DEL-SG-19-82

PROCESSES OF SEDIMENTATION AND GEOLOGIC HISTORY OF THE CAPE HENLOPEN/ BREAKWATER HARBOR AREA, DELAWARE

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Technical Report

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PROCESSES OF SEDIMENTATION AND GEOLOGIC HISTORY OF THE CAPE HENLOPEN/ BREAKWATER HARBOR AREA, DELAWARE

by

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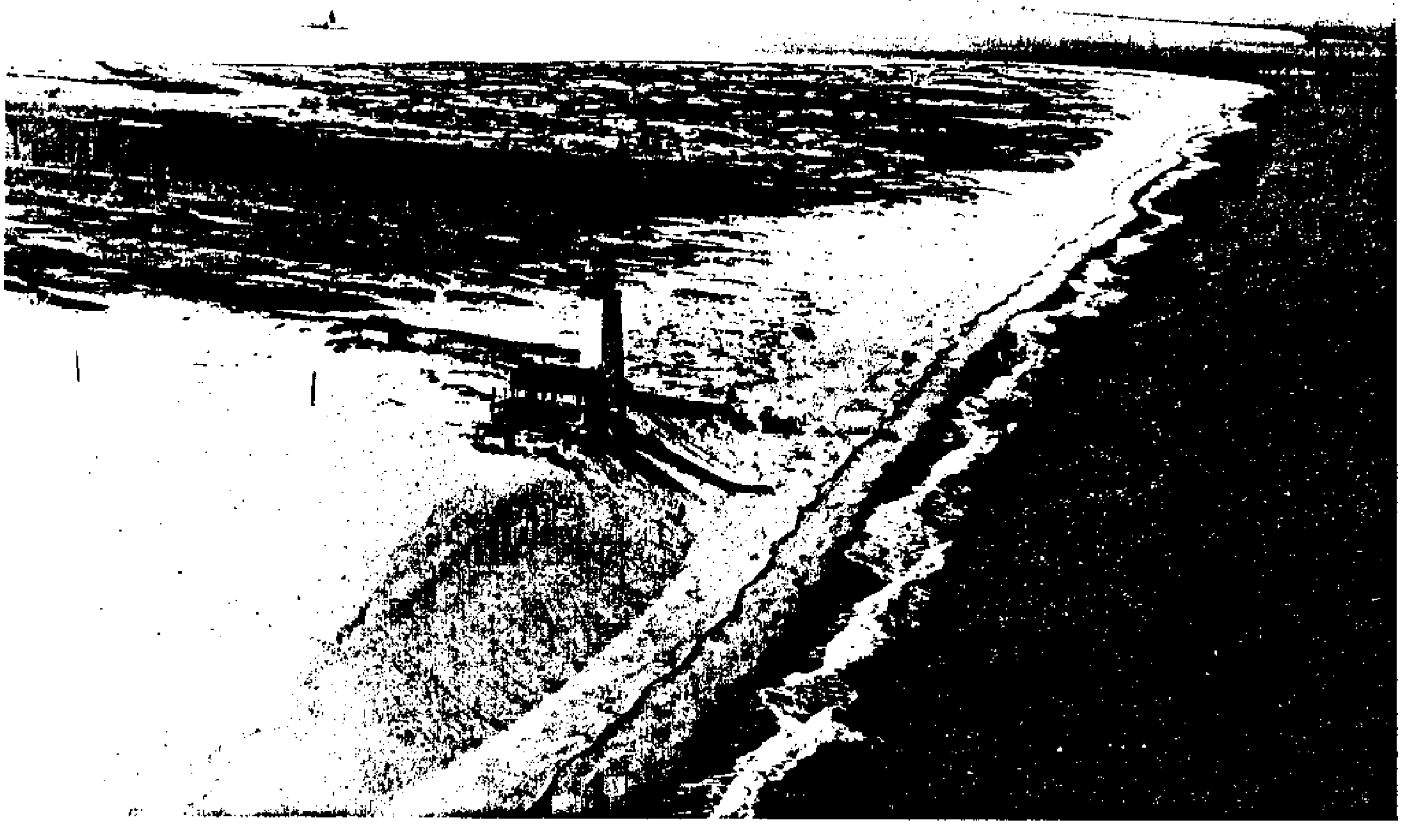
Preface

This volume presents a final summary of the results of research on sedimentation processes in Lewes Harbor, Delaware, funded by N.O.A.A. Sea Grant Contract NA 79AA-00118. A detailed analysis of sedimentation patterns and processes is presented. It is shown that any development of Lewes Harbor should be in the western area of Breakwater Harbor, given present coastal processes and the existence of the inner breakwater (Breakwater Harbor) and the outer breakwater and shears (Harbor of Refuge). Development of the eastern harbor area and/or attempts to maintain a dredged channel entrance from the east is not recommended and could indeed prove to be a very costly mistake. Entrance around the western end of the inner breakwater is highly viable and should remain so over the longer term. Controversy remains amongst the researchers on this project as to when Cape Henlopen will join by accretion to the east end of the inner breakwater. However, this controversy should not have negative bearing on any plans to develop the western portion of Breakwater Harbor. It is the opinion of the Principal Investigator that the changes in sedimentation patterns on Cape Henlopen and the resultant time frame or chances of the Cape joining the inner breakwater are related to disruption in flow of littoral transport of sand from south to north by the jetties at Indian River Inlet and to greatly increased beach nourishment programs in that area. Precission analysis of rates of sedimentation in Breakwater Harbor over the past 20-30 years are not believed to be necessary for harbor development for the next several decades as dredging plans would dramatically alter bottom configurations. However, should more precise data on present sedimentation rates be needed, they could be obtained by study of man-made isotopes fall out included in the sediments of the past three decades.

John C. Kraft
Principal Investigator



Aerial photograph of Cape Henlopen Lighthouse looking northwest (circa 1925). Cape Henlopen, Breakwater Harbor, and the Harbor of Refuge are in the background. The abandoned lighthouse fell into the Atlantic Ocean on April 13, 1926. Notice the well-developed beach cusps and megacusps on the Cape Henlopen Atlantic shoreline as well as the predominance of east-west beach ridges, one of which is the Great Dune at Lewes. Washover features are abundant on Cape Henlopen north of the Great Dune. This high-quality photo was taken by Victor Dallin from an open-cockpit airplane using a German camera captured by the United States in World War I. The camera weighed 85 pounds and had a 6"-diameter lens! From a print loaned by W. S. Taber, former State Forester of Delaware.

ACKNOWLEDGEMENTS

Innumerable people have aided the author in this dissertation, and, being the grateful sort, I want to thank all for their help. Dr. J. C. Kraft was particularly helpful in the embryonic stages of the project and as the principal dissertation advisor, he provided encouragement and direction throughout. Also serving on the committee were Drs. R. Biggs, R. Dean, B. Glass, and J. Wehmiller. I also thank Dr. R. Rumer for serving on my committee during his one-year residence at the University of Delaware. All of the committee members added fruitful suggestions throughout the various phases of the work.

Other University of Delaware faculty helped in providing expertise in areas of history (Dr. J. Munroe), geography, (Dr. B. Mather), mathematics (Dr. C. Lozano), and marine studies (Drs. R. Gibbs and D. Maurer). By its very nature, this study was interdisciplinary, and the guidance of resident experts in other related fields was essential.

