 1974), only 20 m of uplift has occurred at a rate of 0.27 mm/yr (Cronin, 1981). Neither the relatively high rates of uplift suggested by Cronin (1981) nor those proposed by this study, which are about four times as great are reflected in earlier Sangamonian shorelines (oxygen isotope stages 5c and 5e). These shorelines do not show considerably higher present elevations despite higher eustatic sea levels during time of deposition. A possible explanation is that neotectonism works in both directions, up and down, and Sangamon shorelines may have subsided to levels below their original height, and after mid-Wisconsinan time rapid uplift occurred.

There may also be intervals of more rapid uplift or subsidence in some regions (Cronin, 1981). In addition, Blackwelder et al. (1979) note that shelf histories of major coastal compartments may differ considerably. There may also be differences within a particular coastal zone. The present Eastern Shore subsidence rates differ by 0.8 mm over a distance of 100 km (Holdahl and Morrison, 1974). If this rate is constant over a span of 30,000 years, a 24 m difference in elevation will result.

The forebulge that uplifted Virginia during the late Wisconsinan glacial period may explain the present height of Mockhorn Island. With the collapse of the glacial forebulge this region has subsided, but not yet to the level of original barrier emplacement approximately 28,000 years B.P. Indeed, high present subsidence rates of 1.20 to 2.00 mm/yr along the Eastern Shores of Virginia and Maryland may partially reflect this collapse (Holdahl and Morrison, 1974).

Eustatic sea level may have been higher then previously reported during mid-Wisconsinan time. Pollen records between 32,000 and 28,000 years B.P. from New York indicate a temperate climate that perhaps could have raised the sea to levels nearly like the present (Sirkin and Stuckenrath, 1980). The disparity between pollen records from New York (Sirkin and Stuckenrath, 1980) and the Delmarva Peninsula (Sirkin et al., 1977; this study) increases the confusion over mid-Wisconsinan sea levels. Nevertheless, if the New York data is correct, the need for tectonic uplift since the Middle Wisconsin is greatly reduced.

Full glacial conditions existed by approximately 18,000 years B.P with sea level at about -88 m (Dillon and Oldale, 1978). Some erosion of Pleistocene deposits associated with Mockhorn Island certainly took place. Most likely, the Machipongo River entrenched the present day Magothy Bay, and soil profiles were created atop marginal marine sediments.

Pleistocene Summary and Correlation

Although a late Sangamon or early Wisconsinan age for the Mockhorn barrier is better suited to previous sea-level curves and neotectonic rates of uplift, only a mid-Wisconsinan time of deposition is supported by all of the available data from this study. However, some caution is reserved which unfortunately provides more confusion to this controversial sea-level issue. Figure 44 is much like the earlier sea-level curve (Figure 29) except a late Sangamonian (Table 1) date of 72,000 years B.P. from Cronin et al (1981) is included. Some researchers may insist that the ten C-14 dates of this study are radiometrically dead and thus the peaty clays dated are approximately equivalent in age to that of Cronin et al (1981).

With the projected mid-Wisconsinan highstand, Figure 45 summarizes the progression of depositional and erosional events since 30,000 years B.P. The transgressive Mockhorn barrier is shown at top of this figure; subsequent sea-level fall induced sand deposition atop the more landward lagoonal sediments along with scouring of proto-Magothy Bay. Like the sea-level curves presented (Figures 29, 44) the altitude of the Mockhorn barrier complex is uncorrected for tectonism in Figure 45. Sea level during deposition of the Mockhorn barrier system is as high as 2 m below present (MSL).

Figure 44. A proposed late Quaternary sea-level curve from approximately 80,000 years B.P. to the present is shown. Some researchers would adjust this curve so that the 10 C-14 dates of this study are equivalent with the Uranium-series date of Cronin et al. (1981).

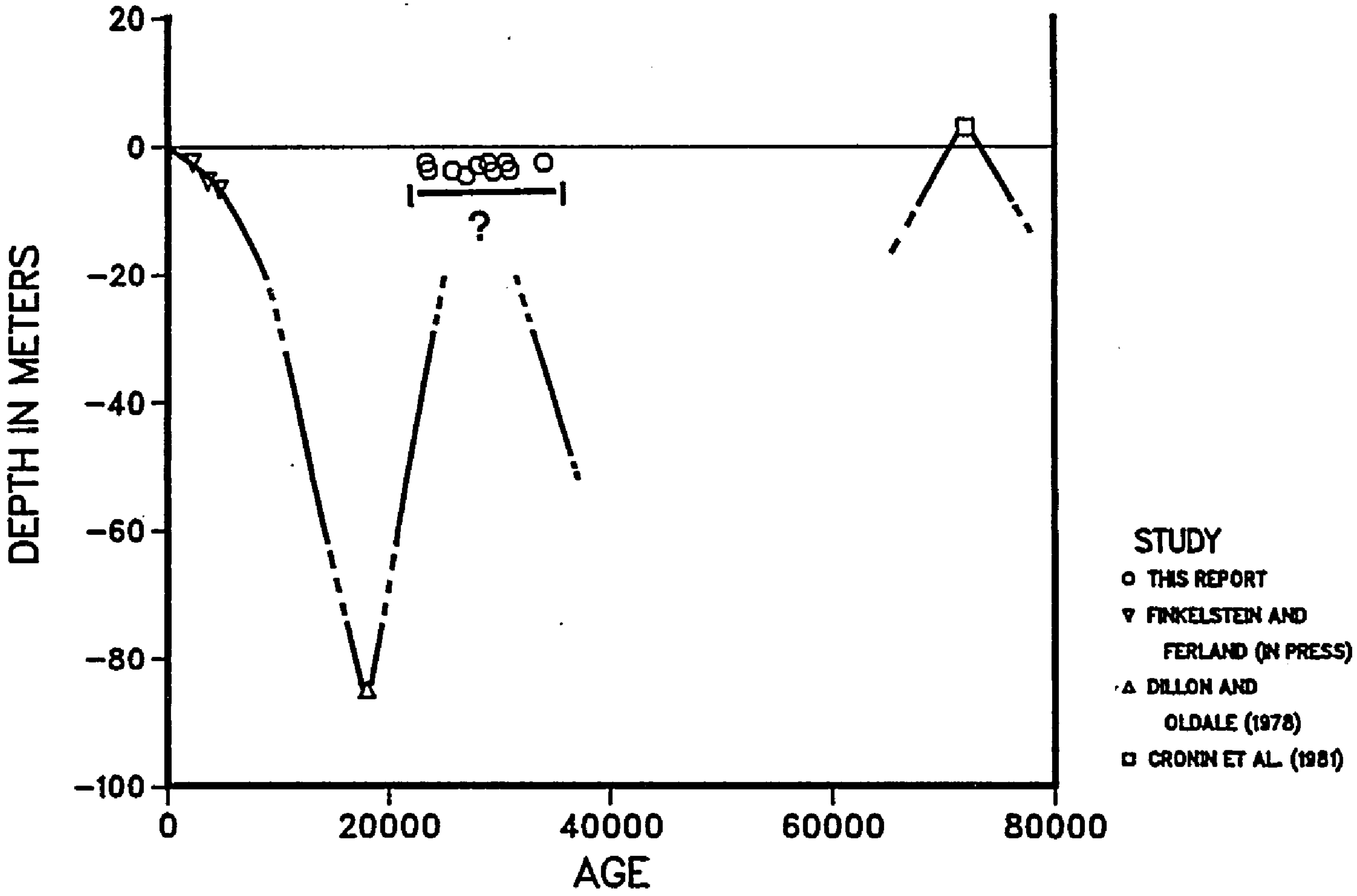
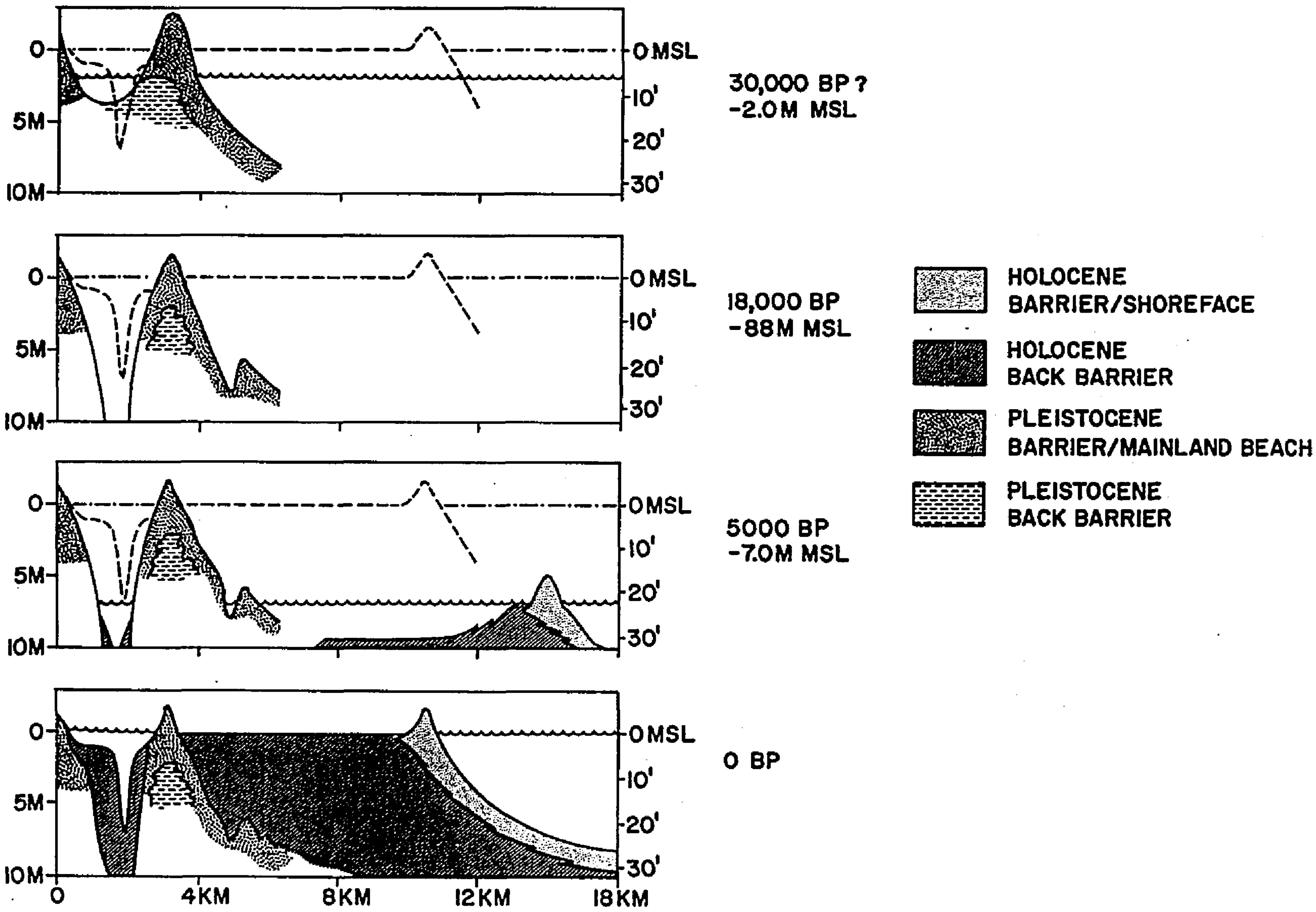

20
0
−20
−40
−60
−80
−100
DEPTH IN METERS
?
0
20000
40000
60000
80000
AGE
STUDY
○ THIS REPORT
▽ FINKELSTEIN AND FERLAND (IN PRESS)
△ DILLON AND OLDALE (1978)
□ CRONIN ET AL. (1981)

Figure 45. The coastal development of the study area is shown. At top Mockhorn Island is emplaced approximately 30,000 (?) years B.P. During glaciation sea level is lower and the Island and proto-Magothy Bay are scoured. With onset of the Holocene marine transgression a new barrier develops and migrates landward. This new island is Smith Island and its position is shown at about 5,000 years B.P. and at present. Note the infilling of Magothy Bay and the backbarrier region behind Smith Island.

COASTAL DEVELOPMENT SMITH-MOCKHORN ISLANDS



Correlations of the Mockhorn sequence with the extensive late Pleistocene marine terraces in the area of the middle Atlantic Coast are not clear. Table 17 exhibits the tentative correlations from this study. Available dates and geomorphic and stratigraphic evidence of the most prominent scarps imply a late Sangamonian or early Wisconsinan age (Mixon et al., 1981). A lowland underlain by mainly coarsening upward sands occurring seaward of these scarps along the Maryland Coast to Bethany Beach, Delaware has been interpreted as marking a major transgression approximately 1.5 m above present around 30,000 years B.P. (Owens and Denny, 1979). This unit is the Sinepuxent Formation and if correlative with the Mockhorn formation, these data together argue that the portrayal of mid-Wisconsinan sea levels lower than present 30,000 years B.P. in existing sea level curves may not apply to this section of the continental shelf. The abundance of micaceous minerals in the Mockhorn backbarrier sediments (Mockhorn formation) and the Sinepuxent Formation distinguishes them from older formations. Both formations are characterized by immature assemblages, i.e., high concentrations of more labile types such as amphiboles (notably hornblende) and small amounts of pyroxene (hypersthene and augite) (written communication, J.P. Owens,). However, the altitude of the Sinepuxent Formation is as high as 6 m, 4 m higher than Mockhorn Island, and therefore an argument correlating it to the Wachapreague Formation can be made.

The correlation of Mockhorn Island to the Sinepuxent Formation is based on their similar C-14 age dates, pollen assemblages, transgressive stratigraphy, and mineralogy. Mockhorn Island

TABLE 17

CORRELATION OF UPPER PLEISTOCENE STRATIGRAPHIC UNITS
IN EASTERN VIRGINIA AND MARYLAND

AGE	Virginia, South and west of Chesapeake Bay		Southern and central Delmarva Peninsula		
	Norfolk area, VA (Peebles, 1985)	James-York Peninsula (Johnson, 1976)	Eastern Shore in Virginia	Eastern Shore in Maryland (Owens and Denny, (1979)	Western Shore in Virginia and Maryland
Mid or early Wisconsinan, post 65,000 years B.P.		Poquoson Member of Tabb Formation	Mockhorn formation (informally named-this study) or upper Wachapreague Formation (Mixon, 1985)	Sinepuxent Formation	Kent Island Formation* (Maryland) (Owens and Denny, 1979)
Sangamon, 65,000 to 125,000 years B.P.	Lynnhaven Member of Tabb Formation	Lynnhaven Member of Tabb Formation	Wachapreague Formation (lower part-Mixon, 1985) Joynes Neck Sand (Mixon, 1985)	Ironshire Formation	Kent Island Formation* (Virginia) (Mixon, 1985) Occohannock Member of Nassawadox Formation (Mixon, 1985)
	Sedgefield Member of Tabb Formation	Sedgefield Member of Tabb Formation			Butlers Bluff and Stumptown Members of Nassawadox Formation (Mixon, 1985)

* Disagreement in age between cited authors.

associated deposition is believed distinct from the Wachapreague Formation as defined by Mixon (1985) due to the probable existence of a lithological contact and differences in altitude and stratigraphy. The Poquoson Member of the Tabb Formation (Johnson, 1976) may also not correlate to the Wachapreague Formation as the latter's altitude is closer to the somewhat older Lynnhaven Member.

The Mockhorn barrier is similar in height to a series of ridges developed along the lower Chesapeake Bay and the Back Bay-Albemarle Sound area. These ridges are identified as the Poquoson Member which formed when sea level was reported to be 1.5 to 3.0 m below present (not tectonically corrected) about 65,000 years ago (Johnson et al., 1985). This date is an estimate that is not based on any isotopic dating method. Quite possibly the Poquoson Member is younger. Such a correlation would need to consider if there is a difference in age.

Late Holocene

Sea-Level Adjustments

A relative sea-level curve for this study area, adapted from Finkelstein and Ferland (in press), is shown in Figure 30. Carbon-14 dates indicate a constant but not linear rise in sea level since 4,600 years B.P. Two inflection points are recognized: the first occurs at approximately 3,800 years B.P. which is located between two basal peats and commences a time of relatively faster sea-level rise, the other is a basal peat of 2,200 years B.P. which begins a time of relatively slower sea-level rise.

The study area is a part of the forebulge area from the last glaciation and within zone II of Clark et al. (1978) and zone D of Quinlan and Beaumont (1981). These studies show sea level continuously rising since at least 11,000 years B.P. Sea level rise for the western Atlantic slowed considerably between approximately 6,000 to 5,000 years B.P. (Lighty et al., 1982). Subsequent sea-level rise is probably from local neotectonic adjustments or sediment compaction rather than eustatic increases. Walcott (1972) discusses the problems of determining eustatic versus neotectonic sea-level changes because elastic and relaxation responses of the earth to the changing loads of late glacial time can be expected to result in differential movements and to persist in postglacial time by continued relaxation effects.

The data base from Figure 30 does not precede 4,600 years B.P. but the assumption is made that sea-level rise was then much greater. Using the age and depth of basal peats, a relatively slow rate of sea-level rise is calculated from 4,600 years B.P. to the historical period. A more rapid rise in sea level began at least 300 years ago (Froomer, 1980). The overall sea-level rise rate is 1.5 mm/yr calculated from 4,600 years B.P. to the present and respectively only 2.0 mm/yr and 1.1 mm/yr for the times of relatively faster and slower sea-level rise. These low rates of sea-level rise for this period agree with Belknap and Kraft (1977) in Delaware but are higher than that found in North Carolina by Heron et al. (1985).

Sedimentation

In response to sea-level and limited sediment availability, Smith Island has migrated landward creating the resulting transgressive stratigraphic sequence. Late Holocene inundation of Magothy Bay water onto Mockhorn Island has resulted in reworking of some Pleistocene sands, Holocene marsh growth, and an erosional scarp on the western shore of the Island. Transgressive lag deposits scattered below lagoonal sediments reflect the initial Holocene marine encroachment over Pleistocene deposits. Brackish water basal peats are found in a similar stratigraphic position below more northerly lagoonal deposits. These basal peats are dated as old as 4,620±80 years B.P. from a depth of -6.60 m (Finkelstein and Ferland, in press). This indicates that Smith Island and the other Virginia barrier islands were in existence at least this long and at a sea level of -6.60 m. Finkelstein and Ferland (in press) show these barrier islands to be 4 km offshore approximately 4,620 years B.P. Historically, Smith Island has retreated rapidly, at mean rates ranging between 4 and 15 m/yr (Rice et al., 1976).

The stratigraphy and subsurface geology point to mostly vertical sedimentary accretion rather than mainland inundation. This is a function of the relatively steep Pleistocene surface topography near the mainland shoreline (Figures 31-33, 37). Cores taken near the mainland show a relatively thick sequence of Holocene sediments. For example, Core MC-4 in transect E-E′ (Figure 37) contains almost 2 m of Holocene sediments (below MSL) but is only about 240 m from the Pleistocene mainland. By using a sea-level rise rate of 2 mm/yr

(Hicks et al., 1983; Finkelstein and Ferland, in press), 1000 years of vertical Holocene sedimentation is calculated. During this time only 240 m of mainland topography has been transgressed. Concurrently, Smith Island has retreated landward at a conservative rate of 5 m/yr. This accounts for the narrowing of the backbarrier region. This trend should continue because (1) the mainland Pleistocene topography is 3 m above MSL only 500 m from the backbarrier shoreline and (2) Smith Island continues to retreat in response to sea-level rise and low sediment supply. The same result was obtained by Finkelstein and Ferland (in press) who found relatively old and deep basal Holocene peats nearly adjacent to the mainland shore behind more northerly Virginia barriers.

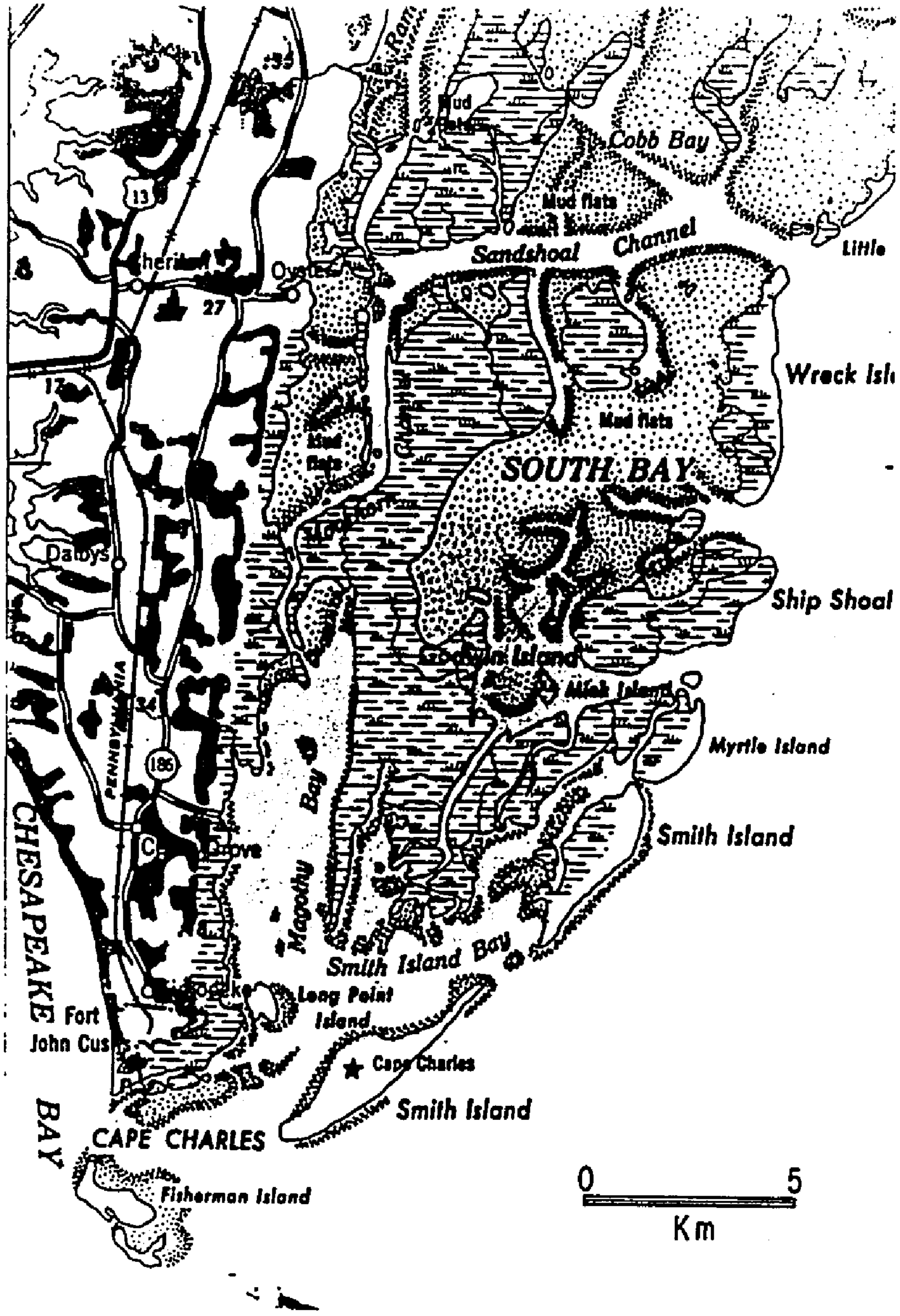
Stratigraphic evidence for a general change from a higher to lower energy environment is found in most backbarrier cores. This reflects the narrowing of the lagoon resulting in sedimentation occurring under progressively lower energy backbarrier conditions. With sand relatively unavailable the system has become dominated by suspended sediment deposition. The change from higher to lower energy depositional conditions in the backbarrier has created a "regressive" sequence of sedimentary deposits. As discussed by Reineck (1972), the regressive sequence from bottom to top consists of deposits of fine sand, mixed flat, mud flat, and salt marsh. A transgressive sequence would be reversed. Therefore despite the transgressing sea and retreating barrier island that create a transgressive stratigraphic sequence, the backbarrier is identified by a sequence of regressive deposits.

Locally, sediments interpreted as a sheltered lagoonal environment are recognized in cores. This environment is a result of deposition in inactive channel fill, small sheltered backbarrier bays, or deeply incised sheltered valleys. The latter is dependent upon the pre-Holocene topography. The initial Holocene transgression invaded these valleys which were conducive to deposition of fine grained sediment. Where the Holocene-Pleistocene contact is relatively shallow, higher energy open lagoon sediments are found. These sediments reflect the overtopping of the valleys by sea level. This interpretation is consistent with the work of Halsey (1978) who found, in interfluve valleys, a lower Holocene quiet water silty clay below a higher energy silty fine sand.

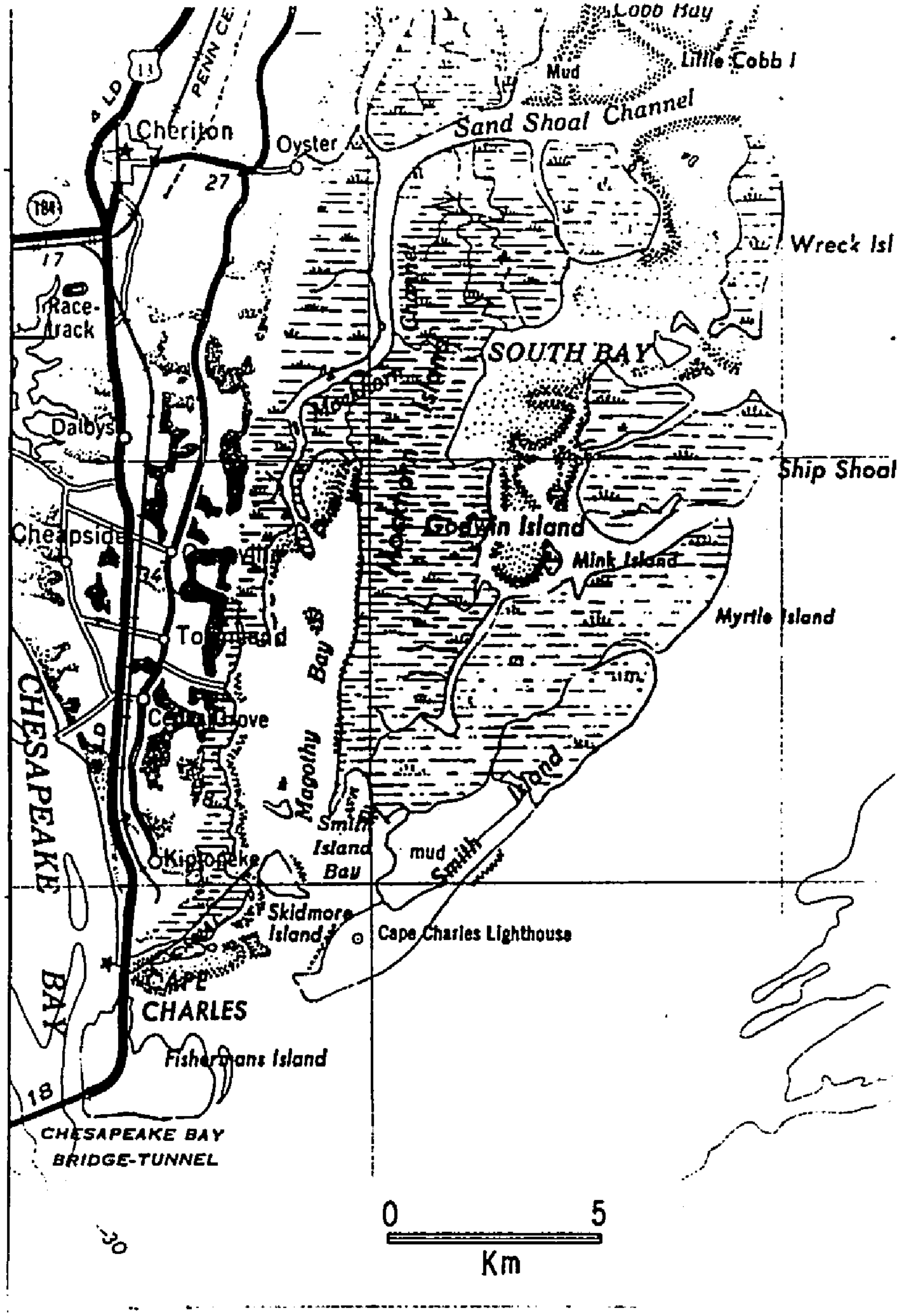
A conceptual model of backbarrier infilling may be correlated to the rate of sea-level rise and narrowing of the backbarrier region. Prior to 5,000 years B.P., Smith Island was farther offshore and retrograding rapidly with backbarrier sedimentation occurring under relatively high energy conditions. During the time of relatively faster late Holocene sea-level rise, between 5,000 and 2,200 years B.P., backbarrier sedimentation occurred subaqueously. Extensive marsh growth could not occur under mostly subtidal conditions. As sea-level rise slowed after 2,200 years B.P., the lagoon continued to slowly fill and extensive marsh growth began as subaqueous sedimentation changed to intertidal sedimentation in many areas. Dated subsurface marsh sediments are as old as approximately 2,000 years B.P. (Table 14). In spite of a more rapid sea-level rise rate of 3.6 mm/yr (Hampton Roads, Virginia) to 2.0 mm/yr (Lewes, Delaware) during the period 1940-1980 (Hicks et al., 1983), marshes continued to grow as suspended sediment deposition increased. Figures 46 and 47 show the tidal flat and marsh infilling behind Smith Island within the 20th Century. Kelley (1983) also noted a decrease in open water from 1880 to 1955, based on historical charts of the New Jersey barrier islands. Possibly deforestation, which began in the Colonial period, increased stream sediment loads and introduced abundant sediment into the estuarine system (Froomer 1980). Subsequently, because suspended sediment supply increased, marshes expanded. Maximum deposition would probably be expected in low marsh habitats (Letzsch and Frey, 1980).

The stratigraphy below backbarrier marshes showing a fining upward sequence supports the concept of, over time, coarse bedload sedimentation giving way to fine-grained suspended sedimentation. Present deposition of fine grained sediments is a reflection of lower backbarrier energy conditions and hydraulic models of inlet flow from Boon and Byrne (1981), and FitzGerald and Nummedal (1983). They indicate a flood dominance of bedload transport in open lagoonal systems, and ebb dominance after lagoonal infilling becomes advanced. Coarser grained bedload material (sand) should be first deposited where lagoonal infilling is less advanced and inlets are flood dominated. Later, with the backbarrier region more restricted and partially filled, such as the present study area, the ebb dominant inlet flushes coarser materials out of the system resulting in infilling of finer grained suspended sediment. Seismic records from Little Inlet indicate ebb dominance which probably result in the

Figure 46. Smith Island, Virginia and vicinity, 1946 (left, from U.S. Army Topographic Command 1.250,000 topographic map) and 1969 (right, from USGS 1.250,000 topographic map). Considerable infilling within the backbarrier region over a span of 23 years can be recognized.



CHESAPEAKE BAY
Cherit
Oyster
13
27
17
Dalbys
PENNSYLVANIA
34
186
C
Grove
Fort John Cus
CAPE CHARLES
Fisherman Island
Magothy Bay
Smith Island Bay
Long Point Island
Cape Charles
Smith Island
Mud flats
Cobb Bay
Sandshoal Channel
Little
Wreck Isl
SOUTH BAY
Mud flats
Channel
Ship Shoal
Godwin Island
Mink Island
Myrtle Island
Smith Island
0
5
Km



Cobb Bay
Little Cobb I
Mud
Sand Shoal Channel
LD
13
PENN CE
Cheriton
Oyster
27
184
17
Race-track
Wreck Isl
SOUTH BAY
Dalbys
Ship Shoal
Cheapside
34
Godwin Island
Mink Island
Myrtle Island
Townsend
Bay
Cedar Grove
CHESAPEAKE BAY
Magothy
Kiptopeke
Smith Island Bay
mud
Smith Island
Skidmore Island
Cape Charles Lighthouse
CAPE CHARLES
Fishermans Island
18
CHESAPEAKE BAY BRIDGE-TUNNEL
30
0
5
Km

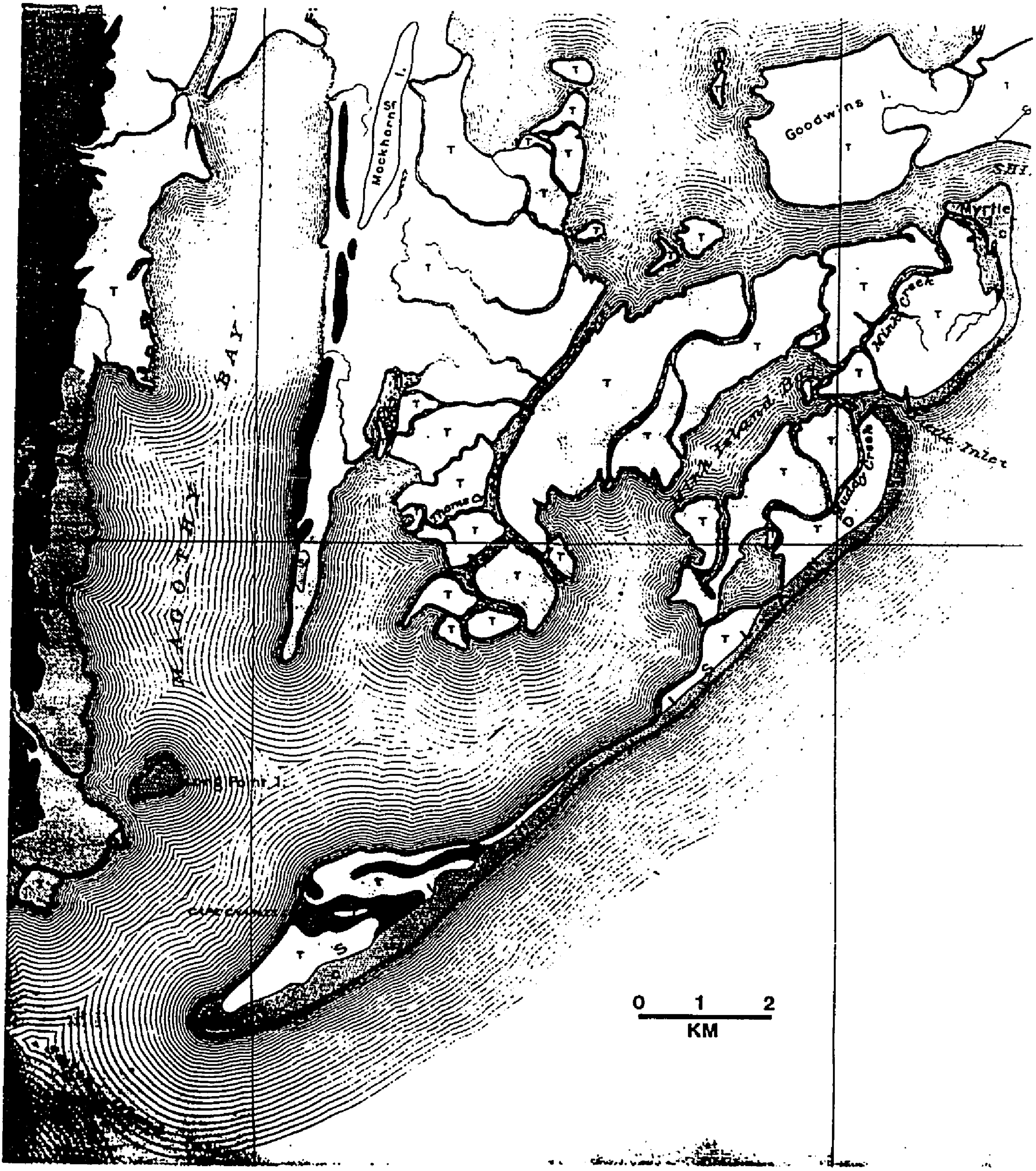


Figure 47. A 1917 Virginia Bureau of Soils map of the study area is shown above. When compared to Figure 46, infilling of the backbarrier region with new growth of salt marsh can be recognized.

present net loss of the coarser sediments from the backbarrier region (Figure 48).

The emergence and development of new salt marsh seems dependent only on the availability of a substrate in a low energy intertidal environment, not on any particular grain size. Relative sea level rise allows for continued growth. The stratigraphic sequence indicates that marshes are more abundant today than at any time during the mid to late Holocene. Additionally, the scarcity of agglutinated foraminifers below the immediate surficial layers suggest that marshes were less widely developed during accumulation of the backbarrier sediments than they are at present.

Unlike the upward fining sequence presented by Berelson and Heron (1985) in response to flood tidal delta deposition, no patterns of episodic sedimentation are observed in backbarrier cores from this study. Mostly continuous deposition of fine grained sediment is attributed to stationary inlets (Morton and Donaldson, 1973; Halsey, 1978) with insignificant flood tidal deltas, small ephemeral inlets, and limited distance of washover deposits. In contrast, a fining then coarsening upward stratigraphic sequence is readily observed in the backbarrier environment of Delaware; the Smith Island backbarrier deposits usually fine upward. Relative to coastal Delaware, the Virginia barrier islands and adjacent backbarrier system are starved of sand. In spite of their close proximity, the Smith Island backbarrier stratigraphic sequence differs from that found behind the Delaware Baymouth barriers.

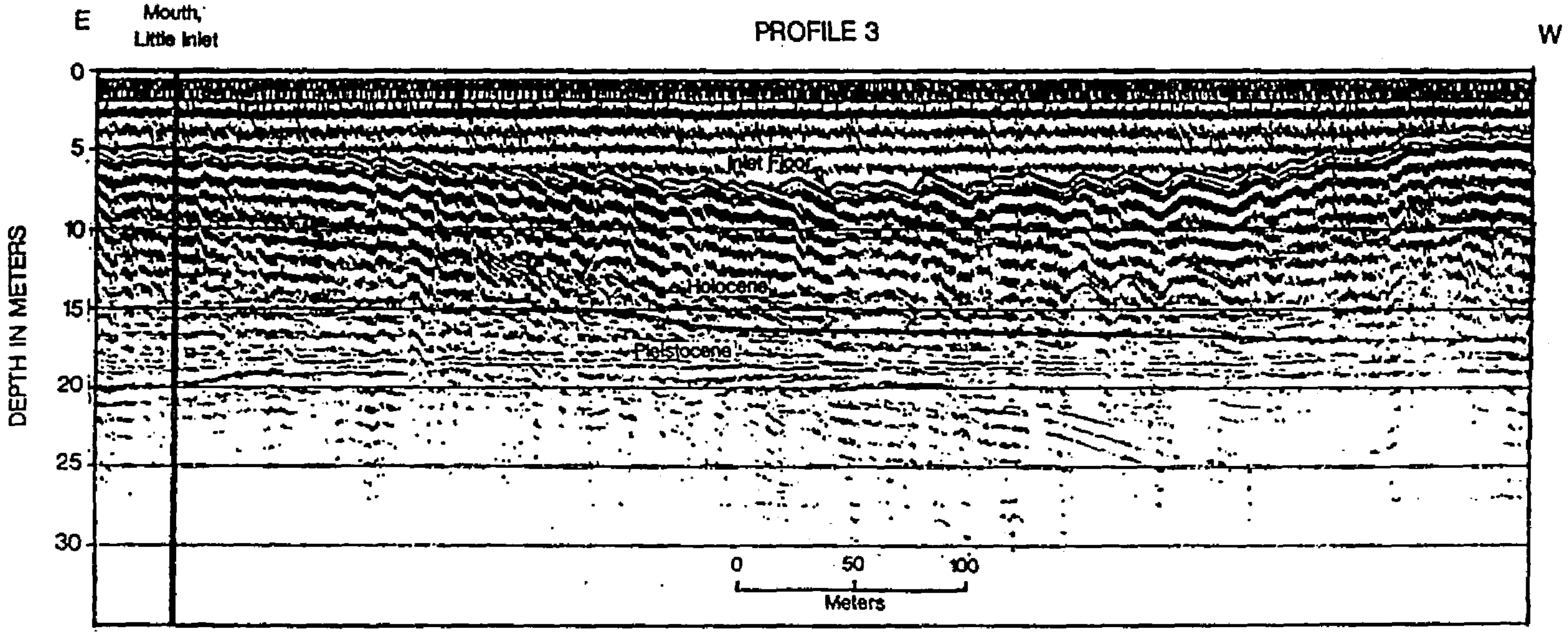


Figure 48. Shown above is a portion of seismic, subbottom profile 3 (see Figure 7 for location) that exhibits ebb-oriented sand waves on the inlet floor. This may indicate ebb-oriented bedload transfer. Also note the 15-17 meter Holocene/Pleistocene contact.

Backbarrier Sediment Sources

Three potential sources of sediment to the backbarrier are overwashed nearshore and barrier island sediments, drainage from the upland, and inlet-transported marine sediments. Each of these contributes some portion of the total sediment accumulation, but the relative proportion of each indicates the processes which are dominant in filling the backbarrier.

Overwash is apparent in many locations along Smith Island but is most evident at locations of former ephemeral inlets. Texture, sorting, and shell lag characteristics of washover sediments are rarely identifiable in the cores. This may be due to bioturbation, but, nevertheless, the large total width (up to 10 km) of the backbarrier system and the overall deficiency in barrier sand precludes the possibility that washover sediments constitute a significant backbarrier sediment source.

The Pleistocene upland may have been a source of sediment during the early filling of the backbarrier region. Coarse sediments are found in cores adjacent to the mainland. Drainage off the upland during the mid-Holocene may have deposited these sediments nearby. Letzsch and Frey (1980) noted the ability of torrential rains to move Pleistocene sand from the terrestrial fringe to the adjacent marsh surface. In addition, during the mid-Holocene, Magothy Bay was possibly nearly as wide and probably deeper. This may have permitted larger waves to develop. The short period chop, characteristic of inland waters, can erode a well-vegetated shoreline, thereby liberating sediment for subsequent sediment transport into adjacent lagoons. However, mainland deposits are presently contributing little sediment to the backbarrier region. Analyses of minerals, discussed earlier, show little or no mica and glauconite in mainland draining creeks despite their abundance in backbarrier sediments. In addition, the few creeks which enter the backbarrier region are small, have shallow gradients and low flow velocities, and probably carry little suspended sediment.

The most likely immediate backbarrier sources are offshore sediments, either carried southward along the coasts, or drifted shoreward from shelf deposits. Inlets represent the most likely avenue of transport of littoral and inner shelf sediments into the backbarrier region. Mineral analyses and inlet hydraulics support these conclusions. Marine derived sediments enter the backbarrier on flood tides, possibly deposited on flood tidal deltas, and are subsequently redistributed by tidal currents. Sands are deposited proximal to the inlets as the velocities drop in the tidal channel network. Silts and clays are carried to more distal portions of the backbarrier complex and subsequently deposited. Figures 46 and 47 exhibit this type of deposition leading to infilling of tidal flats and marshes. Onshore transport of sediment along the mid-Atlantic Bight has also been shown by Meza and Paola (1977) and Kelley (1980; 1983).

PRESERVATION POTENTIAL

Erosion destroys part or all transgressive barrier and backbarrier deposits as the the shoreline migrates landward. This is well documented by the cross-sections in this study. After Holocene barrier retrogradation, barrier sands over backbarrier sediments are replaced by approximately 1.0 m of nearshore sands above 2.5 m of backbarrier sediments (Figure 31). The thicker sands associated with the Pleistocene Mockhorn barrier relative to Smith Island may be a function of the rate of sea-level rise. Fischer (1961) predicted that a very rapid rise in sea level would preserve more of the barrier island section than a slow rise. Hence, the preservation of Pleistocene shoreface sands may indicate a rapid rise in sea level during the Mockhorn Island transgression. Late Quaternary sea-level curves of this and other studies (Figures 29, 43-44) show a rapid interstadial rise in sea level during mid-Wisconsinan time. A relatively slower Holocene rise in sea level is causing erosional transgression with removal of barrier and backbarrier sediment equal to the approximate -7.0 m MSL wave base depth.