Several international scientists with an interest in sedimentology and coastal geology were brought to the University of Delaware as guests during my training here. Dr. J. Hails (Director, Center for Environmental Studies, The University of Adelaide, Adelaide, South Australia, 5001) and Dr. H. Reineck (Director, Institut für Meeresgeologie und Meeresbiologie, Senckenberg-Institut, Wilhelmshaven, West

Germany) were particularly interested and energetic in discussing my project and accompanying me in the field. Dr. J. Gifford (Archaeometry Laboratory, University of Minnesota, Duluth, Minnesota, 55812) provided me with a grain-size analysis technique capable of aiding me in micro-stratigraphic analyses of layers found in vibracores from Breakwater Harbor. Also, Dr. T. Kana's sediment trap device and training on the same were most important for proper use of the device.

Technical assistance was provided by Geology Department technicians B. Bilas, V. Starks, and D. Butters. Other engineering advice on construction of equipment was obtained from University of Delaware professional staff, especially L. Fitler, J. Stuart, M. Mitchell, D. Matthews, P. Palinski, and K. DeSombre (all of the College of Marine Studies).

Discussions with and field help from fellow students is an important part of any scientific dissertation, perhaps even more so in my case because of the extremely heavy sampling schedule which was undertaken. J. Demarest's earlier work on Breakwater Harbor and Cape Henlopen was a great start on the project, but his continued interest and energy throughout the study were even more helpful. The following fellow students (many of whom now hold doctorates) are also thanked for their suggestions, field help, and lab work: A. Abdel-Kader, B. Allen, B. Atwater, A. Benamy, D. Behnke, D. Belknap, M. Boos, W. Carey, C. Chase, K. Drew, D. Dutton, G. Fordes, M. Goettle, L. Hulmes, C. John, K. Kent, E. Maurmeyer, E. Pennock, J. Pennock, K. Pollman, C. Roman, R. Scheinfeld,

M. Swincki, P. Sugarman, and G. Wisker. Also, many students from Recent Sedimentary Environments classes at the University of Delaware during 1977, 1978, and 1979 helped excavate beach trenches in the study area.

Two organizations offered me substantial logistical support and hospitality during the course of my work. First, the Philadelphia Maritime Exchange allowed me to use their Cape Henlopen Speaking Station as an observation post for time-lapse photography of the tidal flats and spit. Secondly, the College of Marine Studies was kind enough to provide me office and lab space in Lewes for nearly three years.

During the first year of my graduate studies (1976-1977), I received the support of a DuPont Fellowship. In the ensuing three years, grants were awarded to Dr. J. C. Kraft (principal investigator) to carry out most of my dissertation research. The grants were provided by N.O.A.A.-Sea Grant Contract NA 79AA-00118 and others. The Sea Grant Contracts in support of this applied research are appreciated greatly.

Finally, my heartfelt thanks go to my wife, Denise, whose support and encouragement were monumental and often sacrificial. The fact that she drafted many of the figures and typed the entire manuscript makes me feel that the document is as much hers as it is mine.

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ABSTRACT

In this study, the present sedimentary processes, past geological history, and future geological evolution of the Cape Henlopen/Breakwater Harbor area of southeastern Delaware Bay have been evaluated using a variety of methods. Fourteen bottom current-meter stations and fourteen drogue studies demonstrated that the hydrologic regime of Breakwater Harbor is strongly ebb dominated, so much so that transportation and erosion of bottom materials occur roughly three-quarters of the time. Deposition of sand in the harbor occurs only during storms, whereas deposition of silt and clay occurs during the brief flood tide and slack water. Surf zone bedload and suspended load sediment concentrations measured at sixteen locations during a variety of environmental conditions revealed that concentrations are an order of magnitude higher than normal during storms (0.3 to 125 gm/l) and that the area south of the inner breakwater is a zone of extremely low surf-zone energy (0.01 to 5 gm/l). Eight beach profile stations periodically were reoccupied from 1976 to 1979 in order to monitor accretion and erosion. Accretion presently is taking place on eastern Cape Henlopen, northern Cape Henlopen, and the entire section from the ferry breakwater to Roosevelt Inlet (the accretion seen during this study on the east side of Roosevelt Inlet was entirely due to beach

nourishment). Erosion occurs along almost the entire shoreline of Breakwater Harbor.

The geologic history of Breakwater Harbor and Cape Henlopen in the Holocene Epoch has been reconstructed based on bottom-sediment character, vertical sedimentary sequences from twenty-six vibracores, seismic and geologic cross-sections, and vertical aerial photographs over the last forty years. The Holocene section is up to 15 m thick and rests unconformably on a Pleistocene, subaerially eroded surface which slopes to the east-northeast at 0.2°. Sedimentation rates in Breakwater Harbor during the last 128 years average 2-3 cm/yr, which is a very rapid rate when compared to other estuaries with humid climates.

The future evolution of Cape Henlopen and Breakwater Harbor has been projected by undertaking a comprehensive geologic and engineering study. Although Cape Henlopen has been prograding rapidly to the northwest in the last 100 years, its rate of northwesterly growth has nearly stopped in the last decade; instead, the Cape has been growing out toward the northeast. Based on recent shoaling trends in Breakwater Harbor, it is predicted that the harbor will not shoal to sea level for another century. Likewise, it is projected that Cape Henlopen will not grow to the northwest and attach to the inner breakwater for another 50 to 100 years. These estimates probably will be affected to a large degree by dredging and other structural modifications which would tend to increase the length of time before these predictions come true.

INTRODUCTION

When Henry Hudson sailed into the mouth of Delaware Bay in 1609, one of the first observations he made was that shoals were quite pervasive in the Bay, particularly in its northeastern part. Other mariners later noticed that the best approach for ships into the Bay was near the southern cape, now called Cape Henlopen. The first decipherable map of the southeastern part of Delaware Bay was drawn by de Vries or his cohorts (circa 1631) on the occasion of the first European settlement there (Kraft and Caulk, 1972). This first Dutch settlement started records of coastal change and shoaling which have continued for 350 years to the present day. Despite this long historical record and geological evidence of change over the past, uncertainty still exists as to how and when the area will change.

By evaluating present geological forces shaping the area and assembling a detailed geological history of Cape Henlopen and the adjacent harbors, the author set out to assemble a scientific dissertation in order to more completely understand the past, present, and future geological evolution of the region. This dissertation is organized into three major parts to accomplish those goals: Part One concerns modern geologic processes; Part Two details geologic history of the area; and Part Three predicts the geologic future.

Geologic Setting

Delaware Bay is located in the central part of the Mid-Atlantic Bight of eastern North America (Figure 1). The northern reaches of the tidal Delaware River lie adjacent to a geological province known as the Appalachian Piedmont, which consists of Paleozoic and pre-Cambrian sedimentary and crystalline rocks. Seaward of the Piedmont lies the Atlantic Coastal Plain consisting mostly of Cretaceous and Tertiary deposits, covered by a thin veneer of Quaternary sediments, which gradually thicken seaward to the edge of the continental shelf (Kraft and others, 1971; Sheridan, 1974). The study area (Figure 1) is on the southern flank of a subsiding geological basin known as the Baltimore Canyon Trough Geosyncline (Drake and others, 1959).

The Delmarva Peninsula, the land located between Delaware and Chesapeake Bays, consists mostly of Tertiary and Quaternary gravels, sands, and muds which have been deposited in fluvial, marginal marine, and marine environments (Jordan, 1964; Belknap, 1979; Belknap and Wehmiller, 1980; Demarest, 1981). Strom (1972) noted that shoals in southeast Delaware Bay consist predominantly of gravels, sands, silts, and bioherms. He thought they were deposited mostly during Holocene time, a conclusion consistent with sediment reworking on this continental shelf during the last 14,000 years, as found by Curray (1965) and further supported in Delaware Bay by the findings of Belknap and Kraft (1977).

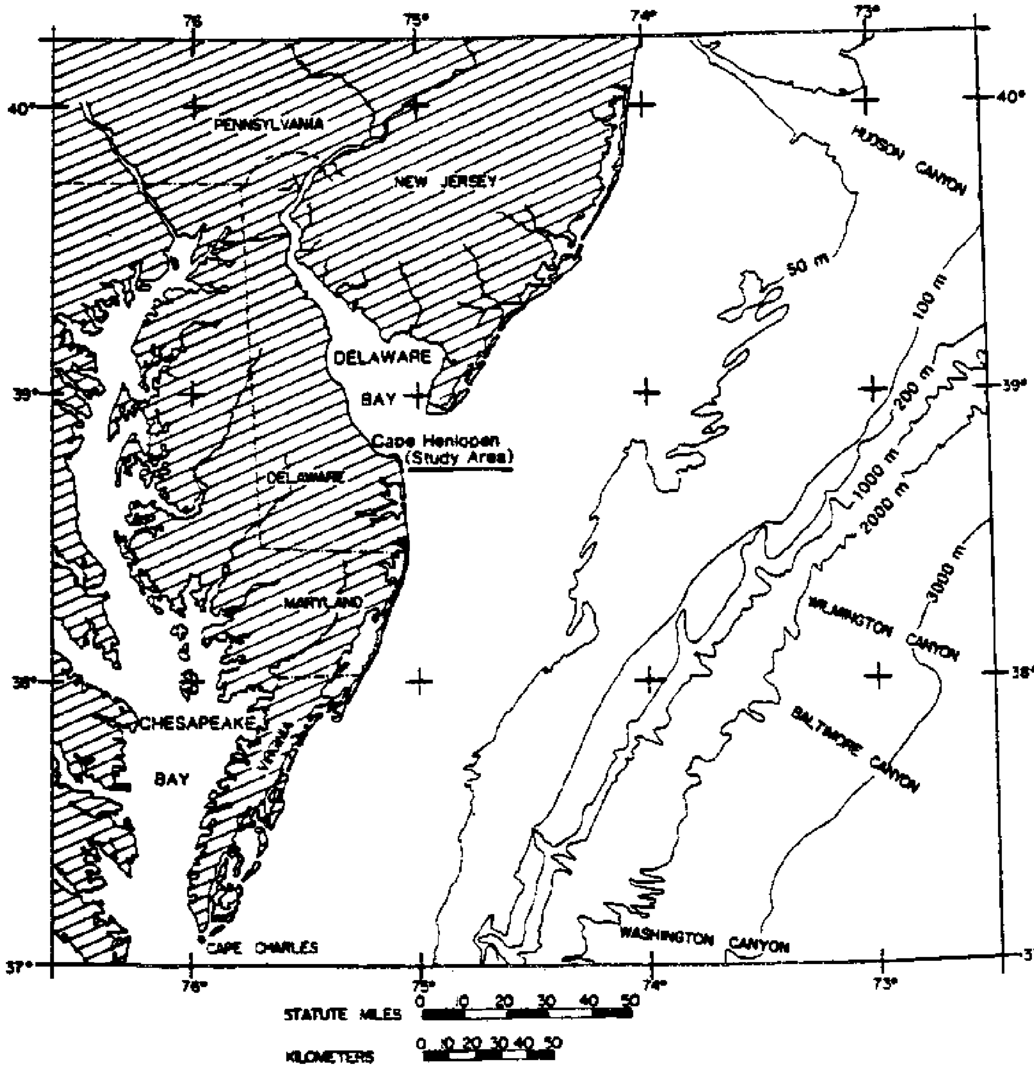


FIGURE 1. Location map of the study area showing a portion of the Mid-Atlantic Bight on the east coast of the United States. Cape Henlopen and Breakwater Harbor are in southeastern Delaware Bay where the bay joins the Atlantic Ocean. The Delmarva Peninsula is that body of land between Delaware Bay and Chesapeake Bay.

Delaware Bay Estuary

The Delaware Bay drainage basin (Figure 2) receives fresh-water runoff from portions of Delaware, Maryland, New Jersey, Pennsylvania, and New York. The estuary has tidal influence north to Trenton, New Jersey, which makes it 210 km long from its mouth to its uppermost reaches (Snyder and Guss, 1974). The width of the bay varies from 18 km at its mouth to 27 km at its widest point; it gradually narrows toward Wilmington, where it is only a few kilometers across (Polis and Kupferman, 1973). Fresh water input to the system averages 11,300 cubic feet per second (320 cubic meters per second) annually which ranks the Delaware River and Bay system as one of the major estuaries on the east coast of North America (Klemas and others, 1973). The average flushing time of bay water is about 100 days, but is as short as 60 days during spring runoff and as long as 120 days during drought (Polis and Kupferman, 1973).

The tidal range at Trenton is 2.1 m and decreases at Cape Henlopen to about 1.2 m: Delaware Bay is therefore classified as a microtidal to mesotidal estuary according to the scheme of Hayes (1975). The geometry of the Bay and the tidal wavelength combine to create peak currents and slack water simultaneously at opposite ends of the bay (Klemas and others, 1973). This vigorous tidal reversal transports a considerable volume of sands, silts, and clays (Oostdam, 1971; Klemas and others, 1973). Oostdam (1971) further stated that, like other estuaries described by Meade (1969), Delaware Bay has a net