The transgressive Mockhorn barrier deposits have been preserved for approximately 30,000 years. Subsequent transgressive events, although generally self-destructive, are needed to create a thicker sequence of barrier deposits. Sediments associated with Mockhorn Island are buried beneath backbarrier deposits associated with a more recent barrier. Slow transgression is removing much of the backbarrier sequence but the new barrier (Smith Island) will eventually migrate over the earlier one (Mockhorn Island). Stacking of transgressive sequences such as these are described in the rock record by Ryer (1977). In order to stack and preserve transgressive sequences, both transgressive and intervening regressive events are essential. Subsidence of the earlier barrier deposits during the subsequent regression and following transgression will provide a better potential for preservation.

The future migration of Smith Island has been calculated in order to generally determine the amount of Holocene and Pleistocene sediment preservation and the resulting facies geometry. A migration rate of 5.0 m/yr, a sea-level rise of 2.0 mm/yr, a wave base at 7.0 m below MSL, and a distance of 7.0 km between the two barriers was used. At these rates it will take approximately 1,400 years for Smith Island to reach Mockhorn Island. In this case, Smith Island will not exactly overtop Mockhorn Island but more likely the two islands will join as sea level will rise only 2.8 m. Nevertheless, cores 7-5, 6-4, 6-7, and 6-10 (Figures 31-33; Appendix 1), for example, show that Pleistocene sands will be preserved below Holocene backbarrier sediments and nearshore sands.

Much of both transgressive sequences could be preserved if relative sea level stops rising and sand becomes more available. In New South Wales, Australia, transgressive Holocene sequences are shown preserved below progradational barriers (Thom, 1984). In this case, sea level had reached its present position ca. 6,000-6,500 years B.P.

and, with sufficient sediment, transgressive deposits were overtopped by prograding bay barriers. Although unlikely, the depositional history of these Australian barriers may be analogous to Virginia providing a dramatic change in coastal dynamics occurs along the mid-Atlantic shoreline.

Economically, these kinds of stratigraphic sequences are potential sources and traps for oil and gas. Holocene and Pleistocene backbarrier sediments, respectively above and below Pleistocene sands, (Figures 31-34) may form impermeable seals and serve as potential source beds. The Pleistocene sands may be thick and widespread enough to act as a stratigraphic trap. Onlapping offshore muds are the best source of hydrocarbons but they lie above thin nearshore sands. Therefore another marine transgression or barrier progradation is needed to make use of this source.

Migrating inlets provide inlet filling sediments which may extend well below wave base, and thus, develop a high preservation potential during any major transgression. Kumar and Sanders (1974) reported that 20-40% of all barriers may be underlain by inlet-filling sediments and these sequences must be significantly common in the geologic record. In North Carolina, Moslow and Heron (1978) found that the Holocene sediments beneath Core Banks may represent a significant percentage of the material preserved within barrier systems. Because primary inlets along the Virginia barrier islands are mostly stationary (Morton and Donaldson, 1973; Halsey, 1978) ephemeral inlets were examined to determine their ability to preserve inlet sediments. Transects D-D′ and D-D″ (Figures 35-36) show the geometry of inlet filling sediments within a large and active ephemeral inlet. The shallow depth of the inlet bottom, approximately -2.5 m MSL, indicates that the preservation of inlet fill sediments is improbable. Only deeper backbarrier sediments found well below the channel bottom may be preserved.

MODERN ANALOGUES

Australia

Several intensive investigations have reconstructed the late Quaternary coastal development and sea-level history of bay barriers in New South Wales (Thom et al., 1978; Roy and Crawford, 1980; Roy and Thom, 1981; Thom et al., 1981). The most striking similarity to the Smith and Mockhorn barrier system are the outer Holocene and late Pleistocene inner barriers. The stratigraphic sequences of these inner and outer bay barriers of Australia are initially transgressive. Unlike Virginia, however, sands added to the Australian inner shelf during previous glacial periods are reworked and transported shoreward after the eustatic rise in sea level ceases (Roy and Thom, 1981; Thom et al., 1981). Subsequently, sand ridges associated with a marine regression are deposited.

Although the barrier complexes of Virginia and New South Wales show respective differences in morphology (barrier islands opposed to bay barriers), age (probably Middle Wisconsinan in contrast to definitely Sangamonian), late Holocene stratigraphy (transgressive versus originally transgressive but presently regressive), and where applicable, causes of sediment deficiency (alongshore, offshore, overwash and inlet fill processes versus deflation of sand from the beach and its movement inland into transgressive dunes), they are directly comparable in terms of mode of formation, stratigraphy at time of emplacement, and sequence of deposition.

Locally, transgressive barriers are present in New South Wales (e.g., Dee Why barrier, Thom, 1984). Should outer bay barriers also migrate landward, as has Newcastle Bight, which during historical times has receded at rates of 1 to 2 m/yr (Roy and Crawford, 1980), upper regressive sands would be destroyed. Subsequently, stratigraphically lower transgressive sequences of both inner and outer barriers may be preserved. The preservation of transgressive sequences from Virginia and Australia would occur from retrogradation of analogous outer barriers.

North America

An inner Pleistocene and outer Holocene barrier complex has been recognized along the Georgia coast. North of St. Catherines Inlet, the Holocene shoreline diverges away from the Pleistocene shoreline; the two shorelines are mostly welded together south of this inlet. These northerly islands are much like the Smith-Mockhorn system in that the lagoon landward of the older barrier has been reoccupied by Holocene backbarrier sediments.

The late Pleistocene barrier islands of Georgia are part of the Silver Bluff shoreline that were formed when sea level was about 1.4 m above the present level (Hoyt and Hails, 1967). Based on geographic position and barrier height, the Silver Bluff shoreline may be correlative to Mockhorn Island. However, differing neotectonic histories makes such a correlation speculative at best. The Silver Bluff shoreline and previous Pleistocene shorelines of Georgia that extend to an elevation of 30 m are generally indicated as transgressive barriers (Hoyt and Hails, 1967). However, no study exists that describes both the stratigraphic sequences below the Holocene and older barriers and discusses the facies relationships between the transgressive units.

Other Pleistocene barriers found behind Holocene barriers include the Live Oak barrier of the central Texas coast (LeBlanc and Hodgson, 1959) and the barriers of the Omar Formation in Delaware (Demarest et al., 1981). The former is found behind the regressive Holocene barrier deposits of Galveston Island and thus is not analogous to this study. Four transgressive barrier shorelines within the Omar Formation are found landward of the Holocene barrier island. Like Mockhorn Island, each barrier originated during a period of rising sea level and was abandoned as sea level fell. The time for deposition of these barrier complexes is relatively short with only the landward most deposits preserved. In some cases, regressive sand deposits are welded to the older Delaware barriers; an indication of a sea-level standstill or fall.

The Mockhorn and Omar barriers (Demerast et al., 1981) on the Delmarva Peninsula incorporate those deposits produced during several thousand years culminating in a sea-level highstand. A complex facies relationship is produced between Holocene backbarrier and barrier island deposits and Pleistocene older barrier units in response to continuous Holocene relative rise in sea level and landward migration of the Holocene barriers. The general model of deposition that emerges from these studies is one of transgressive barrier complexes preserved in a shore-normal direction or stacked on top of each other. Factors that contribute to this model are the low gradient Delmarva coastal plain, Pleistocene sea-level changes, and neotectonic adjustments. A rising sea level provides for a marine transgression with deposits partially preserved due to uplift or overtopping by the following transgression. The abundance of transgressive deposits due to these factors clearly describes the stratigraphy of this region.

SUMMARY AND CONCLUSIONS

82 cores in conjunction with seismic subbottom records were collected on and adjacent to the Smith-Mockhorn barrier island complexes. These data, along with the analyses of subsamples that describe the texture, mineralogy, and paleontology, and interpret the chronology, have provided (1) a local late-Quaternary sea level curve and (2) a model describing the depositional history, facies relationships, and preservational potential of multiple transgressive barrier island deposits.

The conclusions of this study lean heavily on several assumptions. The assumption that the C-14 dates are correct is the most questionable. Despite no proven model that would explain the contamination of samples C-14 dated in this study, the lack of reproducibility is clearly a problem. Although the pollen spectra is much alike other nearby assemblages dated approximately 28,000 years B.P., these dates are also based on a C-14 method that is near the limit of its usefulness. However, the multi-disciplinary data base and plausible explanations from the literature are incorporated to support conclusion 1. Another assumption is that sea level will continue to rise in the future. This continuous rise is necessary for the preservation of Pleistocene and older Holocene transgressive deposits and is used in conclusion 2. Each of these general conclusions is described in more detail below:

1) A relative sea-level highstand during mid-Wisconsinan time, ca. 30,000 years B.P., is determined from the collective data set of this study. These data include the barrier morphology and transgressive stratigraphic sequence below Mockhorn Island, C-14 dates, and micropaleontological analyses. Mockhorn Island is the result of a marine transgression during mid-Wisconsinan time. The uncertainty surrounding a high eustatic sea level at that time or neotectonic uplift raising the barrier as much as 40 m in 30,000 years is not unnoticed. However, the strength of the data from this study (10 C-14 dates, an interstadial pollen assemblage consistent with other mid-Wisconsinan spectra previously reported, and an extant transgressive barrier facies) and the concurring studies in nearby locales support this age for Mockhorn Island. The present position of Mockhorn Island is probably a result of both a higher then previously reported mid-Wisconsinan sea level and subsequent uplift rate.

Those arguing for an early Wisconsinan or late Sangamonian age for the Mockhorn Island transgression would need to totally ignore the C-14 dates. In addition, mainland beach sediments associated with the Mockhorn barrier are not stratigraphically equivalent to the late Sangamonian Wachapreague Formation of Mixon (1985). However, the Mockhorn barrier sequence may be correlative to previously described units in Virginia heretofore labeled as late Sangamon or early Wisconsin.

2) Multiple, yet distinct, sequences of transgressive sediments associated with the late Pleistocene Mockhorn Island and Holocene Smith Island barriers are recognized in vibracores. The Holocene

marine transgression has caused onlapping of backbarrier sediments onto Mockhorn Island and its associated nearshore environment. The contact between the two sequences may be conformable or characterized by a transgressive lag deposit.

Transgressive Mockhorn Island sediments are composed of medium sand overlying lagoonal mud with scattered interbedded peaty clays and fine sand. The peaty clays may be the result of marshes and the fine sand from flood tidal deltas. Seaward of this island are associated shoreface sands presently below Holocene backbarrier deposits. A relatively rapid rise in sea level during Mockhorn Island time probably is responsible for the preservation of these sands.

Similarly, Smith Island overlies backbarrier deposits. Sediment is primarily introduced into the backbarrier environment through tidal inlets; overwash and mainland runoff are less significant. Depositional environments interpreted from the Holocene backbarrier sediments generally fine upward from open lagoon to tidal flat to marsh. A basal Holocene peat is not encountered. The fining-upward sequence is due to a continuous narrowing of the backbarrier region resulting in infilling occurring under progressively lower energy conditions. Rapid retreat of the Holocene barriers and a relatively steep mainland shoreline has provided this depositional setting.

With further Holocene sea-level rise, Smith Island will migrate landward. Although much of the Holocene backbarrier sequence will be destroyed, the lower deposits will be preserved above transgressive sediments associated with Mockhorn Island. A stacking and possible preservation of transgressive deposits should occur. The more rapid the rise in sea level, the more complete the preservation. If the Holocene barrier should prograde in the future, or sea level greatly fall, the transgressive sediments will be preserved both laterally and vertically. Less likely are the preservation of ephemeral inlet deposits. Despite the report of deep ephemeral inlet fill deposits in North Carolina, the inlets periodically open along Smith Island were only 2.5 m deep.

The stratigraphy of the study area is clearly described by transgressive deposits. Transgressive barrier deposits associated with the outer Holocene and the inner Pleistocene islands interact to produce a complex facies relationship. Late Quaternary sea-level fluctuations, neotectonic adjustments, and the relatively low-gradient Delmarva coastal plain provide a general model of deposition that results in barrier complexes preserved shore-normally or stacked vertically.

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APPENDIX

Individual vibracore and pound core logs.

Core: 6A

Date: August, 1984

Elevation (msl): -91 cm

Total Depth: 63 cm

Location: Smith Island upper shoreface
(Transect 6)

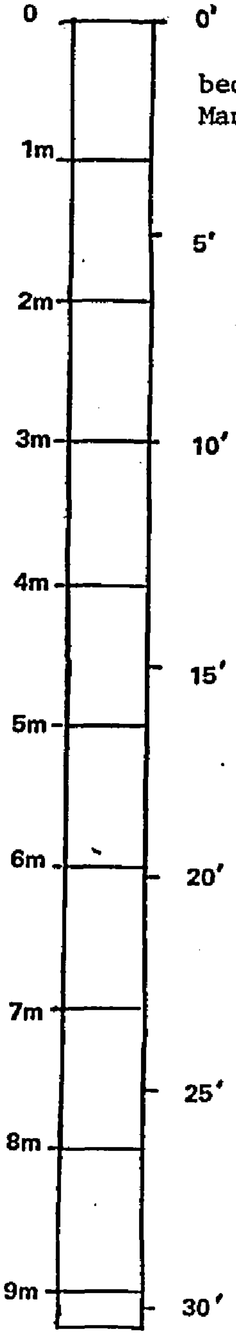
Compaction: None

Note: Diver Pound Core

ENVIRONMENT

DESCRIPTION

Shoreface



Tan, fine sand. Some thick heavy mineral beds and some shell fragments. No bioturbation. Many heavy minerals, no mica.

Core: 6B

Date: August, 1984

Elevation (msl): -1.52 m

Total Depth: 65 cm

Location: Smith Island upper shoreface
(Transect 6)

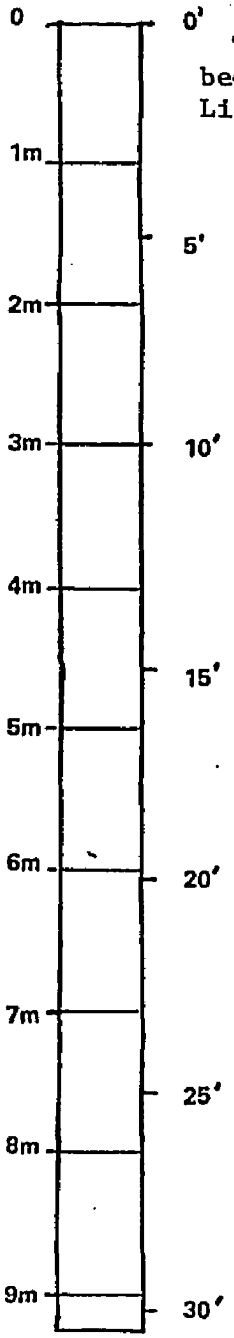
Compaction: None

Note: Diver Pound Core

ENVIRONMENT

DESCRIPTION

Shoreface



Tan fine clean sand. Some thin heavy mineral beds. Small fragments of shell. No bioturbation. Little mica.

Core: 6C

Date: August, 1984

Elevation (msl): -2.44 m

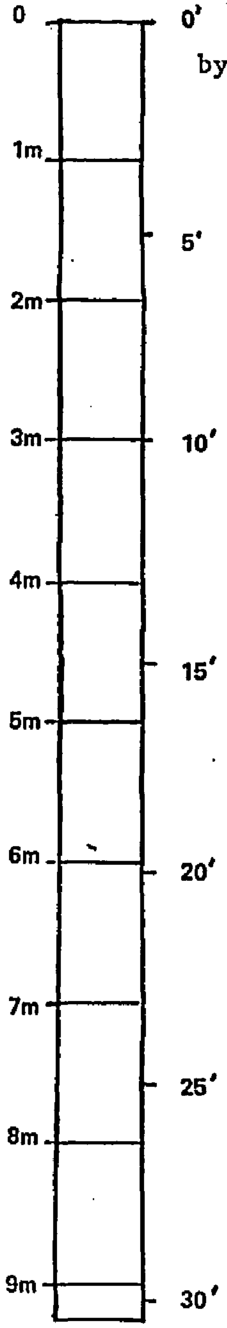
Total Depth: 35 cm

Location: Smith Island upper shoreface
(Transect 6)

Compaction: None

Note: Diver Pound Core

ENVIRONMENT	**DESCRIPTION**
Shoreface	Tan fine sand, very clean. Structures disturbed by coring process.



Core: 6D

Elevation (msl): -4.0 m

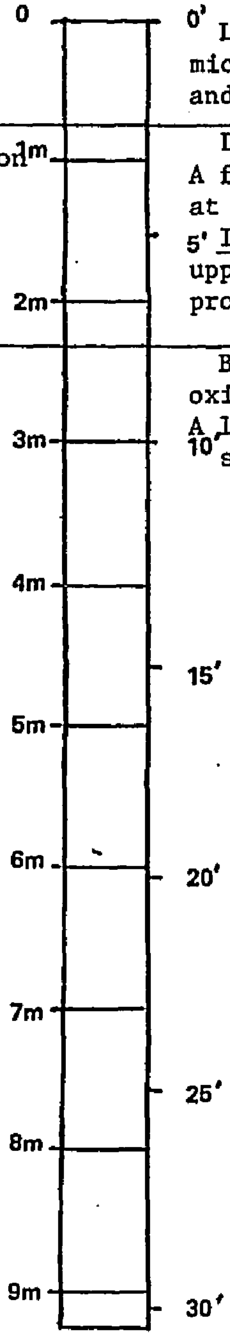
Location: Smith Island shoreface (lower?)

Date: August, 1985

Total Depth: 2.70 m

Compaction: None?

ENVIRONMENT	DESCRIPTION
Shoreface	Light grey sand, fine grained. Considerable mica. A little mud mixed in. Heavy mineral beds and a few round burrows. Sharp lower contact.
Sheltered Lagoon (Tidal Flat?)	Dark grey, much clay and silt. A little vegetation. A few oyster shells and many mud snails, especially at lower contact. At lower contact six whole *I. obsoleta* shells in 3 cm zone. Bottom and upper contact sharp. No distinct burrows; probably completely bioturbated.
Pleistocene Lagoon	Bluish-grey mud and sand, very compacted, some oxidization as recognized by iron staining (orange). A little organic debris and much mica. About 38% sand, the rest silt and clay.



Core: 6E

Date: August, 1985

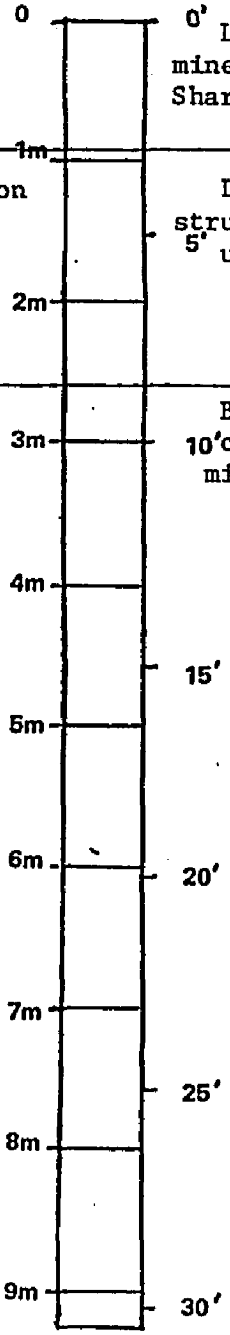
Elevation (msl): -5.18 m

Total Depth: 2.65 m

Location: Smith Island shoreface (lower?) (Transect 6)

Compaction: None?

ENVIRONMENT	DESCRIPTION
Shoreface	Light grey fine sand, a little mud. Some heavy mineral beds. Only a little mica, no burrows. Sharp lower contact.
Sheltered Lagoon (Tidal Flat?)	Dark grey mud, very homogeneous. No sedimentary structures. A few small shell fragments. Sharp upper and lower contacts.
Pleistocene Lagoon	Bluish-grey mud and sand. Some oxidation. Very compacted. A little organic debris and a little mica.



Core: 6-1

Date: July, 1980

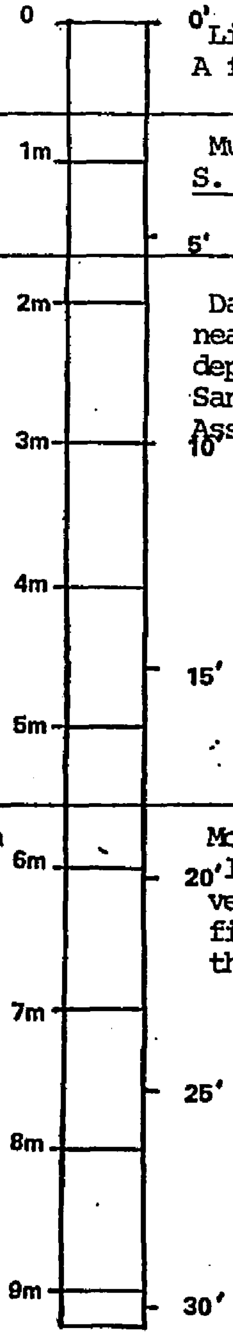
Elevation (msl): +0.3 m

Total Depth: 7.85 m

Location: On small washover landward of northern Smith Island

Compaction: 0.20 m

ENVIRONMENT	DESCRIPTION
Washover	Light grey, mostly fine-grained well-sorted sand. A few assorted shells at surface.
Salt Marsh	Mud and sand but fines downward. Much *S. alterniflora* vegetation.
Open Lagoon	Dark grey mud and sand, burrowing recognized near top of unit. Coarsens to more sand with depth. One burrow near top is 2 cm X 8 cm. Sand beds between 4 m and bottom of unit. Assorted lagoonal shell material found throughout.
Sheltered Lagoon	Mostly heavily bioturbated mud with some sand lamanae. Some tiny cracked shells and some vegetation mixed in with the mud. A few sand filled circular burrows. Texturally much finer than unit above. Also much more homogeneous.



Core: 6-2

Date: July, 1980

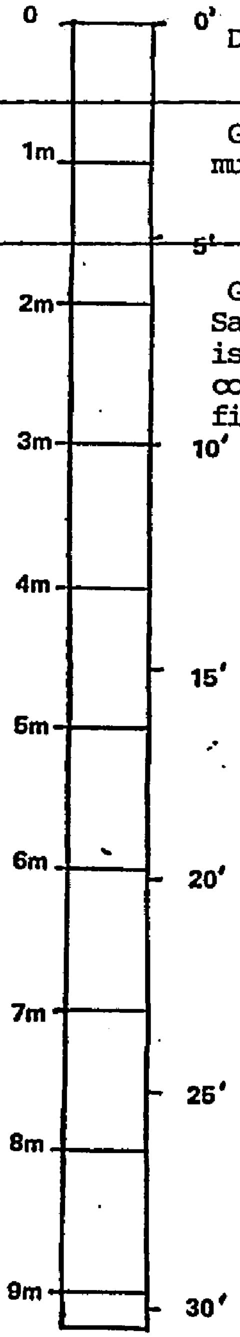
Elevation (msl): at MSL

Total Depth: 6.12 m

Location: In S. alterniflora marsh landward of Smith Island. Just landward of Mink Island Bay.

Compaction: 0.20 m

ENVIRONMENT	DESCRIPTION
Salt Marsh	Dark grey sandy mud with much marsh vegetation.
Tidal Flat	Grey sandy mud with several oyster drills and mud snails. Several sand filled round burrows.
Open Lagoon	Grey muddy sand, becomes more sandy with depth. Sand bedding is not well developed, bioturbation is common. Intact shells include an Atlantic cockle, bay scallops, and a C. cancellata. Sand filled burrows are very common.



Core: 6-3

Elevation (msl): at MSL

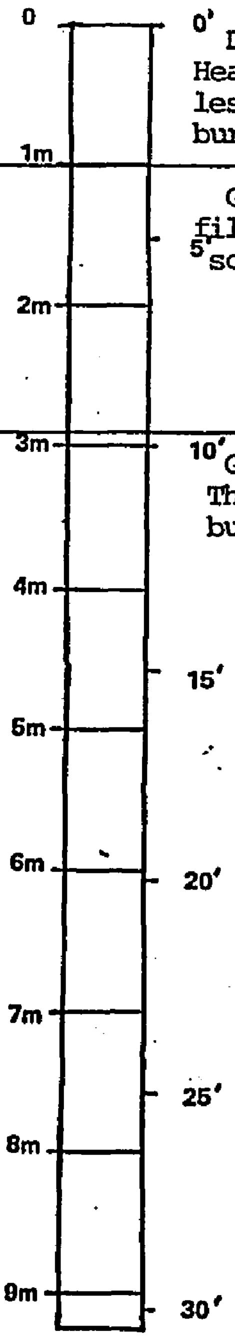
Location: At center of S. alterniflora marsh landward of Smith Island.

Date: July, 1980

Total Depth: 5.87 m

Compaction: 0.20 m

ENVIRONMENT	DESCRIPTION
Salt Marsh	Dark grey mud coarsening down to a sandy mud. Heavy accumulation of S. alterniflora at top, less with depth. Towards bottom some sand filled burrows and sand lamanae.
Tidal Flat	Grey sandy mud. Most sand is mixed in as sand filled burrows. Heavily bioturbated and a few scattered oyster shells.
Open Lagoon	Grey muddy sand with common 1 to 2 cm sand beds. The bedding is planar horizontal. Sand filled burrows are common, especialy near top of unit.



Core: 6-4

Date: July, 1980

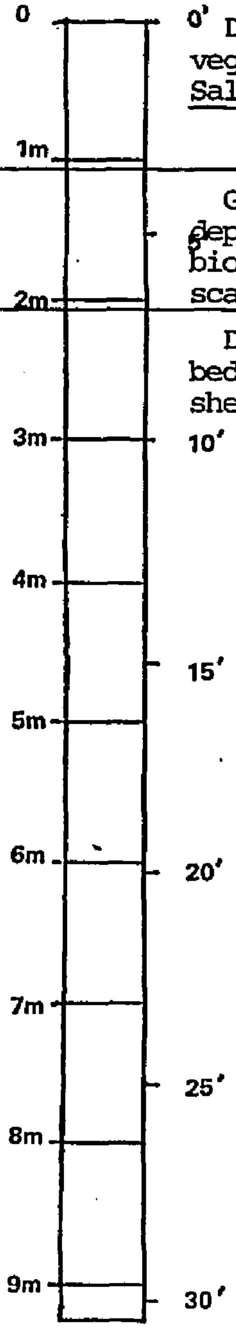
Elevation (msl): at MSL

Total Depth: 5.49 m

Location: Adjacent to western side of Main Ship Shoal Channel

Compaction: 1.0 m

ENVIRONMENT	DESCRIPTION
Salt Marsh	Dark grey silty mud with little sand. Heavily vegetated at top by mostly *S. alterniflora*. A little *Salicornia* also. Less vegetation near lower contact.
Tidal Flat	Grey sand and mud that coarsens to more sand with depth. No sedimentary structures, completely bioturbated. Oyster shells at 1.2-1.5 m and scattered mud snail shells. Scattered vegetation also.
Open Lagoon	Dark grey sand and mud. Some horizontal sand beds. Otherwise bioturbated. Scattered *M. mercenaria* shell fragments. Also some *M. lateralis* shells.



Core: 6-5

Date: July, 1980

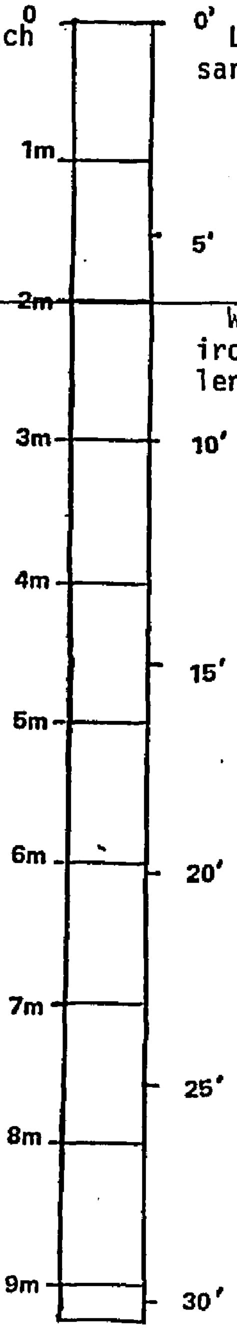
Elevation (msl): -0.5 m

Total Depth: 3.2 m

Location: Lower foreshore of western Mockhorn Island

Compaction: 0.4 m

ENVIRONMENT	DESCRIPTION
Pleistocene Beach	Light tan to orange-tan medium well-sorted sand. Lower contact sharp but conformable.
Pleistocene Lagoon	Well-compacted bluish-dark grey mud with iron-stained (oxidized) sand lenses. Several lenticular beds. At bottom a brownish peat.



Core: 6-6

Elevation (msl): + 0.2 m

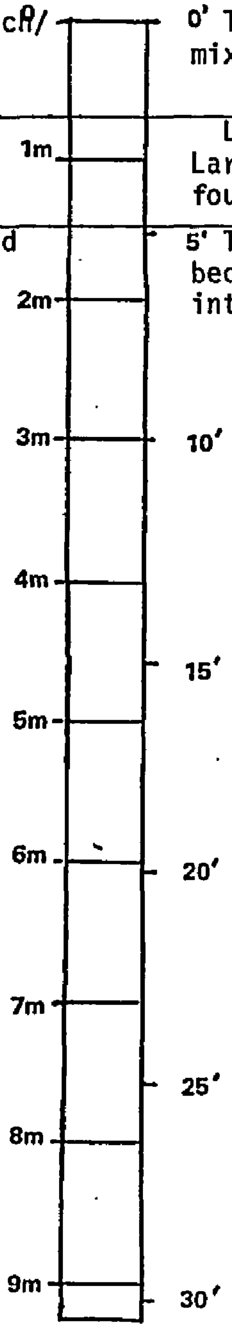
Location: On mainland shoreline

Date: July, 1980

Total Depth: 2.29 m

Compaction: 0.5 m

ENVIRONMENT	DESCRIPTION
Backbarrier Beach/ Salt Marsh	0' Tan medium sand with many stems of S. virginica mixed in.
Soil Horizon	Light grey mostly sand with some mud mixed in. Large tree roots (8-10 cm) or branches also found. Several sand filled burrows.
Pleistocene Sand Beach	5' Tan medium sand, well sorted with heavy mineral beds near bottom. Large red roots at top extend into sand.



Core: 6-7

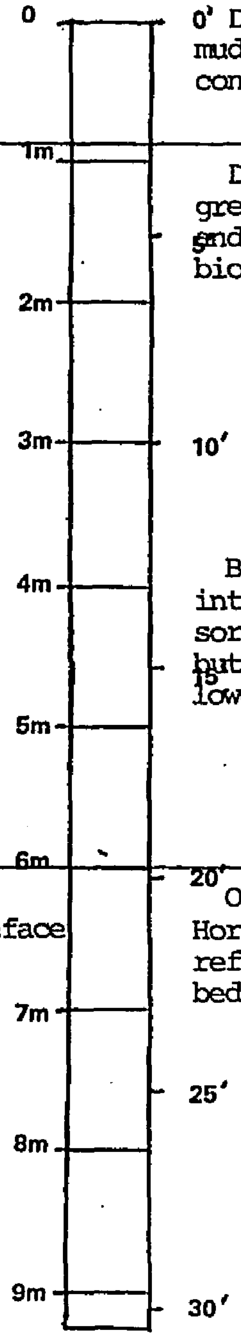
Elevation (msl): at MSL

Location: 750 m landward of Main Ship Shoal Channel

Date: Sept., 1982

Total Depth: 7.77 m

Compaction: 0.75 m



ENVIRONMENT	DESCRIPTION
Salt Marsh	0' Dark grey heavily vegetated (*S. alterniflora*) mud. A little sand at top, more towards lower contact.
Open Lagoon	Dark grey sand and mud with interbedded light grey sand beds. Bedding is thinly interlayered and lenticular. Little bioturbation and no biota. Between 5 and 6 meters the sand and mud grades into a light grey fine sand. This sand is well sorted and very clean. No apparent structures but abundant heavy minerals and mica. Gradational lower contact
Pleistocene Foreshore/Shoreface	Orange-tan fine, well sorted, mica enriched sand. Horizontal bedding. Subtle truncation planes, reflecting brief periods of erosion (?), divide the beds into sets. Some trough cross-bedding.

Core: 6-8

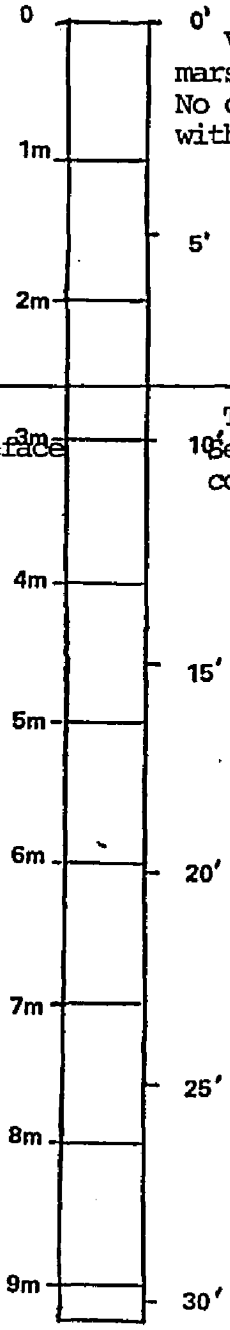
Date: Sept., 1982

Elevation (msl): ≈0.2 m

Location: Adjacent to Eggnog Creek, about 1 km from Mockhorn Island.

Total Depth: 4.10 m

Compaction: 1.0 m



ENVIRONMENT	DESCRIPTION
Tidal Flat	Very massive dark grey mud and sand. Several marsh periwinkles and some vegetation near surface. No clear bioturbation structures. Becomes coarser with depth.
Pleistocene Foreshore/Shoreface	Tan, generally clean, well-sorted fine sand. Several coarse zones consisting of pebbles and coarse sand. Some graded and horizontal bedding.

Core: 6-9

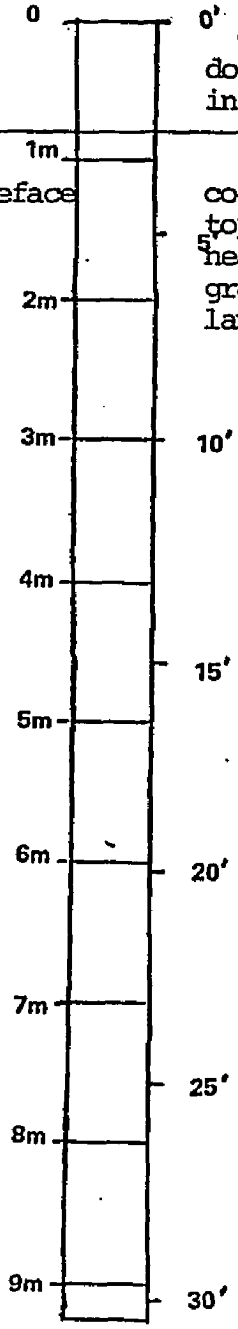
Date: Sept., 1982

Elevation (msl): at MSL

Total Depth: 3.66 m

Location: Approximately 500 m east of Mockhorn Island

Compaction: 0.70 m



ENVIRONMENT	DESCRIPTION
Salt Marsh	Grey mostly sand with mud. Vegetation at top does not extend below 75 cm. Some bioturbation including a 5 cm long, 2 cm wide burrow.
Pleistocene Foreshore/Shoreface	Orange-tan clean sand that grades to zones of coarse sand and pebbles. Some bioturbation at top. Upper portion may be lower shoreface, nearer to bottom is upper shoreface. (i.e., fine grained bioturbated lower shoreface grading into laminated coarser upper shoreface and then foreshore.

Core: 6-10

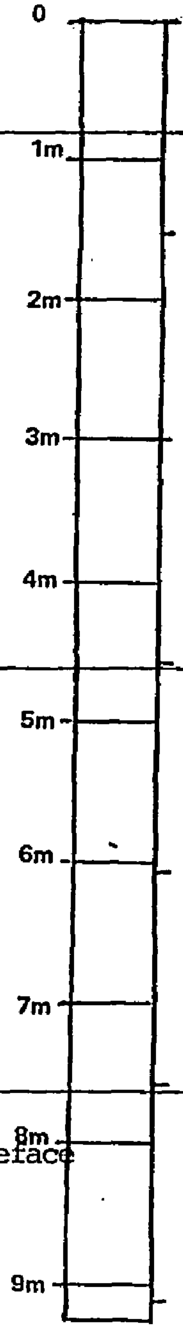
Elevation (msl): at MSL

Location: Adjacent to Eggnog Creek, about 1.25 km west of Main Ship Shoal Channel

Date: Sept., 1982

Total Depth: 8.21 m

Compaction: 0



ENVIRONMENT	DESCRIPTION
Salt Marsh	Grey mud, little sand. Heavily vegetated with S. alterniflora.
Tidal Flat	Grey mud and sand, some muddy and sandy zones. Two zones of oyster shells, one at 3.0 m, the other at 4.3 m. Sediment is massive and completely bioturbated. A little scattered vegetation.
Open Lagoon	Grey sand and mud, mostly sand. No sedimentary structures. A few oyster shells at 6.0 m. Below 7.0 m the sediment is a light grey fine grained sand with just a little mud. Heavy minerals are abundant and appear laminated. Lower contact is gradational.
Pleistocene Foreshore/Shoreface	Tan to orange fine sand. Well developed laminations.

Core: 6-11

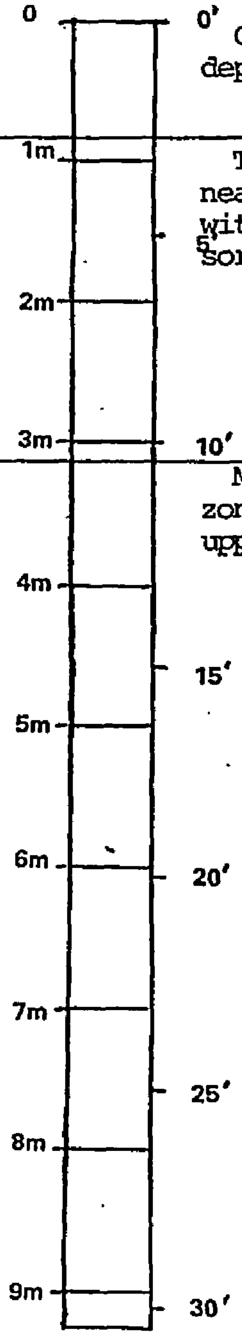
Elevation (msl): +0.3 m

Location: On Mockhorn Island between two beach ridges (old inlet?).

Date: Sept., 1983

Total Depth: 4.88 m

Compaction: 0.5 m



ENVIRONMENT	DESCRIPTION
Salt Marsh	Grey tacky sandy mud that becomes coarser with depth. Much S. alterniflora at surface.
Pleistocene Foreshore	Tan to orange-tan medium sand. Slightly muddy near surface. Some round burrows at top along with mottled appearance. Much cleaner and well-sorted below 2.0 m.
Pleistocene Lagoon	Massive dark grey mud with much clay. Several zones of vegetation but not in situ. Sharp upper contact.

Core: 7-1A

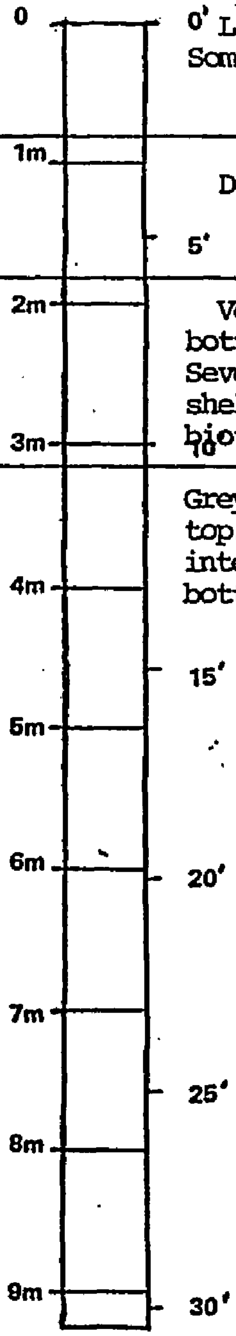
Elevation (msl): +0.5 m

Location: Upper foreshore on Smith Island.

Date: May, 1982

Total Depth: 5.82 m

Compaction: 0.2 m



ENVIRONMENT	DESCRIPTION
Barrier Beach Foreshore	Light grey fine sand with heavy mineral beds. Some storm debris mixed in (plant and wood material).
Salt Marsh	Dark grey mud. *S. alterniflora* vegetation.
Tidal Flat	Very muddy at top becoming sandier towards bottom. Many oyster shells between 2.1 and 2.7 m. Several mud snails along with a cross barred venus shell and a quahog shell recognized. Very much bioturbated throughout.
Open Lagoon	Grey muddy sand with more mud and less sand towards top. Flaser beds at 4.5 m along with many coarsely interlayered sand beds. Some bioturbation near bottom but still quite sandy.

Core: 7-1

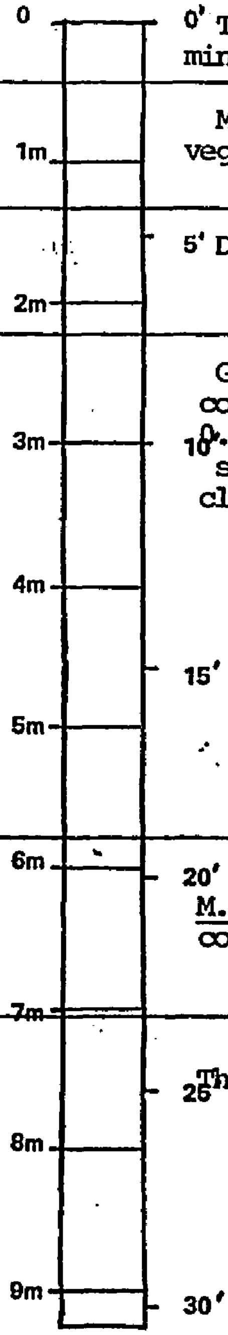
Date: May, 1982

Elevation (msl): +0.5 m

Total Depth: 7.90 m

Location: On small washover landward of Smith Island

Compaction: 0.20 m



ENVIRONMENT	DESCRIPTION
Washover	Tan to light grey fine sand with many heavy minerals. A little marsh vegetation also found.
Salt Marsh	Mostly mud, a little sandier at top. Heavily vegetated with <u>S. alterniflora</u>.
Tidal Flat	Dark grey mud with many half shells of oysters.
Open Lagoon	Grey muddy sand with more mud near upper and lower contacts. Many planar sand beds that range from 0.5 to 3.0 cm in thickness. In more sandy zones some flaser bedding is seen. Several razor clam and quahog shells are also identified.
Sheltered Lagoon	Dark grey mud. Heavily bioturbated. Some <u>M. lateralis</u> shells are also identified. The unit coarsens upward and downward.
Open Lagoon	Light grey fine sand with heavy mineral laminations. Three round burrows identified.

Core: 7-2

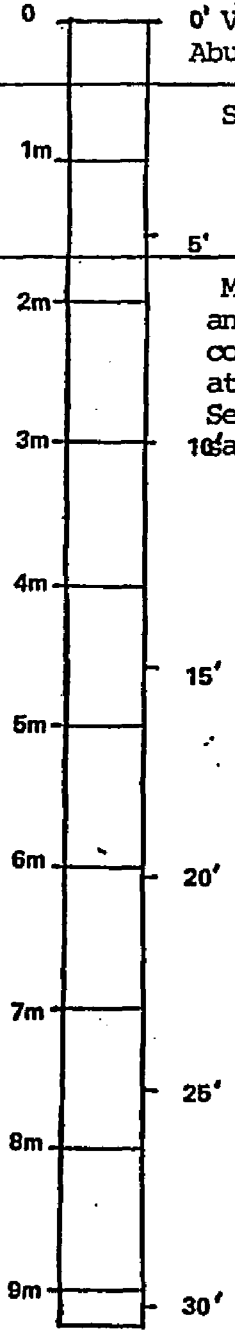
Date: May, 1982

Elevation (msl): at MSL

Total Depth: 6.40 m

Location: In S. alterniflora marsh between Smith Island and Mink Island Bay.