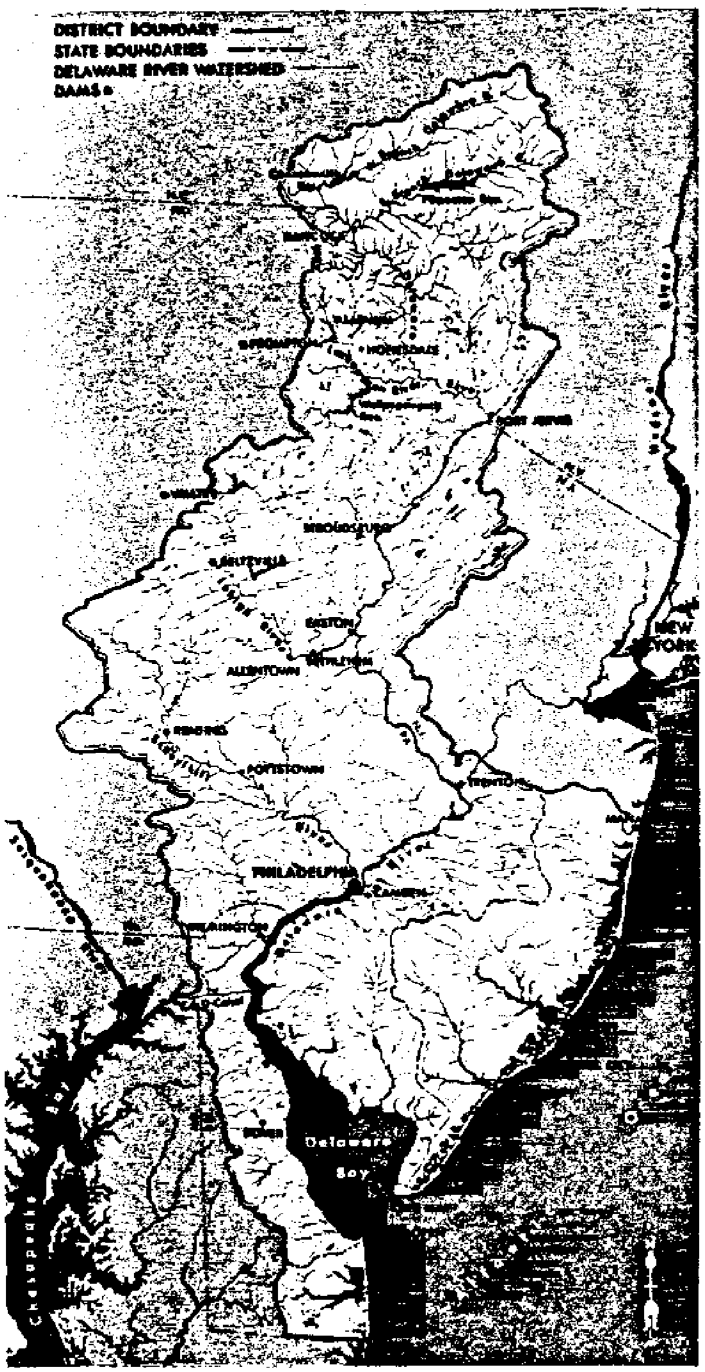


FIGURE 2. Delaware Bay drainage basin (for scale, it is about 100 km from Cape Henlopen to the C & D Canal in northern Delaware Bay). Used with permission of the United States Army Corps of Engineers, Philadelphia District.

outflow of near-surface suspended sediments to the ocean and a net landward transport of near-bottom sediments into the estuary. Based on his measurements of suspended sediments and current velocities in the estuary, Ootsdam suggested that most of the suspended silts and clays are found within about 60 cm of the bottom.

Like other similar estuaries of the world, Delaware Bay is filling with sediments at average rates of 18-20 cm/100 years (Ootsdam, 1971; Reineck, 1967; Rusnak, 1967; and Meade, 1969). However, these rates may have been accelerated recently by sediment runoff caused by rapid deforestation and agricultural activities in the last 200 to 300 years. Ootsdam (1971) has found that shoaling in some central areas of Delaware Bay has kept pace with relative sea level rise, and he therefore concludes that parts of Delaware Bay are in a state of dynamic equilibrium.

Swain (1972) and Ootsdam (1971) have found that the middle part of Delaware Bay traps silts and clays (with the associated organic matter) according to a model proposed by Postma (1967). However, much of the sediment initially trapped in the mid-estuary deposition center presumably bypasses that vicinity and moves down the estuary toward the mouth. This bypassed sediment and the material supplied by shore erosion of marshes along the bay margin provide the immediate source of fine-grained sediment which, in turn, supplies the vicinity of Cape Henlopen and Breakwater Harbor. The supply of sands and gravels in the shore zones of the study area results from littoral transport feeding Cape Henlopen to the north along the Atlantic coast and feeding the study area from the west along the Delaware Bay shoreline (Kraft and others, 1976). Historical trends of sedimentation and erosion in the study area have been affected in a major way by man-made structures in the vicinity (Hoyt, 1979; Demarest, 1979).

History of Coastal Engineering Structures in Study Area

Figure 3 is a base map of the study area which identifies major man-made structures. The inner breakwater, marked "A" in Figure 3, was constructed in two phases. The eastern and western segments were constructed about 1831 by the U.S. Army Corps of Engineers to provide a harbor for commercial sailing ships. By 1890, it became obvious that the breakwater was not preventing the cape from growing northward, so the center segment was filled in to increase the funneling effect of the ebb tide. This strategy failed as the Cape grew northward anyway. By 1900 Breakwater Harbor had shoaled significantly and had become useless because some steamships and newer sailing ships had drafts deeper than depths found in the harbor (Kraft and Caulk, 1972). Consequently, an outer breakwater ("B" in Figure 3) was constructed at the turn of the century to create the Harbor of Refuge. Within a few decades, this outer breakwater, too, became obsolete: larger, steam-powered ships did not require a harbor. The next major construction in the area was Roosevelt Inlet in 1937 ("C" in Figure 3). Sheet-metal jetties extending out about 300 m from shore interrupted the eastward littoral drift of sand (Dennis and Dalrymple, 1978; Hoyt, 1981). Immediately following construction of the outer breakwater in 1900, littoral drift in the study area apparently reversed direction from a

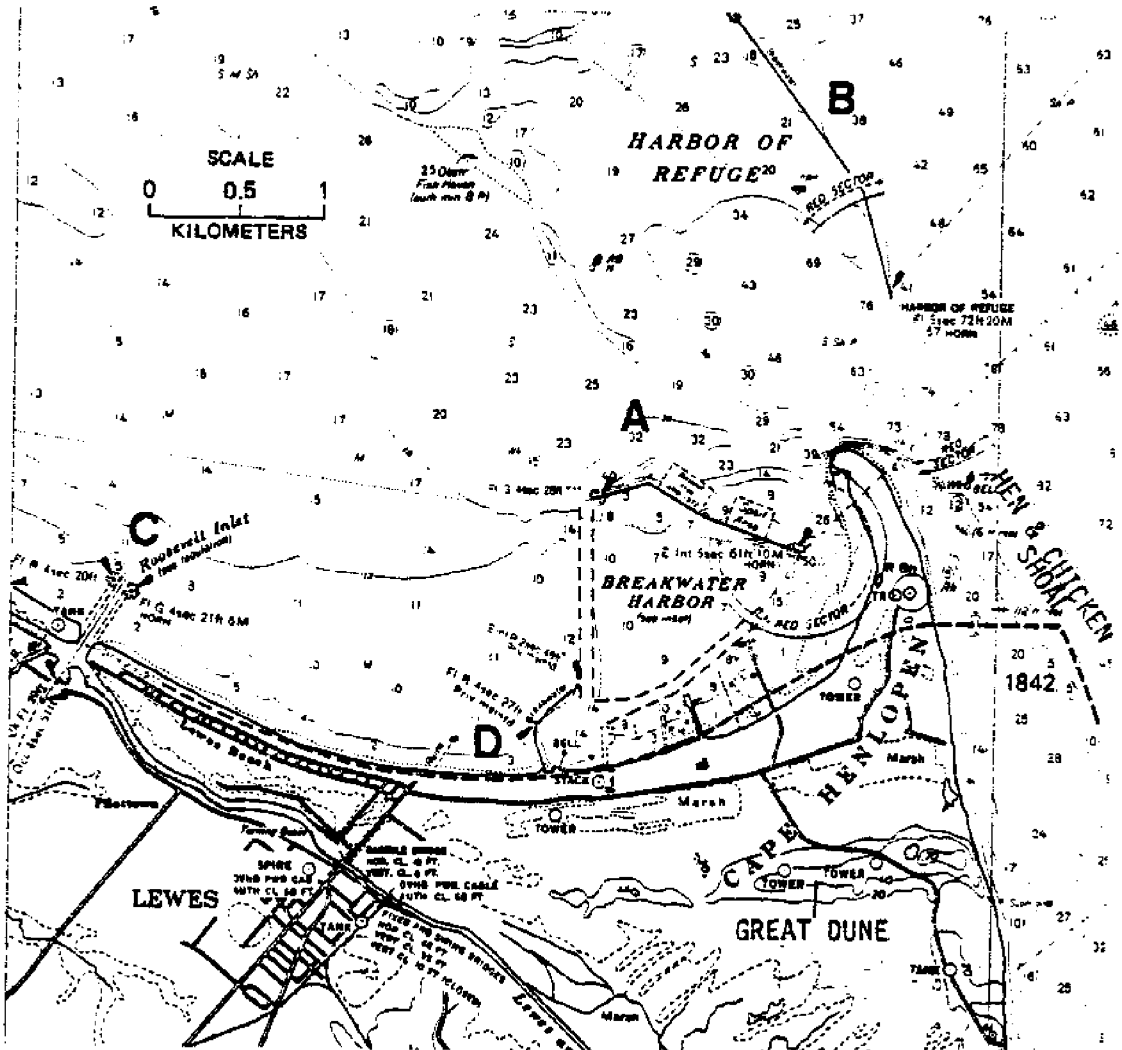


FIGURE 3. National Ocean Survey Chart # 12216 showing the study area. Letters refer to man-made structures discussed in the text. The area of study for this dissertation has the following approximate limits: east to Hen and Chickens Shoal, north to the north point of the outer breakwater (B), west to Roosevelt Inlet (C), and south to the Great Dune at Lewes.