Compaction: 0.10 m



ENVIRONMENT	DESCRIPTION
Salt Marsh	Very fine brown sand with some marsh vegetation. Abundance of sand may be related to washover event.
Tidal Flat	Sand and mud very bioturbated, mostly homogeneous.
Open Lagoon	Muddy sand, dark grey with interbedded finely and coarsely interlayered sand beds. Mostly coarsely interlayered at top and finely interlayered at bottom. Two large oyster shells at 5.0 m. Several small vertical burrows. Becomes mostly sand at very bottom of core.

Core: 7-3

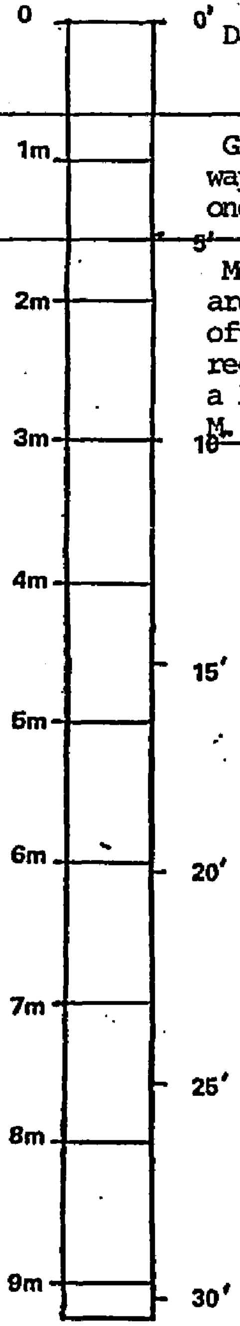
Elevation (msl): at MSL

Location: In S. alterniflora marsh just landward of Mink Island Bay.

Date: May, 1982

Total Depth: 6.60 m

Compaction: 0.50 m



ENVIRONMENT	DESCRIPTION
Salt Marsh	Dark grey mud with much S. alterniflora vegetation.
Tidal Flat	Grey, mostly mud but some sand introduced by way of burrows. Lots of shell fragments and one oyster shell. Heavy bioturbation.
Open Lagoon	Mostly light grey sand with some mud. Mud beds are well developed, vary in thickness, and are often discontinuous. Flasar bedding is also recognized. Near bottom are many shells from a large eared ark, razor clam, quahog, and M. lateralis.

Core: 7-4

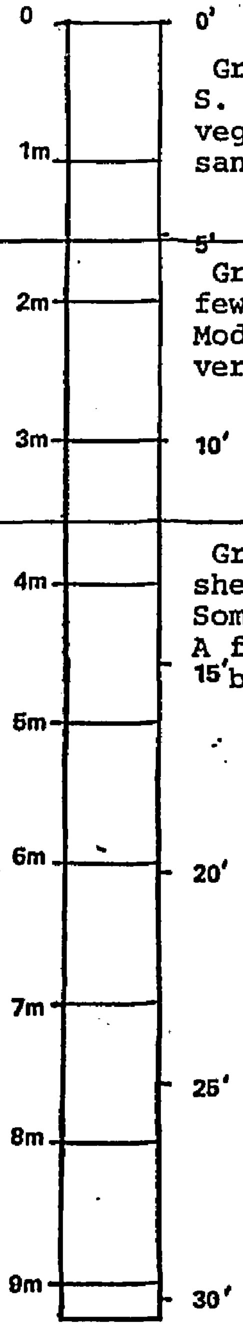
Date: May, 1982

Elevation (msl): at MSL

Total Depth: 7.30 m

Location: In S. alterniflora marsh adjacent to Black Rock Channel

Compaction: 0.10 m



ENVIRONMENT	DESCRIPTION
Salt Marsh	Grey, mostly fine grained with much S. alterniflora marsh vegetation. Less vegetation toward bottom of unit. Some sand introduced from bioturbation.
Tidal Flat	Grey mud with more sand with depth. A few large sand beds near bottom of unit. Moderately bioturbated, horizontal and vertical burrows seen.
Open Lagoon	Grey muddy sand. Many broken *M. lateralis* shells. Several broken ark and cockle shells. Some burrows and several worm tubes recognized A few discontiuous planar horizontal sand beds.

Core: 7-5

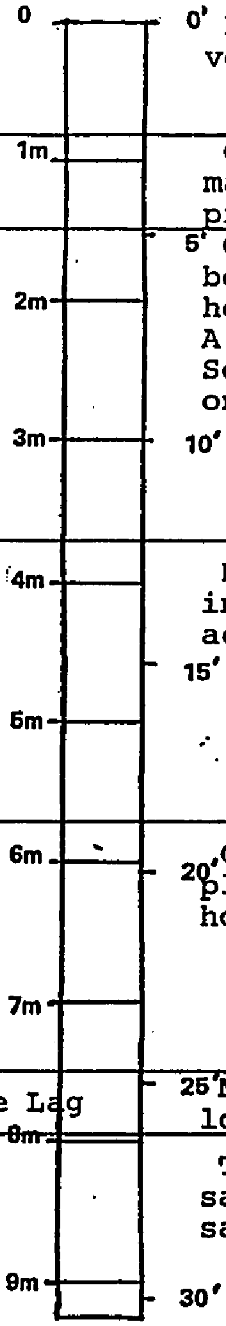
Date: May, 1982

Elevation (msl): at MSL

Total Depth: 9.05 m

Location: Just landward of Main Ship Shoal Channel

Compaction: 0.20 m



ENVIRONMENT	DESCRIPTION
Salt Marsh	Dark grey mud with much S. alterniflora vegetation
Tidal Flat	Grey mud with oyster shells. Unit is massive as no sedimentary structures are present.
Open Lagoon	Grey muddy sand with many thick sand beds near bottom of unit. Many discontinuous horizontal coarsely interlayered beds. A few lenticular beds in upper section. Several large burrows especially a vertical one at 2.5 m.
Sheltered Lagoon	Dark grey mud with some vegetation mixed in. Several zones of heavy vegetation accumulation.
Open Lagoon	Grey muddy sand with several discontinuous planar sand beds. A few vertical and horizontal burrows.
Transgressive Lag	Many broken shells and vegetation. Erosiona lower contact.
Pleistocene Foreshore/ Shoreface	Tan-orange (oxidized) well-sorted fine sand. Interbedded with blue clay. Some sand is cross-bedded.

Core: 7-6

Elevation (msl): at MSL

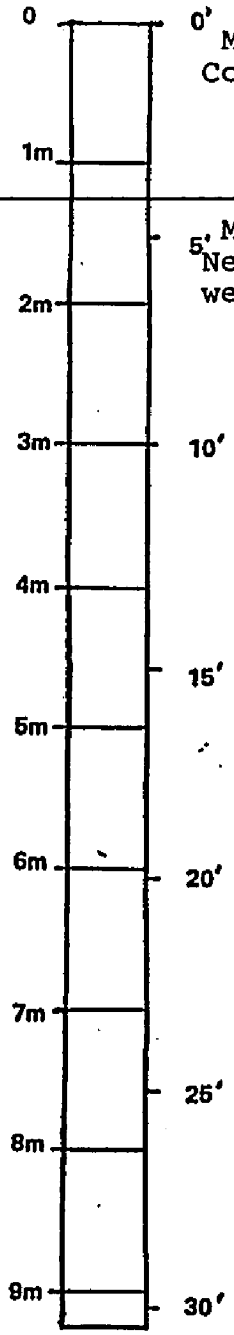
Location: Half way between Main Ship Shoal Channel and Mockhorn Island.

Date: May, 1982

Total Depth: 5.20 m

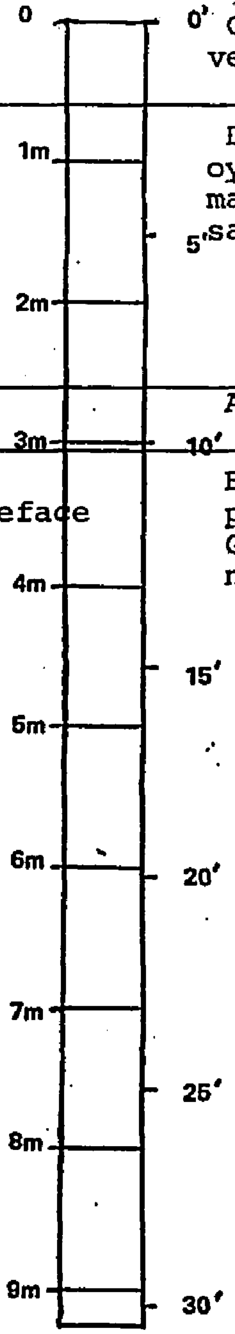
Compaction: 0.20 m

ENVIRONMENT	DESCRIPTION
Salt Marsh	Mud with much S. alterniflora vegetation. Coarsens downward, much sand near contact.
Open Lagoon	Muddy sand with many lenticular sand beds. Near bottom of unit grades into a clean well-sorted fine-grained sand



Core: 7-7
Date: May, 1982
Elevation (msl): at MSL
Total Depth: 4.23 m
Location: About 300 m east of Mockhorn Island.
Compaction: 0.75 m

ENVIRONMENT	DESCRIPTION
Salt Marsh	Grey mud with much S. alterniflora vegetation.
Tidal Flat	Dark grey mud with some sand. Many oyster shells, none articulated but many whole halves in good shape. Several sand filled burrows.
Transgressive Lag	A few shells and pebbles. A gradational contact above and below. Transition zone.
Pleistocene Foreshore/Shoreface	Brown to tan, fine to medium sand with pebbles. Cleaner and coarser downward. Graded sand beds. Two large marsh stems near top.



Core: 7-8

Date: May, 1982

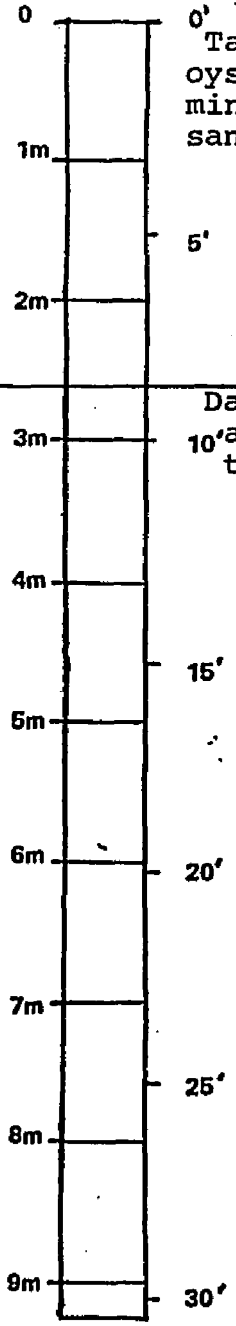
Elevation (msl): at MSL

Total Depth: 2.75 m

Location: At Mockhorn Island foreshore

Compaction: 0.70 m

ENVIRONMENT	DESCRIPTION
Pleistocene Beach	Tan to light orange, medium sand. Several oyster shells at surface. Many heavy minerals on bedding planes. A few scattered sand filled burrows. Sharp contact.
Pleistocene Lagoon	Dark grey mostly clay. Very compacted and dewatered. One organic rich zone that was C-14 dated.



Core: 7-9

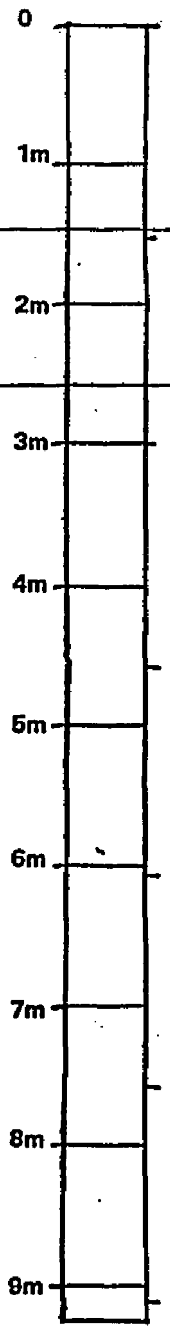
Date: May, 1982

Elevation (msl): at MSL

Total Depth: 4.2 m

Location: At seaward jutting marsh on mainland side of Magothy Bay

Compaction: 0.70 m



ENVIRONMENT	DESCRIPTION
Salt Marsh	0' Dark grey organic-rich mud. Much marsh vegetation.
Tidal Flat	5' Grey medium sand with some mud. Some dark heavy minerals and a little marsh vegetation also mixed in. A somewhat transitory zone between upper and lower units.
Pleistocene Beach	Light grey to tan medium sand interbedded with 10' finer darker sand. Two coarse zones with pebbles. Coarse zones are poorly sorted and the pebbles subangular. Contact to above very subtle.

15'

20'

25'

30'

Core: 7-10

Date: October, 1982

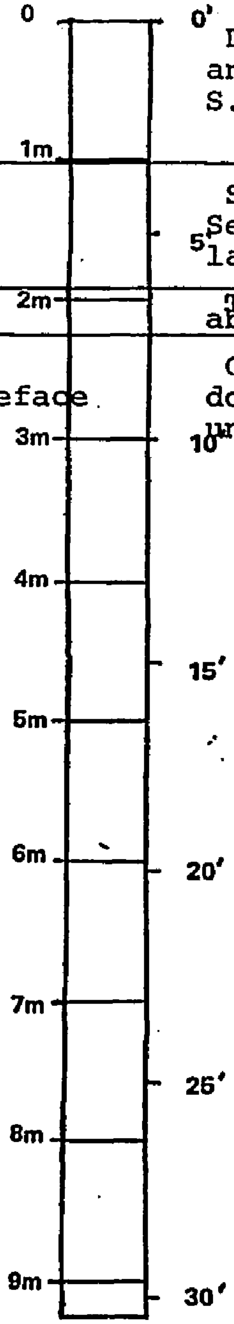
Elevation (msl): +0.3 m

Total Depth: 3.52 m

Location: 50 m east of Mockhorn Island
in small high marsh zone.
(Possibly a relict beach ridge)

Compaction: 0.70 m

ENVIRONMENT	DESCRIPTION
Salt Marsh	Dark grey mud. Tackier (more clay) and and sandier near lower contact. Much S. alterniflora at top, less with depth.
Tidal Flat	Sand and mud, coarsening downward. No Sedimentary structures except for one large vertical burrow.
Transgressive Lag	Transition zone between predominantly mud above and sand below. Some pebbles in mud.
Pleistocene Foreshore/Shoreface	Graded sand beds and pebbles. Coarsens downward. Mostly fine sand at top of unit. Graded beds show a cyclicity.

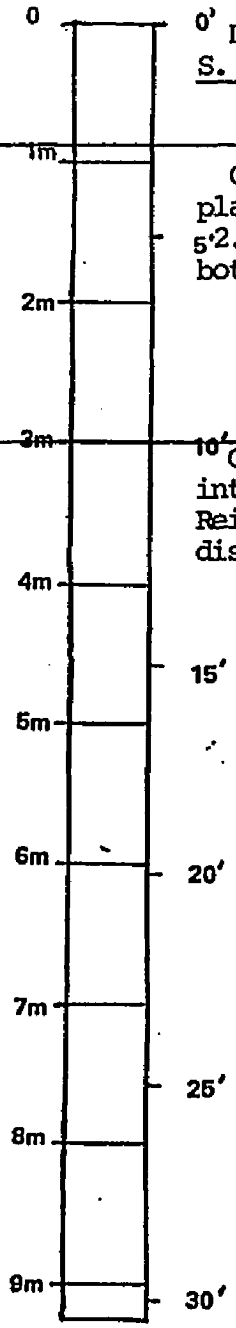


Core: 8-2 Date: May, 1982

Elevation (msl): at MSL Total Depth: 4.27 m

Location: Adjacent to New Mud Hole Inlet Channel Compaction: 0.20 m

ENVIRONMENT	DESCRIPTION
Salt Marsh	Dark grey mostly mud, little sand. Much *S. alterniflora* vegetation but less with depth.
Tidal Flat	Grey mud with some sand. Sand found in thin planar horizontal beds. One sandy zone between 2.1 and 2.4 m. At top some worm burrows and near bottom of section some bivalve burrows.
Open Lagoon	Grey to light grey muddy sand. Many finely interlayered beds (Rhythmites as shown by Reineck and Singh). Some of the bedding is disrupted by burrows.



Core: 8-3

Date: May, 1982

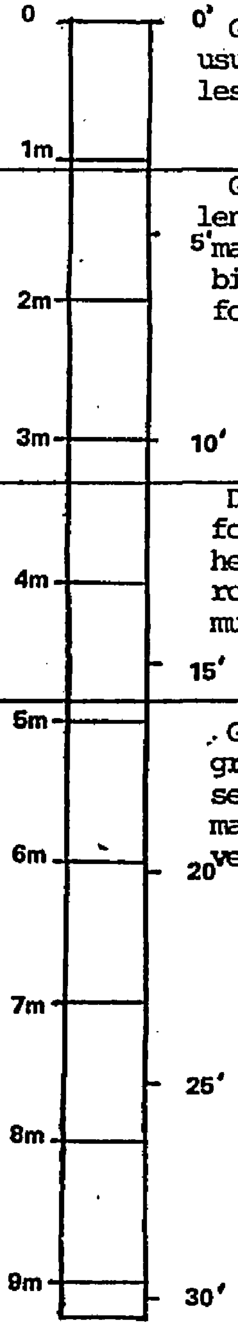
Elevation (msl): at MSL

Total Depth: 7.31 m

Location: In center of backbarrier region in *S. alterniflora* marsh.

Compaction: 0.40 m

ENVIRONMENT	DESCRIPTION
Salt Marsh	Grey mud and sand. Sandier marsh section than usually found. Much *S. alterniflora* vegetation, lessens toward bottom of section.
Tidal Flat	Grey mud and sand. A few discontinuous lenticular sand beds seen. Three mud snails and many pieces of decayed marsh vegetation. Lightly bioturbated. A few pieces of oyster shell also found.
Sheltered Lagoon	Dark grey mud, little sand. Some marsh debris found throughout section. One zone shows very heavy decayed marsh deposition. A few small round burrows but mostly a massive structureless mud.
Open Lagoon	Grey sand with somemud beds. Sand is very fine grained. Some cyclic sand and mud zones. Also several zones of 0.5 to 1.0 cm thick organic material made up of decayed marsh debris. A few vertical and horizontal burrows also identified.



Core: 8-4

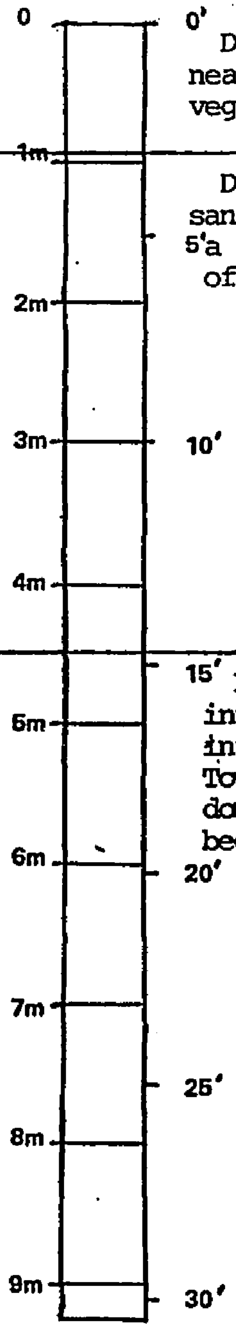
Date: May, 1982

Elevation (msl): at MSL

Total Depth: 7.50 m

Location: Adjacent to Main Ship Shoal Channel in center of backbarrier environment.

Compaction: 0.30 m



ENVIRONMENT	DESCRIPTION
Salt Marsh	Dark grey mostly mud. Becomes a little sandier near bottom of section. Heavy S. alterniflora vegetation.
Tidal Flat	Dark grey sandy mud. Several planar horizontal sand beds, mostly thin. One mud snail found and a few oyster shells. Several organic rich beds of marsh vegetation.
Open Lagoon	Light grey sand and dark grey mud, usually interbedded as lenticular, coarsely and finely interlayered bedding. No bioturbation or biota. Towards bottom of section, sand becomes more dominant. Much flaser bedding and wavy mud bedding in bottom half of section.

Core: 8-5

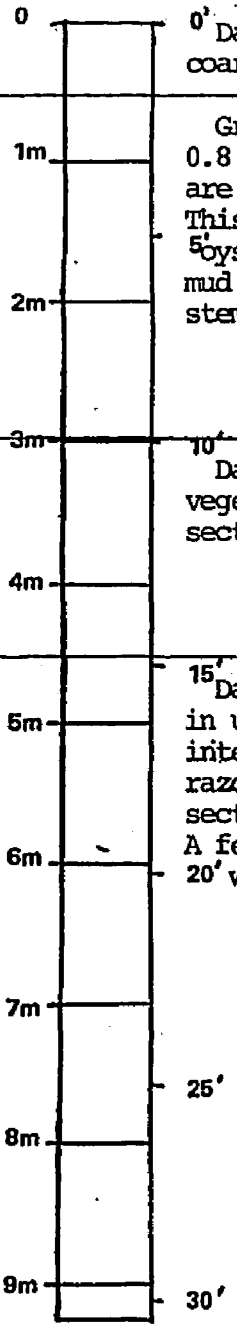
Elevation (msl): at MSL

Location: On Thomas Creek

Date: May, 1982

Total Depth: 6.00 m

Compaction: 0.50 m



ENVIRONMENT	DESCRIPTION
Salt Marsh	Dark grey muddy sand. Mostly mud at very top, coarsens downward. Much marsh vegetation.
Tidal Flat	Grey mud and sand. Oyster shell zones between 0.8 and 1.2 m, and 2.1 and 3.0 m. The oyster shells are not articulated but whole halves were found. This section fines toward bottom. Also finer where oyster shells are found, sandier in between. Many mud snails near bottom of section. A few marsh stems(?) mixed in at top.
Sheltered Lagoon	Dark grey mud, very little sand. Much marsh vegetation mixed in. Some mud snails at bottom of section. This section is mostly a massive mud.
Open Lagoon	Dark grey mud and light grey interbedded sands in upper half of section. Both coarsely and finely interlayered bedding, some flasers also. Much razor clam debris in muddier zones. Bottom half of section is a light grey fine sand with much mica. A few shell fragments also. Moderately burrowed with mud introduced from the bioturbation.