westerly to an easterly flow (Maurmeyer, 1978). Speculation suggests that this reversal may have been caused by a combination of factors: by the inner and outer breakwaters reducing incident wave energy from the east and by Cape Henlopen forming a simple spit, preventing any westerly flow of sand. The present condition of Roosevelt Inlet results in a sand-starved shoreline downdrift (east) of the inlet at Lewes Beach (Hoyt, 1980). Repeated dredging and beach nourishment operations, however, have moved sand from the inlet channels to Lewes Beach. Also, state and federal agencies have emplaced nine groins downdrift of the inlet on Lewes Beach in order to help trap sand (Dennis and Dalrymple, 1978). The most recent major construction in the area, the ferry-harbor breakwater ("D" in Figure 3), was constructed in 1964 and further reduced the amount of sand entering Breakwater Harbor shorelines from the west.

Previous Studies of the Cape Henlopen/Breakwater Harbor Area

In the late 1960's and early 1970's, Kraft and his co-workers began to study the geological history of the vicinity surrounding Cape Henlopen. Using old maps, Kraft (1971) assembled a history of geomorphic change of Cape Henlopen from 1631 to 1968 (Figure 4). In the time of the early Dutch settlements, Cape Henlopen was in the shape of a broad, cuspate foreland, much like present-day Cape Henry, Virginia. In the 1800's, the Cape began to elongate into a simple spit. In the 1900's up to the present day, the Cape was attempting to take on the shape of a recurved spit, much like Sandy Hook, New Jersey. Kraft and

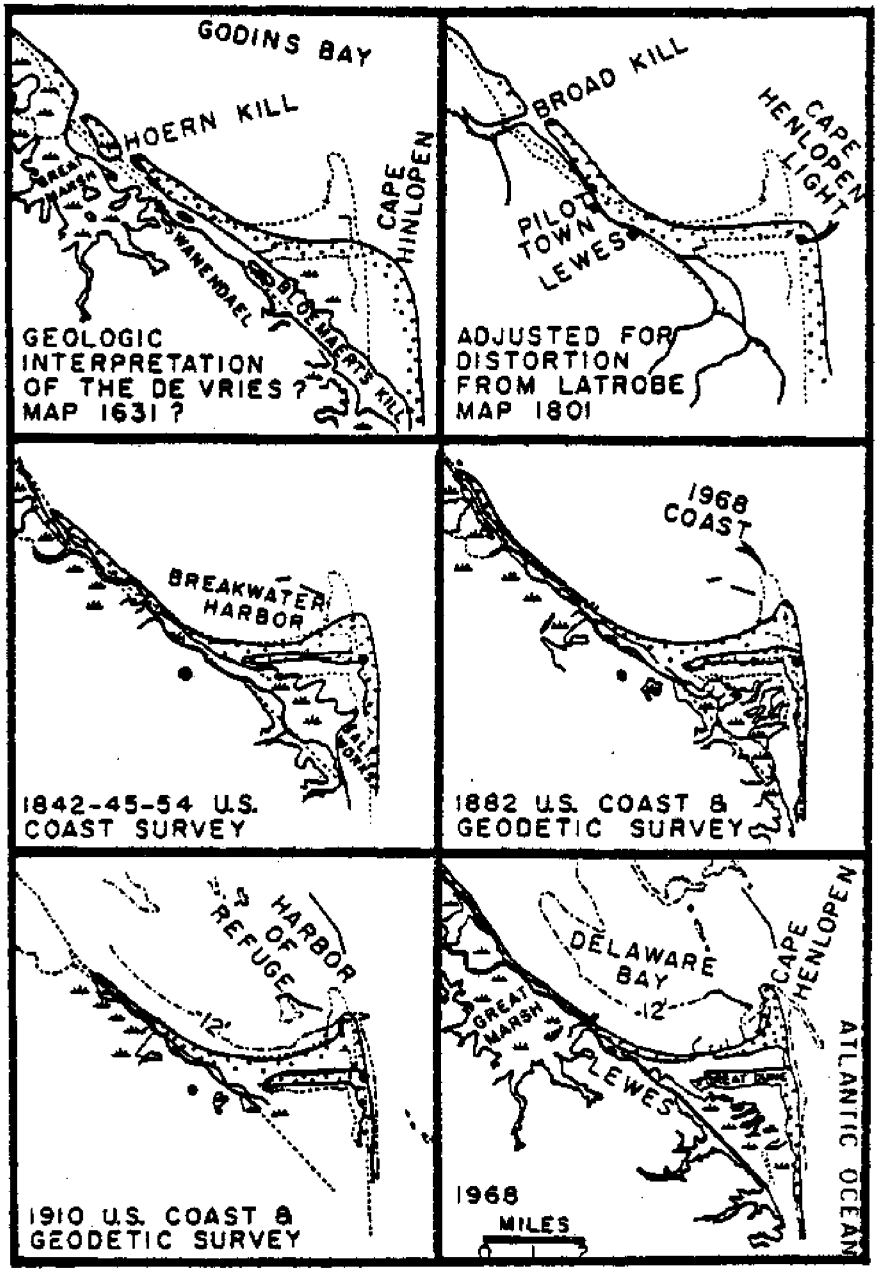


FIGURE 4. Historical growth of Cape Henlopen from 1631 to 1968 (from Kraft, 1971a). The dashed line refers to the location of present-day Cape Henlopen. The spit has changed shape and has migrated to the northwest since the 1600's.

others (1978) believe that Cape Henlopen is going through an evolutionary phase which must include a recurved spit in the future. These evolutionary phases of spits are based on observations of Fisher (1967), who noted that coastal compartments exist along the sandy coastal plain of eastern North America. The sequence of spit phases consists of a broad, cuspate foreland followed by a simple spit, in turn followed by a recurved spit. Then a recurved spit would evolve gradually into a broad, cuspate foreland and the cycle would continue.

Evidence of an earlier recurved Cape Henlopen spit has been discussed in detail by Kraft (1971), Kraft and others (1976), and Kraft and others (1978). Tree-covered spit tips now exist south of the Great Dune (Figure 4). These ridges are covered with numerous shell middens and associated artifacts which date to approximately 2,000 years B.P. (Kraft and others, 1978). Even as recently as 1631, the Dutch anchored in open water to the south of the last spit recurve in what is now Lewes Creek (Kraft and Caulk, 1972). The Great Dune itself is a 3-4 km-long sand hill, which is as high as 25 m above sea level; its origin probably is due to deforestation of the area in 1829-31, when trees were used as a mat underlying the inner breakwater (Kraft and Caulk, 1972). North of the Great Dune lies a beach accretion plain which formed from approximately 500 years B.P. to the present (Kraft and others, 1976).