Core: 8-6

Elevation (msl): at MSL

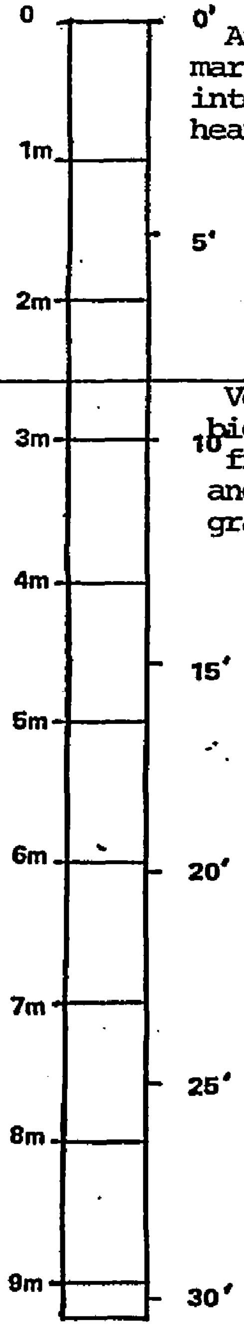
Location: On foreshore of Mockhorn Island

Date: May, 1982

Total Depth: 3.11 m

Compaction: 0.3 m

ENVIRONMENT	DESCRIPTION
Pleistocene Barrier Beach	At and near top, dark tan medium sand with some marsh vegetation mixed in. Quickly grades down into tan to orange-tan medium sand with some heavy minerals. No sedimentary structures.
Pleistocene Lagoon	Very dewatered mud with some sand. Moderately bioturbated. Some orange-tan sand introduced from burrowing. Also near bottom some flaser and lenticular sand beds. Contact is surprisingly gradational.



Core: 8-7

Date: May, 1982

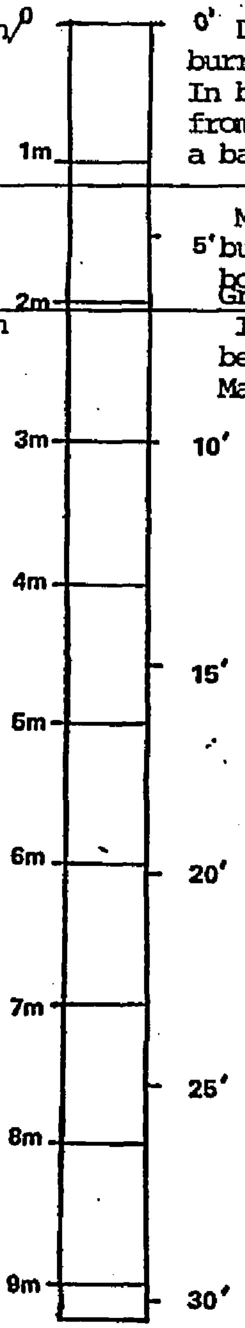
Elevation (msl): +0.5 m

Total Depth: 3.20 m

Location: Sandy mainland beach west of Magothy Bay.

Compaction: 1.00 m

ENVIRONMENT	DESCRIPTION
Backbarrier Beach/ Salt Marsh	Dark tan and light grey medium sand with many burrows. *S. patens* at top encroaching onto sand. In bottom half of section are marsh remains separated from above by a fairly sharp contact. Probably a backbarrier beach over the salt marsh.
Tidal Flat	Muddy grey sand with mud introduced through burrowing. A little coarser towards section bottom. Some coarse sand near bottom (transition). Gradational upper and lower contacts.
Pleistocene Beach	Interbedded fine grey sand and medium tan sand beds ranging in size from 0.25 to 1.0 cm thick. Many heavy minerals.



Core: 8-8

Elevation (msl): +0.5 m

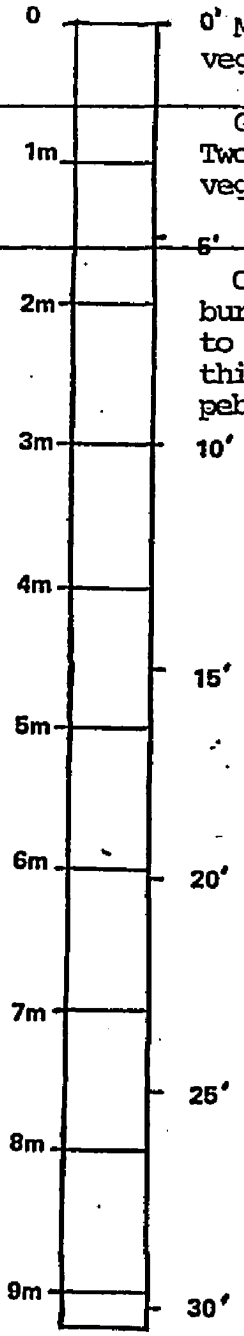
Location: On high marsh seaward of Mockhorn Island

Date: May, 1982

Total Depth: 3.12 m

Compaction: 0.10 m

ENVIRONMENT	DESCRIPTION
Salt Marsh	Medium grained sand with much mud. Much marsh vegetation and bioturbation.
Tidal Flat	Grey and orange-tan clayey sand. Tacky texture. Two long 1.5 X 8.0 cm mud filled burrows. Some vegetation near top of unit.
Pleistocene Beach	Orange tinted tan medium sand. Some round mud burrows at very top. Otherwise massive medium to coarse sand. Horizontal sand beds 1 to 4 cm thick in bottom half of unit. Also some subrounded pebbles.



Core: 9A

Date: August, 1985

Elevation (msl): -3.66 m

Total Depth: 1.75 m

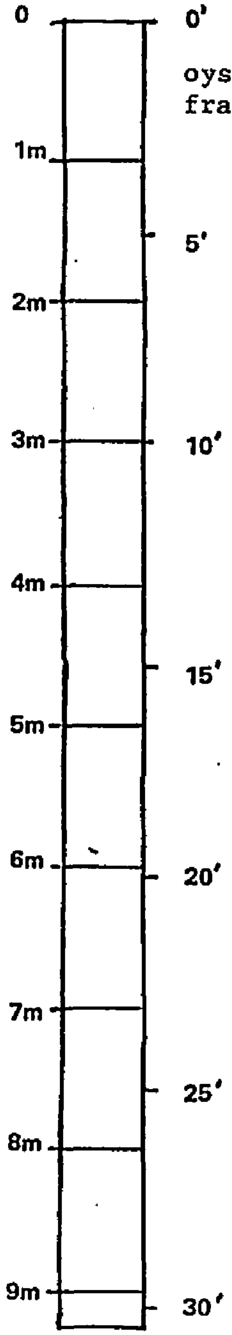
Location: Smith Island lower shoreface
adjacent to Bungalow Inlet site

Compaction: None?

ENVIRONMENT

DESCRIPTION

Shoreface



Light grey sand, fairly clean. Many half oyster shells at bottom. Lots of mica and shell fragments.

Core: 9-1A

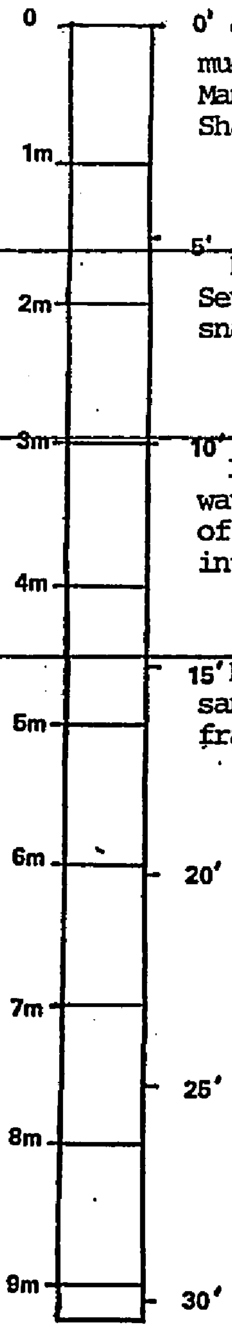
Date: May, 1982

Elevation (msl): +0.5 m

Total Depth: 5.25 m

Location: At Smith Island foreshore at the site of the former Mud Hole Inlet.

Compaction: 0.40 m



ENVIRONMENT	DESCRIPTION
Barrier Beach	Tan fine sand grading down to coarse sand with much shell debris. (may be ephemeral inlet fill). Many heavy mineral beds in upper half of section. Sharp lower contact.
Tidal Flat	Dark grey mud and sand, more sand near bottom. Several intact oyster shells, also quahogs, mud snails, and many burrows.
Open Lagoon	Light grey, mostly fine sand with interbedded wavy flaser beds. More mud near top and bottom of this section.interbedded with coarsely interlayered sand beds.
Sheltered Lagoon	Dark grey, heavily bioturbated mud. Many round sand filled burrows. Some dwarf surf clam fragments. Much of this section is massive mud.

Core: 9-1

Date: May, 1982

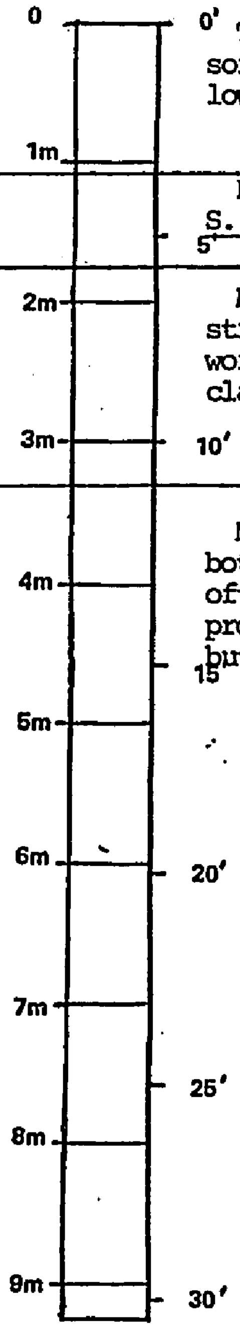
Elevation (msl): +0.5 m

Total Depth: 6.22 m

Location: On washover fan at the site of the former Mud Hole Inlet.

Compaction: 0.10 m

ENVIRONMENT	DESCRIPTION
Washover	Tan to light grey fine to medium grained well sorted sand. Some heavy mineral bedding. Sharp lower contact.
Salt Marsh	Dark grey mud. Heavily vegetated with S. alterniflora. Less vegetation with depth.
Tidal Flat	Mud and sand, coarsens downward. Many biogenic structures; burrows from mud snails, clams, and worms. Three mud snails and an articulated razor clam found in this unit.
Open Lagoon	Mud and sand at top, grading to all sand at bottom. Numerous coarsely interlayered sand beds often discontinuous. Some shell fragments, probably dwarf surf clams. Sand at bottom is bedded but disrupted by small vertical burrows.



Core: 9-2

Elevation (msl): at MSL

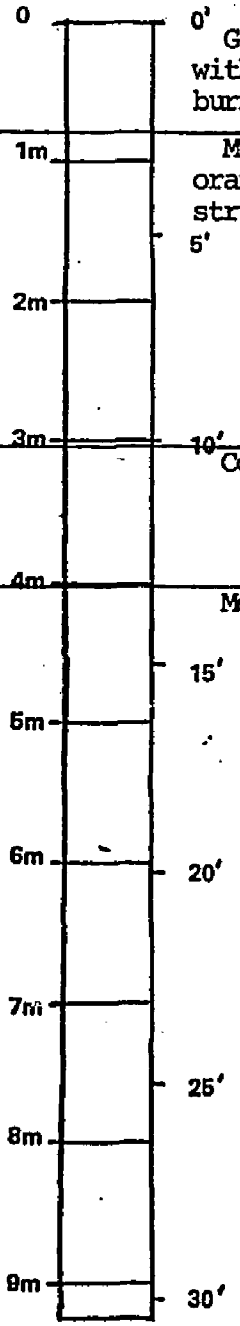
Location: Center of Mockhorn Island near southern end. Adjacent to canal of mansion.

Date: May, 1982

Total Depth: 4.42 m

Compaction: 0.10 m

ENVIRONMENT	DESCRIPTION
Salt Marsh	Grey and orange-tan mud. Somewhat dewatered with a tacky texture. Clean tan, sand filled burrows. Heavily bioturbated. Much marsh vegetation.
Pleistocene Barrier Beach	Muddy fine sand at top grading down to medium orange-tan sand. Sand is massive with on sedimentary structures.
Pleistocene Lagoon	Compacted grey mud, partially stained orange.
Pleistocene Sand Shoal	Medium sand with some heavy mineral beds.



Core: 9-3

Elevation (msl): at MSL

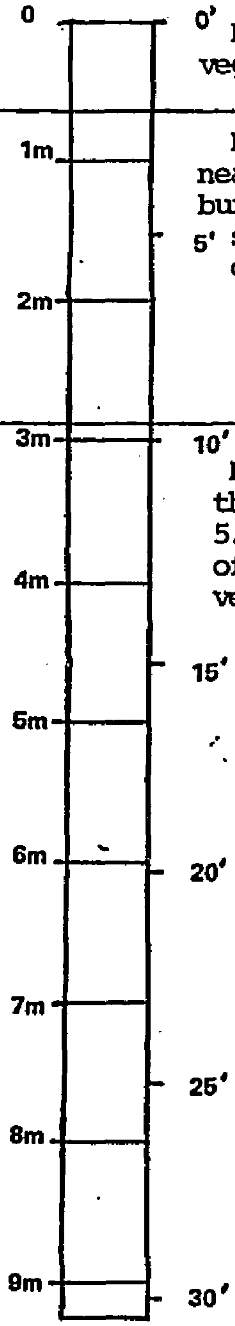
Location: Center of S. alterniflora marsh

Date: May, 1982

Total Depth: 6.31 m

Compaction: 0.20 m

ENVIRONMENT	DESCRIPTION
Salt Marsh	Dark grey mud with much S. alterniflora vegetation. Fairly sharp lower contact.
Tidal Flat	Dark grey, mostly homogeneous mud. Sandier near lower gradational contact. Only a few worm burrows. Near upper contact some shell fragments, some marsh debris, and an articulated razor clam.
Open Lagoon	Dark grey mud and sand. Only a little coarser than section above. A few sand beds at 4.0 m and 5.2 m. Many round sand filled burrows near top of section. Also some shell debris and plant vegetation in upper half of section.



Core: 9-4

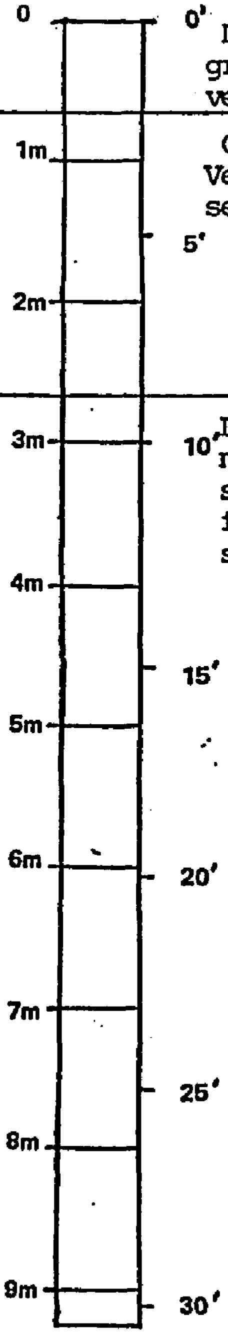
Date: May, 1982

Elevation (msl): at MSL

Total Depth: 3.33 m

Location: In center of S. alterniflora marsh adjacent to Main Ship Shoal Channel

Compaction: 0.75 m



ENVIRONMENT	DESCRIPTION
Salt Marsh	Dark grey mud and sand, mostly mud at top grading down into more sand. Much S. alterniflora vegetation, especially at top.
Tidal Flat	Grey mud, more sand near upper and lower contacts. Very massive mud but some mud snail shells and several large pieces of S. alterniflora recognized.
Open Lagoon	Light grey sand and a little mud. Grades from mud and sand at upper contact to almost all sand. A many lined Lucine (P. multilineata) found. Some mica seen with sands. No sedimentary structures.

Core: 9-5

Date: May, 1982

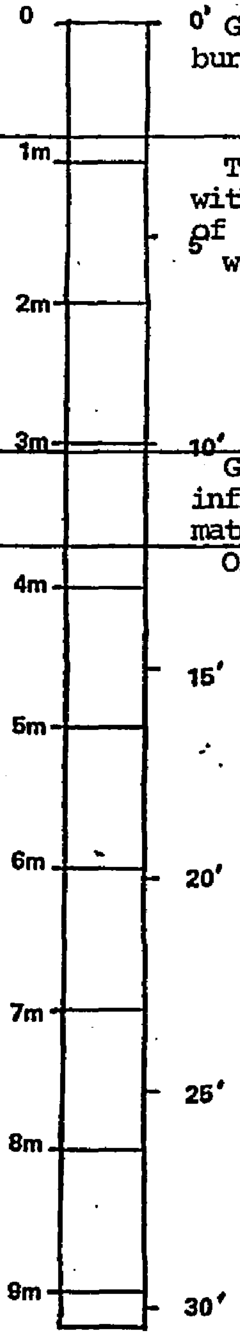
Elevation (msl): at MSL

Total Depth: 3.70 m

Location: At Mockhorn Island washover with marsh taking root.

Compaction: 0.3 m

ENVIRONMENT	DESCRIPTION
Salt Marsh	Grey medium sand with some mud mixed in as burrows. Heavily vegetated with S. alterniflora.
Pleistocene Barrier Beach	Tan medium sand, some mud at top, much cleaner with depth. A large vertical burrow near top of unit. Bottom half of unit is mostly orange-tan well sorted sand. Sharp lower contact.
Pleistocene Lagoon	Grey dewatered mud, some orange staining due to influx of iron/oxidation. Some decayed plant material near bottom of unit.
Pleistocene Sand Shoal	Orange-tan fine micaceous sand.



Core: 9-6

Date: May, 1982

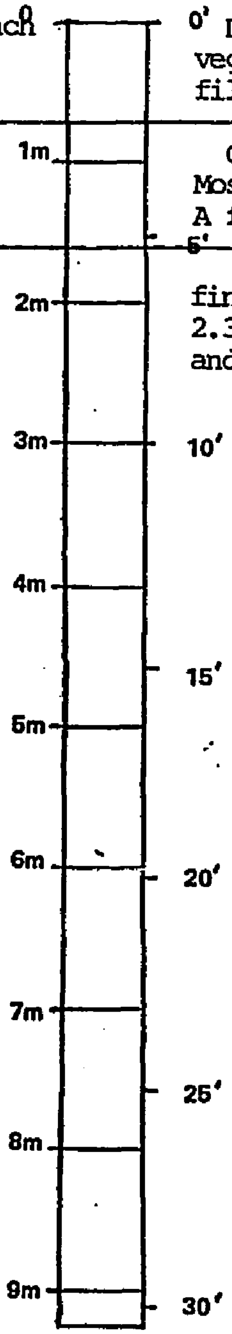
Elevation (msl): +0.5 m

Total Depth: 3.10 m

Location: On sandy backbarrier beach on west (mainland) side of Magothy Bay

Compaction: 0.80 m

ENVIRONMENT	DESCRIPTION
Backbarrier Beach and Salt Marsh	Dark grey medium sand and mud with much marsh vegetation. Also many light grey to tan sand filled burrows.
Tidal Flat	Grey muddy sand or sandy mud. Very compacted. Mostly massive but some recognizable burrows. A fewlarge sand grains and pebbles at bottom.
Pleistocene Beach	Light grey to orange-tan at bottom. Some dark fine sand beds alternating with medium sand between 2.3 and 2.7 m. Several zones of gravel, pebbles, and sand. Larger material subangular.



Core: 9-7

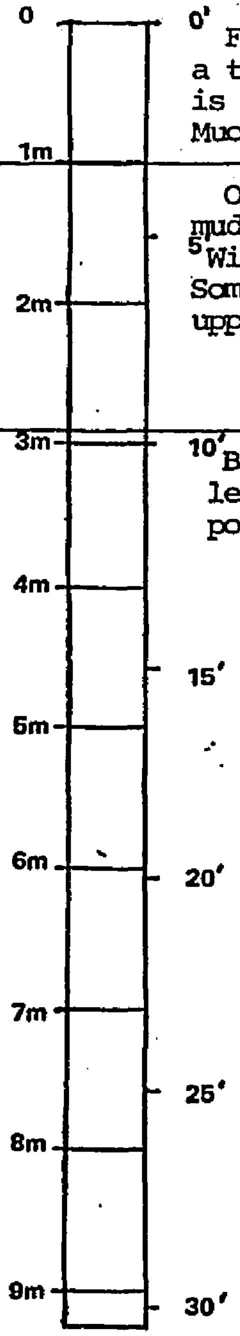
Date: May, 1982

Elevation (msl): at MSL

Total Depth: 4.12 m

Location: At fringing marsh on east side of Mockhorn Island

Compaction: 0.10 m



ENVIRONMENT	DESCRIPTION
Salt Marsh	Fine to medium sand at top grading down into a tacky clay and sand mixture. At top the color is tan and grey, becomes orange stained with depth. Much marsh vegetation mixed in.
Pleistocene Barrier Beach	Orange-tan medium sand, medium grained. Some mud at top of unit along with a few burrows. With depth, sand is better sorted and cleaner. Some graded beds. Sharp lower contact, gradational upper contact.
Pleistocene Lagoon	Bluish-grey compacted mud with some orange-tan lenticular sand beds. Many burrows in upper portion of this unit.