Generalized sedimentary processes and sediment transport rates were reviewed by the U.S. Army Corps of Engineers (1956), Turner (1968), Kraft (1971), Kraft and others (1978), and Demarest (1978). Turner estimated that littoral transport along the Delaware Atlantic coast varies from 103,000 m^3/year to 344,000 m^3/year. Of this amount, the U.S. Army Corps of Engineers estimated that 106,000 m^3/year is deposited in the Cape Henlopen spit complex, which includes the emerged portion of the spit, as well as some submerged shoals (e.g. Hen and Chickens Shoal shown to the southeast of the spit in Figure 3).

Earlier studies of Breakwater Harbor (sometimes referred to as Lewes Harbor) include those of Kraft and Caulk (1972), Rothman (1972), and Demarest (1978). In addition, an excellent historical accounting of developments in the area since European man's arrival are recorded in Beach (1979) and in the history of the Philadelphia District, U.S. Army Corps of Engineers (Snyder and Guss, 1974). Although Kraft and Caulk (1972) noted that shoaling of Breakwater Harbor has occurred due to sands derived from Cape Henlopen and silts from Delaware Bay, it was not until the work of Demarest (1978) that the shoaling was quantified. Rothman's brief engineering analysis of deposition in Breakwater Harbor concluded that current velocities in the eastern part of the harbor [where a 17 meter- (57 ft.) deep hole exists] were too high to allow deposition. Demarest's (1978) analysis of shoaling, based on bathymetric maps since 1842, has been very useful as a guide to choosing coring sites to investigate mechanisms of shoaling in this study. A more detailed discussion of these studies will be included in the appropriate chapters which follow.

PART ONE

MODERN GEOLOGIC PROCESSES

CHAPTER I

HYDROLOGIC REGIME OF THE STUDY AREA

Introduction

In this chapter, hydrologic factors affecting sediment transport and deposition will be considered. This section includes measurements of current velocities and water temperature. Also considered is the wave energy as it affects the region. Much of the information presented in this chapter is used in later chapters.

Tidal Currents

An estimate of the near-surface tidal flow in and out of Delaware Bay can be obtained from the predicted tidal current tables for the Atlantic Coast of North America (published annually by the National Ocean Survey). For a typical lunar cycle (e.g., November, 1981), the maximum current velocity during ebb tide at the mouth of Delaware Bay exceeds the current velocity during flood tide by about 3.5% (91 cm/sec on ebb and 88 cm/sec on flood). Likewise, the duration of ebb tide exceeds the duration of flood tide at the Delaware Bay by 6.7% (about 6.4 hours for ebb and 6 hours for flood). The mean tidal period is 12.42 hours. The dominance of ebb tide in the estuary as a whole reflects the net fresh water outflow of the system (Ootsdam, 1971).

More importantly for this study, however, are the tidal currents and tidal asymetries found in Breakwater Harbor itself. Because of the configuration of Delaware Bay (Figure 2) and the tendency of the Coriolis Force to deflect flowing water to the right in the northern hemisphere, ebb tide experiences an even longer duration and higher current velocities in the vicinity of Breakwater Harbor (Figures 2 and 3). Moreover, the funnel shape of Breakwater Harbor itself causes tidal currents to be faster and of longer duration than at the mouth of Delaware Bay. Also, the presence of Cape Henlopen to the east of Breakwater Harbor causes the flood tide to bypass the harbor and thereby decreases the intensity and duration of flood currents.

Tidal currents can be measured by a variety of methods, all of which use either the Eulerian or Lagrangian principle. Eulerian methods fix a calibrated current meter in one location and measure the current moving past that device. For the detailed measurements needed in Breakwater Harbor adjacent to Cape Henlopen, both types of measurement methods were used. Current meters deployed on the bottom were used to record velocities for long periods of time (one month), while drogues were used to obtain very accurate information on the pathways currents took over the short term (one tidal cycle).

Fourteen separate drogues were placed into the study area at the times and locations shown in Table I-1 and Figure I-1. The ebb-tide drogues (A and B) display a curving path out of the eastern end of the harbor around Cape Henlopen. As the ebb tide wanes (drogues C

TABLE I-1. DROGUES

DROGUE LABEL	TIDAL CONDITION	DATE	DISTANCE TRAVELED (m)	TIME TRAVELED (hrs.)	VELOCITY (cm/sec.)	WIND (km/hr.)	NOTES
A	Ebbing	7/7/78	1,625	1.50	30.1	SSE @ 30	
B	Ebbing	7/7/78	1,530	1.40	30.0	SSE @ 30	
C	Late Ebb	7/14/78	1,440	2.03	19.7	SSW @ 30	
D	Late Ebb	7/14/78	1,500	1.88	22.0	SSW @ 30	
E	Flooding	7/14/78	1,190	1.53	21.6	SSW @ 30	
F	Flooding	8/11/78	1,625	0.90	50.0	SE @ 15	
G	Flooding	8/11/78	190	1.05	5.0	SE @ 15	
H	Flooding	8/11/78	1,125	1.10	28.4	SE @ 15	
I	Flooding	8/11/78	125	0.23	14.9	SE @ 15	GROUNDED
J	Flooding	8/11/78	625	0.83	20.8	SE @ 15	
K	Flooding	8/11/78	250	0.28	24.5	SE @ 15	GROUNDED
L	Flooding	8/11/78	280	0.47	16.7	SE @ 15	GROUNDED
M	Flooding	8/11/78	315	0.40	21.9	SE @ 15	
N	Flooding	8/11/78	250	0.55	12.6	SE @ 15	

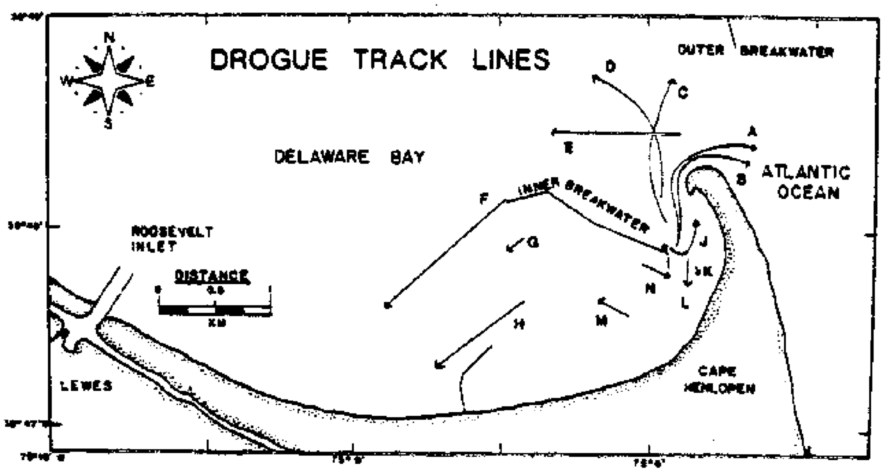


FIGURE I-1. Paths described by drogues with the drogue element located 1 meter below the water surface during various tidal conditions.

and D), water moves out of Breakwater Harbor's east exit and begins to move back up Delaware Bay. Drogues E through N show water movements during flood tide. In general, current velocities in Breakwater Harbor are about 15 cm/sec in various gyres; only drogues F and H on the western boundary of the harbor show sustained velocities on flood tide. The problem with the drogues used in this study is that they measure surface (1 m depth) current velocities. The sedimentologist and engineer, however, must also know the bottom current velocities in order to characterize the current regime the sediments experience. Therefore, a program of bottom, long-duration current measurements was set up and carried out over a 21-month period.