Core: M-1

Elevation (msl): at MSL

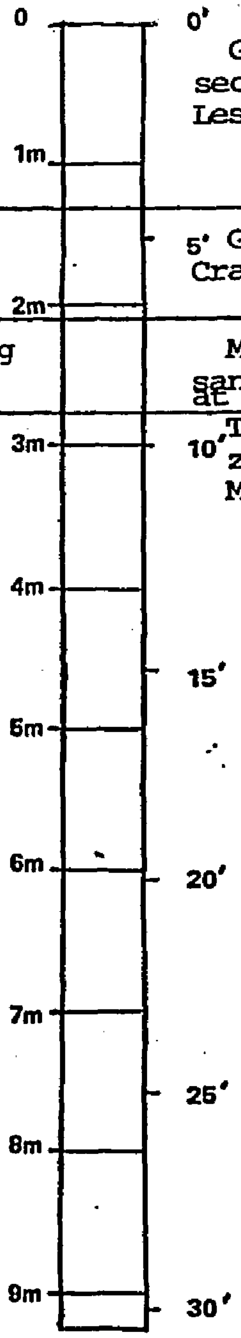
Location: 300 m west of Mockhorn Island
at northern extent of study area

Date: May, 1982

Total Depth: 3.27 m

Compaction: 0.50 m

ENVIRONMENT	DESCRIPTION
Salt Marsh	Grey mud, a little more sand towards bottom of section. Much <u>S. alterniflora</u> vegetation. Lessens with depth.
Tidal Flat	Grey muddy sand with many burrows (Fiddler Crab?). Some marsh vegetation at top.
Transgressive Lag	Mostly coarse sand and gravel but some fine sand mixed in. A few pieces of wood and mud clasts at bottom.
Pleistocene Beach	Tan medium to fine sand. Well sorted. One 4 cm zone (3.0–3.4 m), indicating a washover event (?). Many 1 cm heavy mineral beds.



Core: M-2

Date: May, 1982

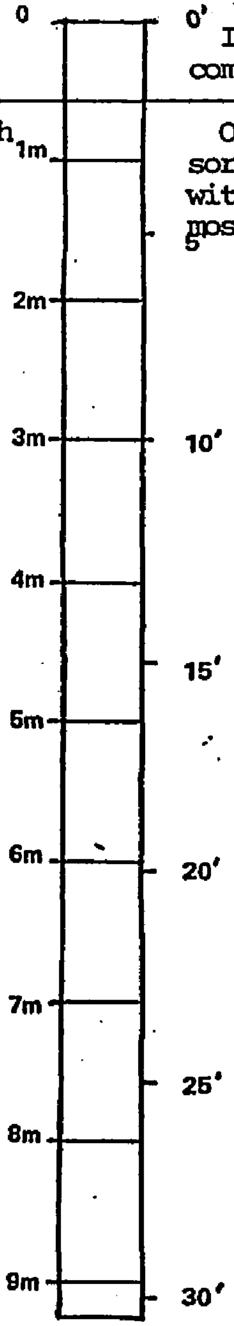
Elevation (msl): +0.75 m

Total Depth: 2.72 m

Location: 75 m west of Mockhorn Island at northern end of study area. In high marsh.

Compaction: 1.00 m

ENVIRONMENT	DESCRIPTION
Salt Marsh	Iron stained, orange-tan muddy sand, somewhat compacted. Moderate amount of high marsh vegetation.
Pleistocene Beach or Channel	Orange-tan sand, gravel, and pebbles. Poorly sorted. Sorting becomes worse and grain size larger with depth. Also many heavy minerals. Pebbles mostly sub-angular, not well-rounded.



Core: M-3

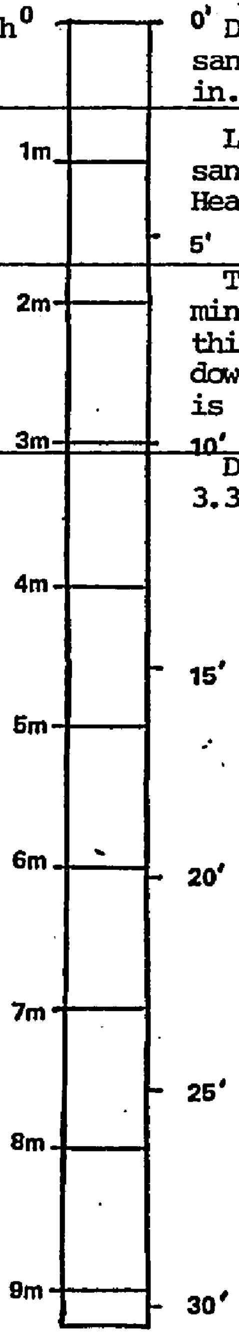
Date: October, 1982

Elevation (msl): +0.7 m

Total Depth: 3.58 m

Location: On small sandy beach associated with Mockhorn Island but separated from main part of Island by a small marsh.

Compaction: 0.2 m



ENVIRONMENT	DESCRIPTION
Backbarrier Beach	Dark tan sand, mostly medium but some coarse sand and gravel also. Some shell fragments mixed in. Also some organic material near bottom.
Salt Marsh	Light grey grading downward to dark grey medium sand and mud. Very organic rich, many marsh fragments. Heavily bioturbated.
Pleistocene Barrier Beach	Tan, well sorted, medium sand. Some thin heavy mineral beds, especially near bottom. At top many thin vertical (worm?) burrows. More physical structure downward. Upper contact is gradational, lower contact is sharp.
Pleistocene Lagoon	Dark grey with a 4 cm thick brown peat zone at 3.3 m depth in core. Mud is very compacted.

Core: M-4

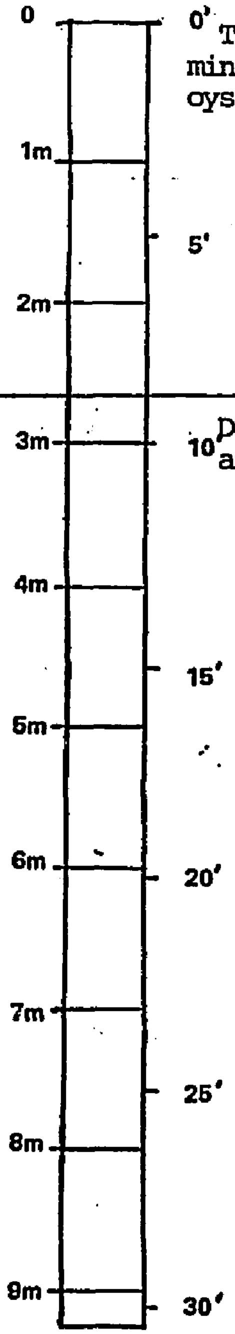
Date: October, 1982

Elevation (msl): +0.2 m

Total Depth: 3.50 m

Location: Mockhorn Island foreshore

Compaction: 0.35 m



ENVIRONMENT	DESCRIPTION
Pleistocene Barrier Beach	Tan, orange-tinted medium sand. Many heavy minerals especially near bottom of unit. Whole oyster shells at surface.
Pleistocene Lagoon	Dark grey compacted mud with a black peat zone at about 3.0 m.

Core: M-5

Date: October, 1982

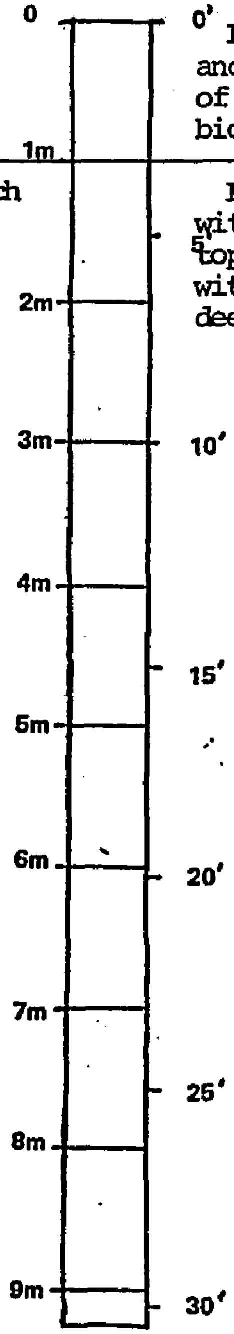
Elevation (msl): +0.5 m

Total Depth: 3.32 m

Location: At western edge of Mockhorn Island in northern end of study area. Adjacent to Stringer's Ditch.

Compaction:

ENVIRONMENT	DESCRIPTION
Salt Marsh	Light and/or orange brown muddy sand. B. frutescans and S. patens vegetation at surface and in much of section. Muddy sand is mostly massive, no distinct bioturbation recognized.
Pleistocene Beach or Channel	Light brown/orange coarse sand beds interbedded with tan medium sand beds. Some burrows at very top. A few pebbles, mostly sub-angular mixed in with coarser zones. Some heavy minerals, especially deeper in the section.



Core: M-6

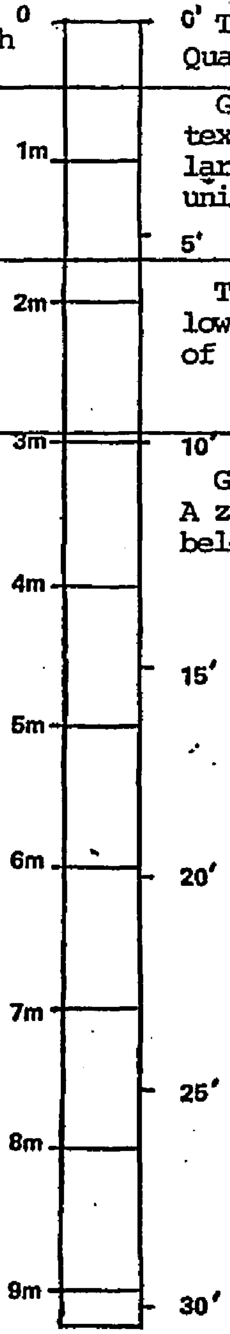
Elevation (msl): +0.5 m

Location: On small sandy beach associated with Mockhorn Island but separated from main part of Island by a large marsh.

Date: October 1982

Total Depth: 4.78 m

Compaction: 0.20 m



ENVIRONMENT	DESCRIPTION
Backbarrier Beach	Tan, somewhat muddy sand, moderately sorted. Quahogs and oyster shells at top. Moderately burrowed
Salt Marsh	Gray muddy sand, orange where oxidized. Tacky texture. Much <u>S. alterniflora</u> vegetation. Several large sand filled burrows. Gradational contact to unit below, sharp contact above.
Pleistocene Barrier Beach	Tan sand, fines upward. Sharp but conformable(?) lower contact. Some heavy mineral beds near bottom of unit. A couple of round burrows at top.
Pleistocene Lagoon	Grey very muddy with much clay. Also very compacted A zone of high organic content between 2 and 3 m below MSL. Little bioturbation recognized.

Core: M-7/M-7A

Date: October, 1982

Elevation (msl): at MSL

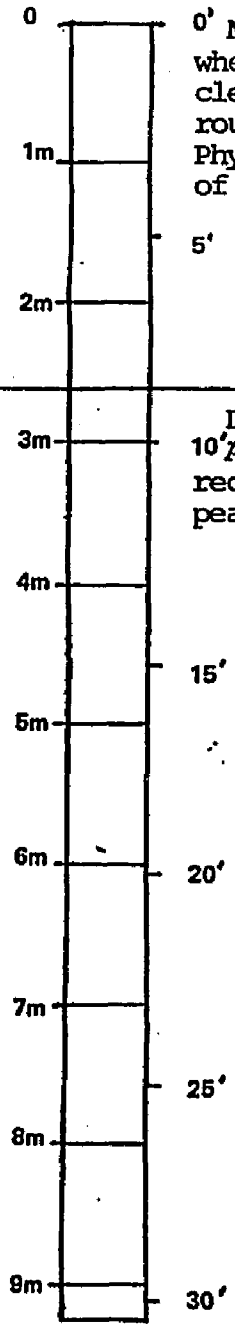
Total Depth: M-7A is 3.30 m
M-7 is 1.60 m

Location: On lower foreshore of Mockhorn Island. Both cores taken in same place.

Compaction: Both 0.3 m

Note: The lithology of the shorter core is the smae as the top half of the longer core.

ENVIRONMENT	DESCRIPTION
Pleistocene Barrier Beach	0' Mostly medium sand, tan color except near top where some sand has an orange tint. Sands are cleaner and bedding better with depth. Many round burrows near surface. Oxidation is spotty. Physical structures better preserved in bottom half of unit.
Pleistocene Lagoon	Dark grey mud with much clay, very compacted. 10' At around 3.2 m some lenticular sand beds are recognized but they are mostly scattered. A brown peat zone is seen at about 3.0 m



Core: M-8

Elevation (msl): at MSL

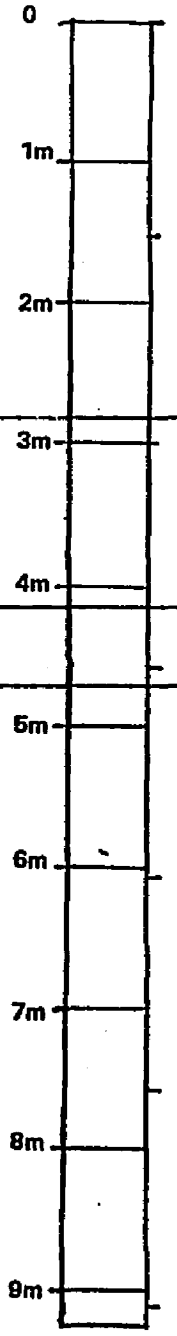
Location: On lower foreshore of Mockhorn Island

Date: October, 1982

Total Depth: 4.81 m

Compaction: 0.50 m

ENVIRONMENT	DESCRIPTION
Pleistocene Barrier Beach	Muddy tan sand showing some bioturbation grading down into tan, very clean, well sorted, medium sand. Several horizontal burrows. Some cross-bedded sand near lower sharp contact.
Pleistocene Lagoon	Dark grey compacted mud with some well-developed lenticular sand beds. Very little bioturbation. Peat zone at bottom of unit, dark brown. Grades downward to sand in unit below.
Pleistocene Sand Shoal	Mostly light tan, clean sand that grades into vegetated rich sand that grades into peat above. Good bedding in lower portion of unit.
Pleistocene Lagoon	Compacted mud much like lagoonal mud described above.



Core: M-9

Date: October, 1982

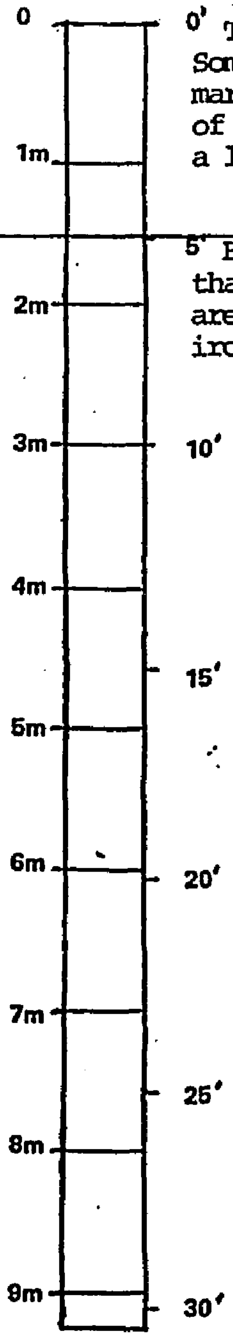
Elevation (msl): +0.3 m

Total Depth: 3.76 m

Location: Southern tip of Mockhorn Island

Compaction: 0.40 m

ENVIRONMENT	DESCRIPTION
Pleistocene Barrier Beach	0' Tan to light grey, well sorted medium sand. Some shell debris at and near top, and some marsh vegetation also near top. Towards bottom of unit sand becomes more orange in color and a little coarser in grain size. Sharp lower contact.
Pleistocene Lagoon	5' Bluish-grey compacted mud with some sand lenses that are iron-stained (orange in color). There are a few zones that show heavy accumulation of iron.



Core: M-10

Date: May, 1983

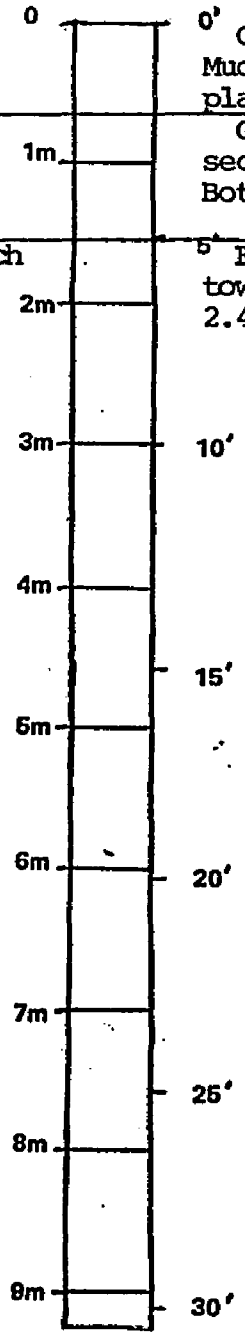
Elevation (msl): at MSL

Total Depth: 3.63 m

Location: On Old House Creek, about 500 m from east side of Mockhorn Island

Compaction: 1.00 m

ENVIRONMENT	DESCRIPTION
Salt Marsh	Grey mud, sandier toward bottom of section. Much S. alterniflora vegetation. Many red-orange plant fragments.
Tidal Flat	Grey and orange sandy mud, sandier near bottom of section. Many burrows, some marsh vegetation. Bottom may be transgressive lag that is very subtle.
Pleistocene Beach	Fine, well-sorted, sand that becomes coarser towards bottom. Many heavy mineral beds between 2.4 and 3.1 m.



Core: M-11

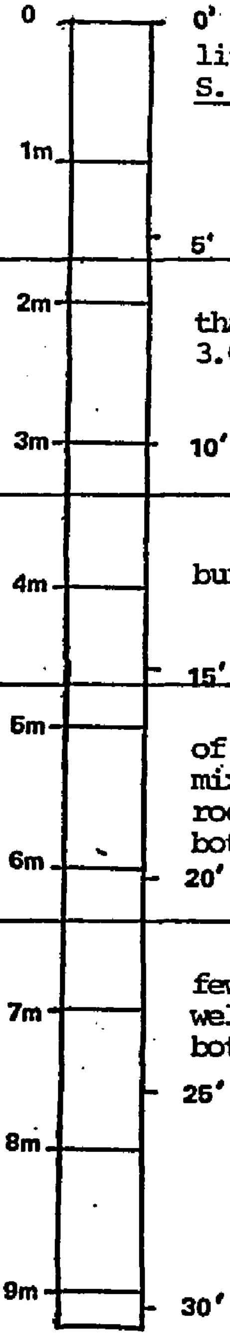
Elevation (msl): at MSL

Location: Adjacent to Mockhorn Channel on west side, near light 246.

Date: May, 1983

Total Depth: 7.73 m

Compaction: 0.60 m



ENVIRONMENT	DESCRIPTION
Salt Marsh	Dark grey mud. Little sand, even towards bottom little increase in sand content. Much *S. alterniflora* vegetation throughout section.
Tidal Flat	Dark grey homogeneous mud, a little more sand than above but not much. Many oyster shells at 3.0 m.
Sheltered Lagoon	Grey mud, a little sand. Several large vertical burrows but mostly a massive sand.
Channel Fill (Channel Bottom)	Tan to brown sand with some mud lenses near top of section. Coarsens downward but a little mud mixed in. At bottom, many pebbles and a 5.5 X 7.5 cm rock. Very sharp lower contact. Definite channel bottom.
Open Lagoon	Light grey to tan fine sand with much mica. A few muddy sand beds and some mud flaser beds. Many well developed heavy mineral laminations. Toward bottom, a structureless muddy sand. Channel above probably cut above these sediments.

Core: G

Date: July, 1981

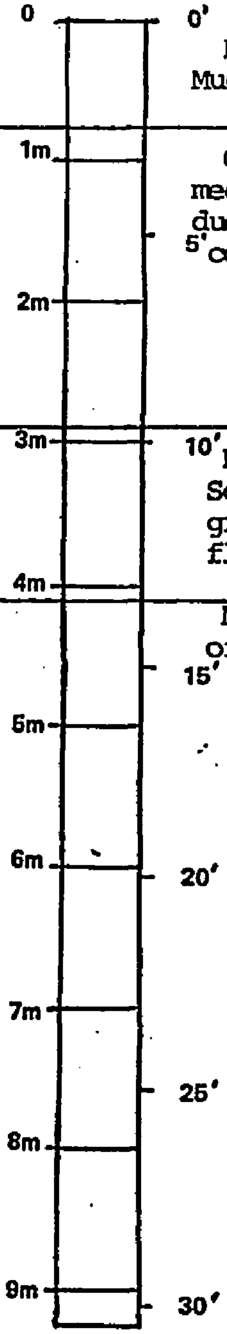
Elevation (msl): +0.3 m

Total Depth: 5.65 m

Location: In marsh on east side of southern Mockhorn Island

Compaction: 1.50 m

ENVIRONMENT	DESCRIPTION
Salt Marsh	Medium to coarse light grey sand, subrounded. Much marsh vegetation.
Pleistocene Barrier Beach	Clayey sand near top of unit grading down to a medium sand that is slightly yellow-brown in color due to iron staining. No fossils. Sharp lower contact.
Pleistocene Lagoon	Mostly massive grey structureless mud and sand. Some limonite-cemented aggregates of much finer grain size. Also much muscovite present as flakes.
Pleistocene Sand Shoal	Medium to fine light grey sand. Minor amounts of mica. All sand grains are subrounded.