Fourteen current meter stations were occupied as part of this study for six to 35 days at each station (Table I-2 and Figure I-2). In order to prevent biological fouling, the current meter was painted with antifouling paint. The information was collected with a General Oceanics Model 2010 film-recording, tilting current meter which recorded a measurement every 15 minutes. The method of deployment and retrieval was outlined by Demarest (1978a, b) and is illustrated in Demarest (1978b) and Hoyt and Kraft (1980). The 8 mm black and white Tri-X reversal film was read and the current data recorded onto sheets like the one shown in Appendix A. Inclination was converted into cm/sec by means of a calibration curve supplied by the manufacturer. At each of the 14 stations, the center of the current meter was about 50 cm above the bed; consequently, the current velocities which are reported here are partly diminished by bottom friction. However, it is precisely

TABLE I-2.

BREAKWATER HARBOR AND VICINITY CURRENT METER LOCATIONS

(Tilting, film-recording General Oceanics #2010)

STATION #	LOCATION, EXACT NAVIGATIONAL FIXES, COMMENTS	DEPTH (Datum is MLW)
1 Placed: 10/24/76 Retrieved: 11/24/76 Duration: 32 days.	Central Breakwater Harbor Sextant Angles: Pilot speaking station to Red stack 109° 17' Red stack to ferry jetty end beacon 23° 37' (Data collected by J. M. Demarest)	3.7m (12 ft.)
2 Placed: 4/16/77 Retrieved: 5/8/77 Duration: 23 days.	East entrance of Breakwater Harbor, between east end of inner breakwater and Cape Henlopen tidal flat. Sextant Angles: Pilot speaking station to tower south of sp. sta. 48° 27' Line: West end of inner B. W. and E. Inner B. W. lt.	12.1m (40 ft.) (Data collected by J. M. Demarest)
3 Placed: 5/23/77 Retrieved: 6/26/77 Duration: 35 days.	North of Cape Henlopen tip Sextant Angles: Pilot speaking station to E. In. B. W. lt. 38° 20' E. In. B. W. lt. to W. In. B. W. beacon 46° 14'	15.1 m (50 ft.
4 Placed: 8/6/77 Retrieved: 9/17/77 Duration: 32 days.	Inside Hen and Chickens shoal, east of Cape Henlopen Sextant Angles: Tower east of Great Dune to tower west of G. D. 13° 57' Tower west of G. D. to red stack 26° 15' to tower S. 13°15'	7.6m (25 ft.)
5 Placed: 9/10/77 Retrieved: 10/7/77 Duration: 28 days.	Western Breakwater Harbor Sextant Angles: West In. B. W. beacon to E. In. B. W. lt. 51° 10' E. In. B. W. lt. to red stack 80° 47' to Lewes T. 40° 20' Line: Red stack and ferry jetty end beacon; outer B. W. lt. and In. B. W. westernmost dogleg.	4.25m (14 ft.)
6 Placed: 10/22/77 Retrieved: 11/21/77 Duration: 31 days.	Eastern entrance B. W. Harbor, east of location #1 Sextant Angles: S. edge of E. In. B. W. pier to Outer B. W. lt. 86° 32' Pilot speaking sta. to S. Cape Henlopen tower 52° 04' Line: W. In. B. W. lt. and pier south of E. In. B. W. lt.	6.1m (20 ft.)

TABLE I-2 (CONT'D)

BREAKWATER HARBOR AND VICINITY CURRENT METER LOCATIONS

STATION #	LOCATION, EXACT NAVIGATIONAL FIXES, COMMENTS	DEPTH (Datum is MLW)
7 Placed: 1/28/78 Retrieved: 2/12/78 Duration: 16 days.	West-southwest B. W. Harbor, north of ferry jetty Sextant Angles: W. In. B. W. beacon to E. In. B. W. lt. 57° 44' E. In. B. W. lt. to S. Cape Henlopen tower 29° 04' Line: Red stack and ferry jetty end light Note: Data were collected until 2/26/78, but were illegible due to cold water malfunctioning of meter.	3.7m (12 ft.)
8 Placed: 2/26/78 Retrieved: 3/18/78 Duration: 21 days.	Southwest Breakwater Harbor W. In. B. W. beacon to E. In. B. W. lt. 75° 20' Line: Lewes chruch spire and ferry jetty end beacon.	2.75m (9 ft.)
9 Placed: 3/18/78 Retrieved: 4/6/78 Duration: 20 days.	Northern Breakwater Harbor E. In. B. W. lt. to S. C. H. tower 28° 0' S. C. H. tower to red stack 62° 30' Line: Coast Guard tower and ferry jetty end beacon.	1.85m (6 ft.)
10 Placed: 5/20/78 Retrieved: 6/9/78 Duration: 21 days.	Central B. W. Harbor E. In. B. W. lt.to S. C. H. tower 50° 40' S. C. H. tower to red stack 83° 52' Red stack to ferry jetty end beacon 22° 52' Line: Blue water tower and tower above boathouse. Note: Much of record past 5/25/78 can't be read due to light source malfunction on that date.	3.7m (12')
11 Placed: 6/9/78 Retrieved: 6/14/78 Duration: 6 days.	East Breakwater Harbor E. In. B. W. lt. to pilot speaking station 64° 0' S. C. H. tower to red stack 81° 5' Line 1: Blue water tower and small stack. Line 2: Coast Guard beacon and radio beacon.	2.75m (9 ft.)
12 Placed: 6/14/78 Retrieved: 6/27/78 Duration: 14 days.	West of Breakwater Harbor W. In. B. W. beacon to E. In. B. W. lt. 30° 44' E. In. B. W. lt. to red stack 65° 0' Line 1: Coast Guard radio beacon and tower S. of stack. Line 2: W. end of Oc. Hse. Hotel and silver water tower.	3.35m (11 ft.)

TABLE I-2 (CONT'D)

BREAKWATER HARBOR AND VICINITY CURRENT METER LOCATIONS

STATION #	LOCATION, EXACT NAVIGATIONAL FIXES, COMMENTS	DEPTH (Datum is MLW)
13 Placed: 6/27/78 Retrieved: 7/7/78 Duration: 10 days.	North of Roosevelt Inlet Sextant Angles: Red stack to silver water tower 31^{o} 28' Silver water tower to CMS radio beacon 47^{o} 30' Line 1: Red jetty marker on Roosevelt Inlet w/ radio b. Line 2: Blue water tower and tower west of Great Dune.	3.65m (12 ft.)
14 Placed: 7/7/78 Retrieved: 7/14/78 Duration: 8 days.	North of west end of Inner Breakwater Line 1: W. In. B. W. beacon and red stack. Line 2: S. Cape Henlopen tower and sharp marker rock 100m from west end of inner breakwater.	12.8m (42 ft.)