Core: Cl-1

Elevation (msl): +0.5 m

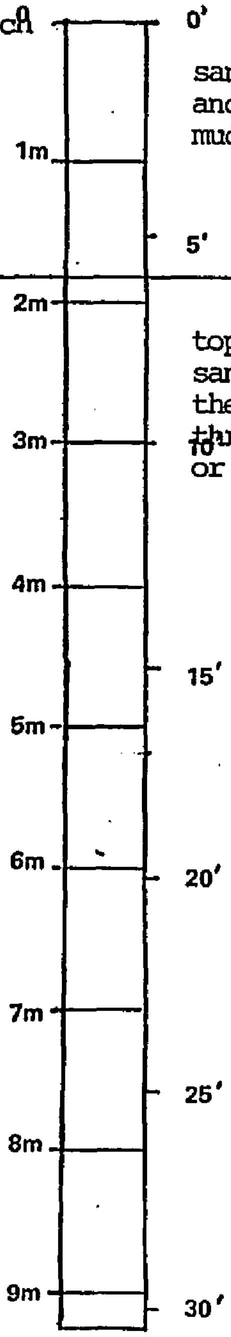
Location: 200 m south of Cushmans Landing
on mainalnd fringing marsh

Date: May, 1982

Total Depth: 4.12 m

Compaction: 0.70 m

ENVIRONMENT | **DESCRIPTION**



Backbarrier Beach
and
Salt Marsh

Very sandy at top, almost completely clean sand, but becomes muddier with depth. Salicornia and oyster shells at surface. Heavily mottled mud below the sand with S. alterniflora vegetation.

Pleistocene
Foreshore

Tan, clean well-sorted medium to fine sand at top with interbedded zones of pebbles and coarse sand below. Coarse material is poorly sorted and the pebbles subangular. Heavy minerals and mica throughout. Very prominant heavy mineral laminations or beds between 2.2 and 3.0 m.

Core: BI-1

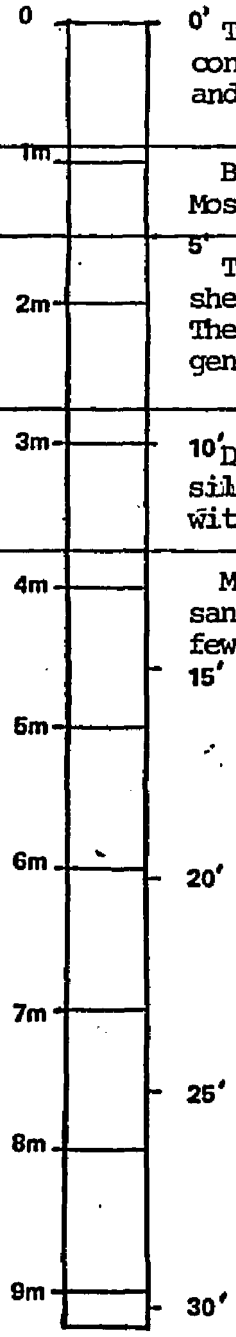
Date: October, 1982

Elevation (msl): +0.75 m

Total Depth: 6.40 m

Location: Near south end of former inlet (Bungalow Inlet), 30 m landward of berm.

Compaction: 0.70 m



ENVIRONMENT	DESCRIPTION
Barrier Beach/ Washover	Tan medium sand, reduced near bottom. Sharp contact to marsh vegetation below. Some burrowing, and a few oyster shells at surface.
Salt Marsh	Black-brown mud with much marsh vegetation. Mostly silt and clay. Gradational lower contact.
Inlet Fill	Tan medium to fine grained sand with beds of shells. At bottom is a 5 cm thich shell bed. The lower contact is sharp and erosional. Sand generally fines upward.
Tidal Flat	Dark grey very and very muddy. Mostly mud and silt with some sand near bottom. Very homogeneous with several half shells of oysters mixed in.
Open Lagoon	Mostly grey muddy sand with a few small lenticular sand beds. Several 2 cm X 2 cm mud clasts. Also a few bay scallop half shells.

Core: BI-2

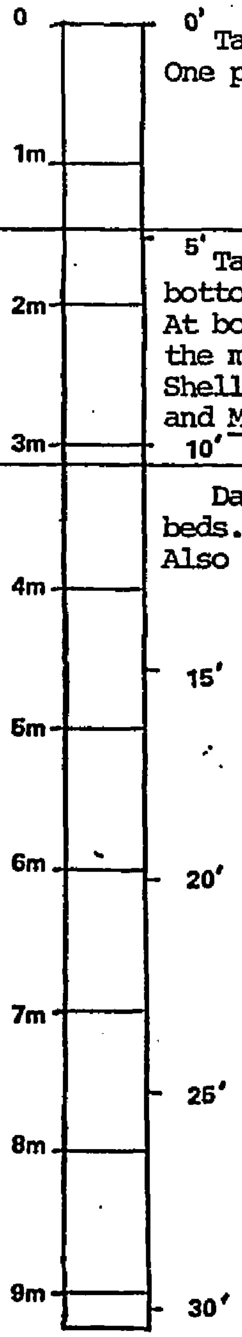
Elevation (msl): +0.8 m

Location: Center of former inlet (Bungalow Inlet):, 30 m landward of berm.

Date: October, 1982

Total Depth: 6.30 m

Compaction: 0.40 m



ENVIRONMENT	DESCRIPTION
Barrier Beach/ Washover	Tan fine sand with many heavy mineral beds. One piece of an oyster shell found.
Inlet Fill	Tan medium sand with muc shell debris near bottom. Often shell debris is in bedding planes. At bottom a 5 cm zone of oyster shells is cut into the muds below. Lower contact is thus erosional. Shells includ razor clams, a small ark, oysters, and M. lateralis.
Open Lagoon	Dark grey muddy sand with a few lenticular sand beds. Some rounded and thin vertical burrows. Also a few pieces of oyster shells.

Core: BI-3

Date: October, 1982

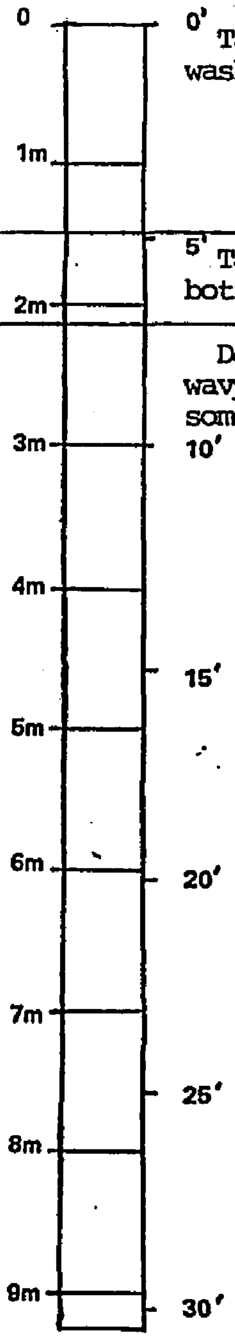
Elevation (msl): 0.8 m

Total Depth: 2.70 m

Location: Near north end of former inlet (Bungalow inlet), 30 m landward of berm.

Compaction: 1.0 m

ENVIRONMENT	DESCRIPTION
Barrier Beach/ Washover	Tan fine sand with heavy mineral beds and some washed over shells.
Inlet Fill	Tan sand with a 5 cm zone of shell debris at bottom. Erosional lower contact.
Open Lagoon	Dark grey muddy sand with interbedded lenticular, wavy, and flaser bedded sands. More mud at top, some bioturbation there.



Core: BI-4

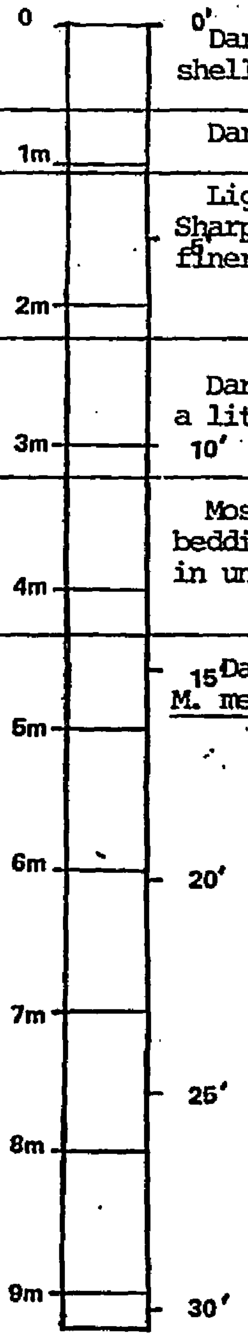
Date: October, 1982

Elevation (msl): +0.5 m

Total Depth: 7.90 m

Location: 150 m landward of Core BI-1.
On washover fan.

Compaction: 0.20 m



ENVIRONMENT	DESCRIPTION
Barrier Beach/ Washover	Dark tan medium to fine grained sands with much shell debris.
Salt Marsh	Dark grey muddy sand with much marsh vegetation.
Inlet Fill	Light grey to tan, medium to fine grained sand. Sharp contact to mud below. Less shell debris and finer grained than comparable unit of Cores BI-1 to 3.
Tidal Flat	Dark grey mostly mud. Some small shell debris and a little plant vegetation. Much bioturbation.
Washover	Mostly fine sand. A little mud with som flaser bedding within. Erosional contact to mud and sand in unit below.
Open Lagoon	Dark grey homogeneous muddy sand. Several <u>M. mercenaria</u> shells found within.

Core: BI-5

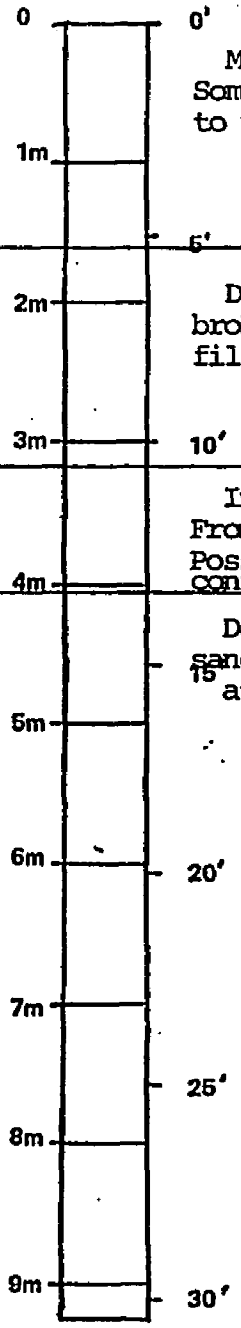
Date: October, 1982

Elevation (msl): +0.3 m

Total Depth: 6.60 m

Location: 300 m west (landward) of BI-1.
On sand flat from older washover event.

Compaction: 1.00 m



ENVIRONMENT	DESCRIPTION
Washover	Mostly fine sand with heavy mineral beds. Some mud beds near the bottom. Erosional contact to mud below.
Tidal Flat	Dark grey very muddy with several pieces of broken shells. Several round and planar sand filled burrows. Coarsens downward.
Washover	Increasingly coarser with depth within this unit. From sands with mud at top to all sand at bottom. Possibly erosional contact below, gradational upper contact.
Open Lagoon	Dark gray sandy mud with scattered lenticular sand beds. A well preserved angel wing half shell at bottom. Burrows are common and sand filled.

Core: MB-1

Date: June/1984

Elevation (msl): -1.0 m

Total Depth: 4.6 m

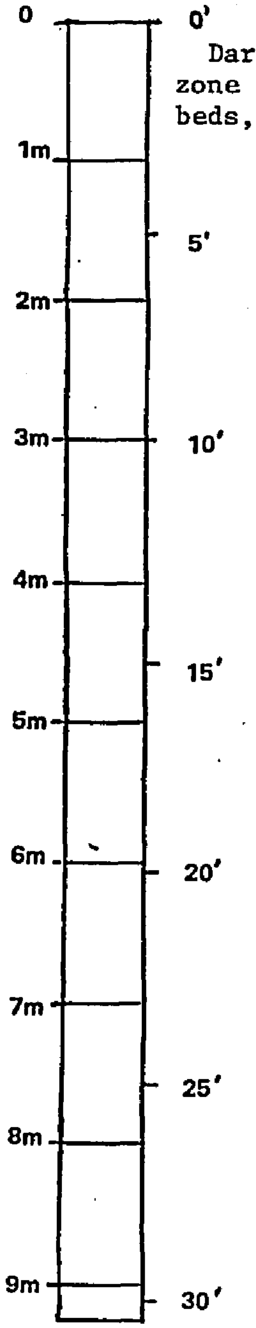
Location: 100 m northwest of red day marker #254 of Mockhorn Channel in Magothy Bay

Compaction: 10 cm

ENVIRONMENT

DESCRIPTION

Open Lagoon



Dark grey thick sequence of sandy mud. Reduced zone below surface, very anoxic. Some thin sand beds, planar, a few 1 cm thick. A few shell pieces.

Core: MB-2

Date: June/1984

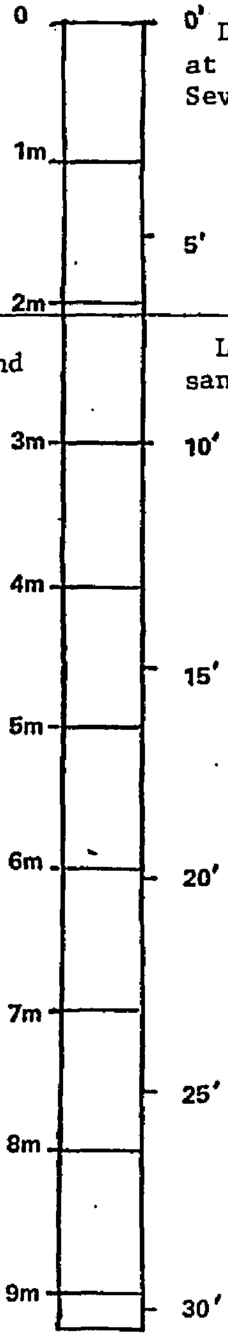
Elevation (msl): -0.7 m

Total Depth: 4.0 m

Location: 100 m east of red day marker
#254 of Mockhorn Channel in Magothy Bay

Compaction: 10 cm

ENVIRONMENT	DESCRIPTION
Open Lagoon	Dark grey muddy sand. Abrupt change to sand at bottom. Oyster zone between 0.9 and 1.0 m. Several sand filled burrows.
Pleistocene Sand (Shoreface)	Ligt grey to dark tan dirty medium to coarse sand.



Core: MC-1

Elevation (msl): +1.0 m

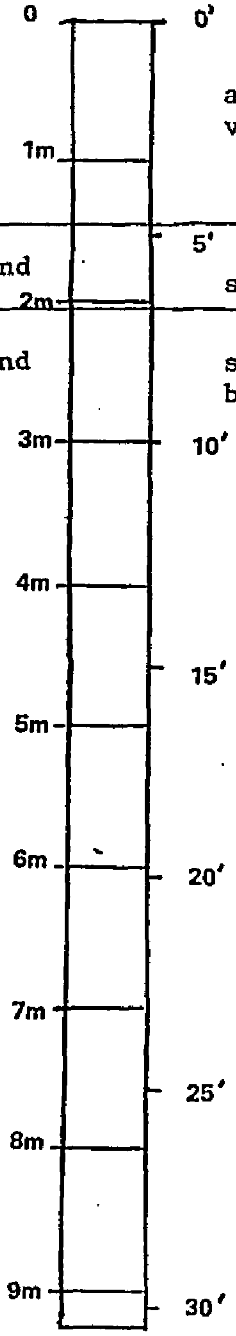
Location: Adjacent to Mill Creek at *S. patens*/treeline

Date: 22 February 1986

Total Depth: 2.93 m

Compaction: None

ENVIRONMENT	DESCRIPTION
Soil Horizon	Mottled pale blue-grey and orange sand and clay. Very tacky texture. Top 60 cm is vegetation rich. Sand increases with depth.
Pleistocene Sand	Tan, mostly homogeneous fine well-sorted sand. No physical structures but some burrows.
Pleistocene Sand Beach	Tan, fine to medium sand with dark iron-stained coarse sand beds. Many heavy mineral beds. Horizontal bedding



Core: MC-2

Date: 22 February 1986

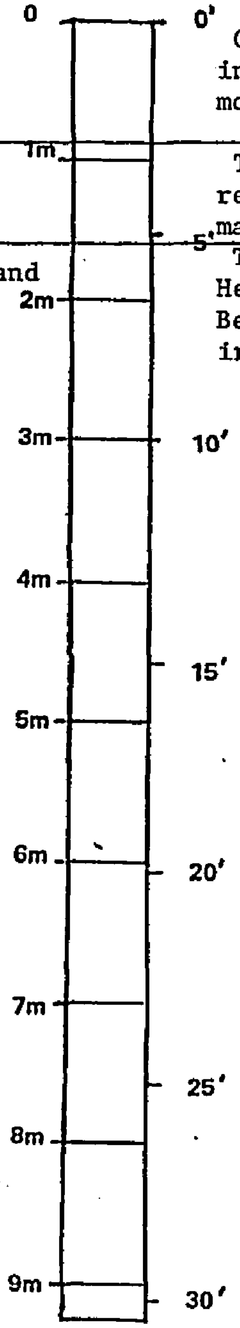
Elevation (msl): +0.65 m

Total Depth: 2.70 m

Location: Adjacent to Mill Creek at seaward extent of S. patens and I. frutescens.

Compaction: None

ENVIRONMENT	DESCRIPTION
Salt Marsh	Grey high marsh vegetation with root penetration into lower sands. Much clay at top grading into mostly sand at bottom.
Holocene Sand (Tidal Flat)	Tan, massive fine sand with pebbles. Probably reworked Pleistocene sediments from Holocene marine transgression.
Pleistocene Sand Beach	Tan, some orange from oxidation, fine sand. Heavy mineral beds between 1.5 and 2.2 m. Below 2.2 m are beds of fine and coarse sand with iron mixed into coarser sands.



Core: MC-3

Date: 22 February 1986

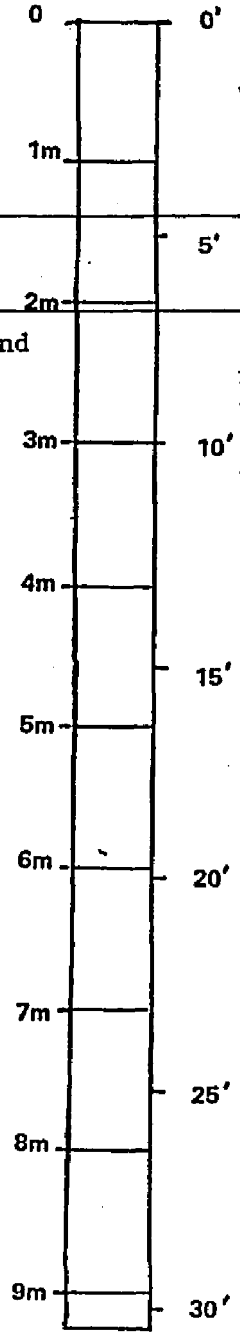
Elevation (msl): +0.30 m

Total Depth: 2,52 m

Location: Adjacent to Mill Creek at seaward extent of *S. virginica* marsh.

Compaction: None

ENVIRONMENT	DESCRIPTION
Salt Marsh	Mottled grey and orange-grey mud with increasing sand towards bottom. Much vegetation but less with depth.
Holocene Sand (Tidal Flat)	Tan and orange-tan pebbles and sand. Grades into marsh above. From reworked Pleistocene sediment.
Pleistocene Sand Beach	Very oxidized rust-colored fine sands with heavy mineral bedding. Oxidation probably from groundwater as amount not found in other cores that include this unit. Coarse sands and gravel fell out of core bottom.



Core: MC-4

Elevation (msl): at MSL

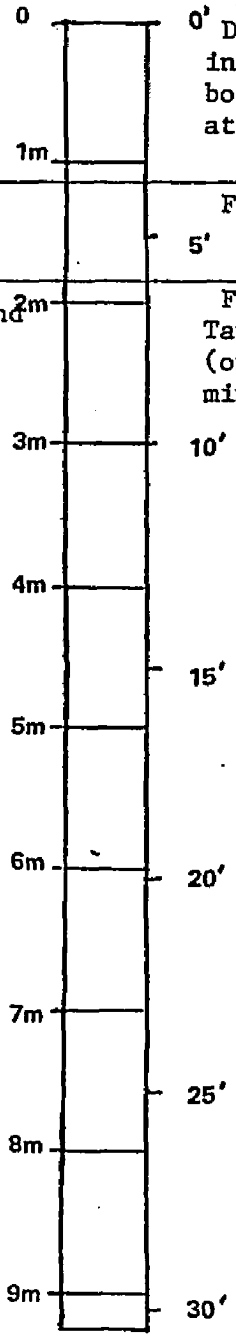
Location: Adjacent to Mill Creek in *S. alterniflora* marsh

Date: 22 February 1986

Total Depth: 3.15 m

Compaction: 0.2 m

ENVIRONMENT	**DESCRIPTION**
Salt Marsh	Dark-grey at top, bluish-grey with much orange in middle. Mottled. Silty at top. Sand at bottom, medium grained. Marsh vegetation abundant at top.
Holocene Sand (Tidal Flat)	Fine to medium sand with some pebbles. Tan.
Pleistocene Sand Beach	Fine-grained sand with many heavy mineral beds. Tan color. Below these sands are tan to orange (oxidation) zones of fine sand or pebbles. Many mineral types in coarse sands and pebbles.



VITA

KENNETH FINKELSTEIN

Born in Queens, New York, 5 December 1955. Associated with undesirable elements of society until completion of B.S. degree in Earth and Space Sciences from the State University of New York at Stony Brook in 1977. Received M.S. degree in geology from the University of South Carolina in 1979. Began professional career as a research geologist for Research Planning Institute of Columbia, South Carolina in 1979. Most experience was obtained while a research geologist for the U.S. Army Corps of Engineer's Coastal Engineering Research Center at Fort Belvoir, Virginia and Vicksburg, Mississippi between 1980 and 1984. Initiated Ph.D. at the University of Maryland in 1982-83 as a part-time graduate student. Completed most of the dissertation research after entering the doctoral program in geological oceanography at the College of William and Mary, School of Marine Science in 1983.