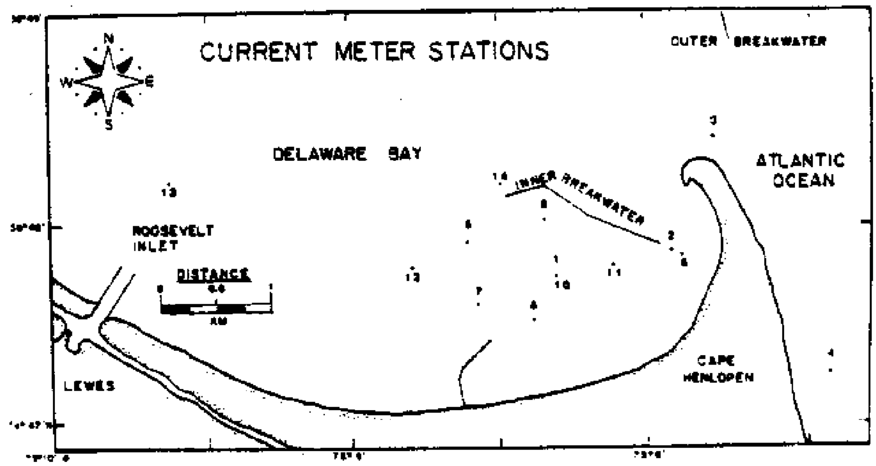


FIGURE I-2. Location of bottom, long-duration current meter stations.

this bottom drag caused by bed friction which is so important for a consideration of bottom sedimentation in this study.

Current meter stations 1 and 10 are at the same location, in order to test repeatability of results. In most of the analyses that follow, the data from these two stations are very similar: repeatability is good. Abberations in repeatability were caused by strong winds affecting local direction and speed of currents. Data from current meter stations 1 and 2 were collected by Demarest (1978) who found that mean ebb velocities at Station 1 were 30-40 cm/sec toward the east and mean flood velocities there were 10-20 cm/sec toward the northwest. At Station 2, Demarest (1978) found mean ebb velocities to be 40-50 cm/sec toward the northeast out the eastern end of the harbor. Flood velocities averaged about 30-40 cm/sec toward the southwest.

Collaboration with D. Behnke for mutual use of current meter data (Behnke, 1980) facilitated collection and data reduction. Initially, average tides (not during a neap or spring condition) were plotted for Stations 1 and 2 using "Whisker Plots," (after a method described by Fox and Davis, 1980). This method of displaying current meter data (Figure I-3) plots a vector showing direction and velocity of the current each hour.

At Station 1 in the central area of Breakwater Harbor, there are nine consecutive hours of easterly flow on ebb tide and only about 3.4 hours of westerly flow on flood tide. The tidal currents flow toward the east almost three-quarters of the time and to the west on

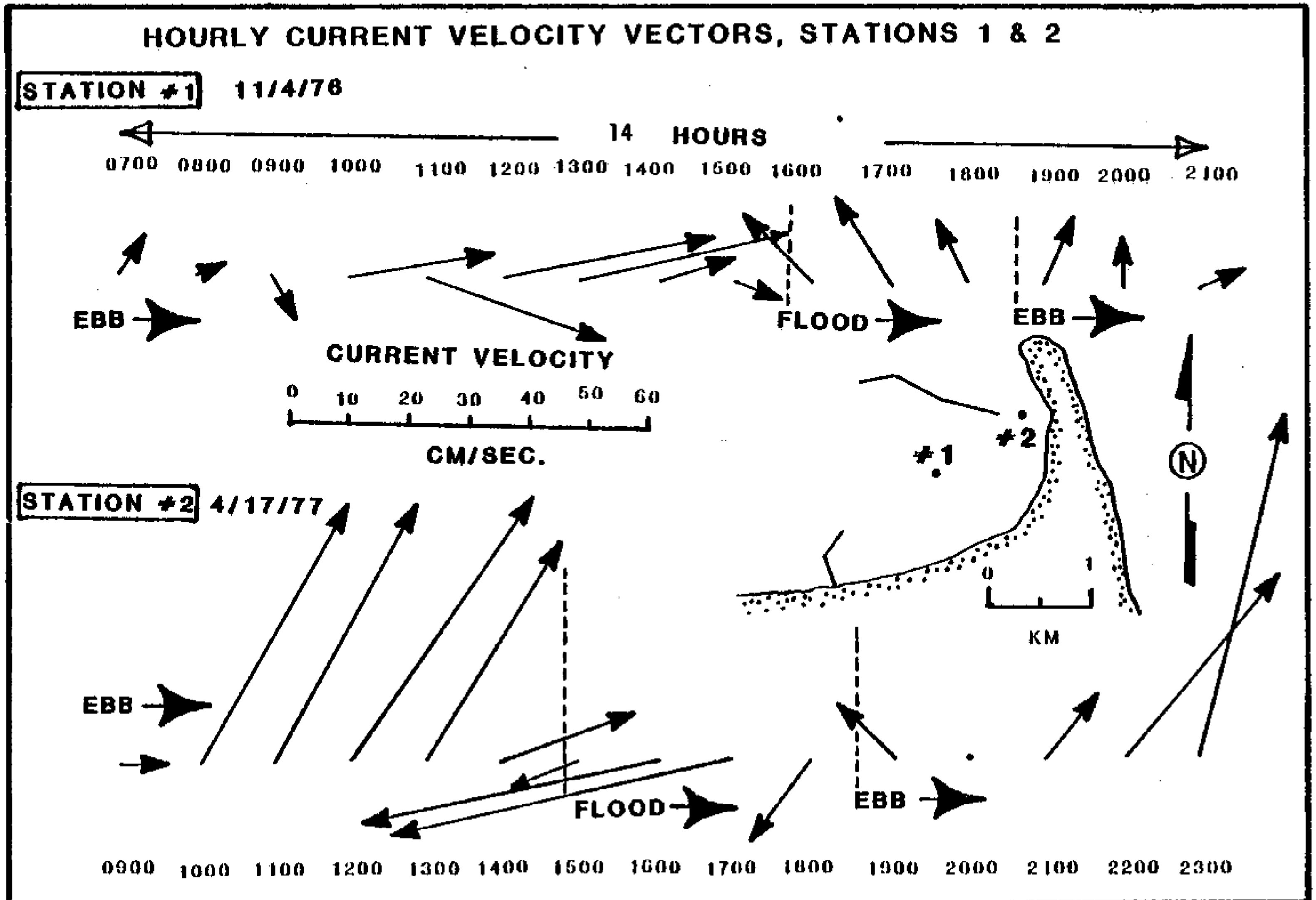


FIGURE I-3. Wisker diagram plot of current vectors for central and eastern Breakwater Harbor.

flood only about one-quarter. Mean ebb velocities (30 cm/sec) are similar to those reported by Demarest (1978). Mean flood velocities (15 cm/sec) are also similar to those reported by Demarest. The data used here from Stations 1 and 2 are the same as those used by Demarest (1978a, b). Only the style of data presentation differs.

For Station 2 at the eastern entrance of Breakwater Harbor, the "Whisker Plot" (Figure I-3) shows again that the ebb tide dominates both in velocity and in time. However, the ebb tide here flows for only 58% of the time, compared with 73% at Station 1. This must mean that there are gyres in the harbor on flood tide, a fact that is corroborated by the drogue results discussed earlier (Figure I-1). At Station 2, mean ebb tides are 40-50 cm/sec and mean flood tides are about 30-40 cm/sec; these results, as expected, also agree with those of Demarest (1978).

A more thorough and comprehensive method of displaying the current meter data is shown in Figures I-4 to I-9. These figures show current velocities for three average tidal cycles at each of the 14 stations. Current velocities vary from the average by about 10%; with higher velocities during spring tides and lower velocities during neap tides. Six "snapshots" of tidal currents are shown at approximately two-hour intervals. Figure I-4 shows early ebb tide (referred to as Hour 0). Velocities are toward the east throughout the harbor, ranging from 10-20 cm/sec at Stations 5, 9, and 12 to 40-50 cm/sec throughout the central harbor area. Notice that Stations 2, 6, and 11 (all of which are in deeper water at the eastern end of the harbor) all show more rapid current velocities (50-80 cm/sec) as a result of the

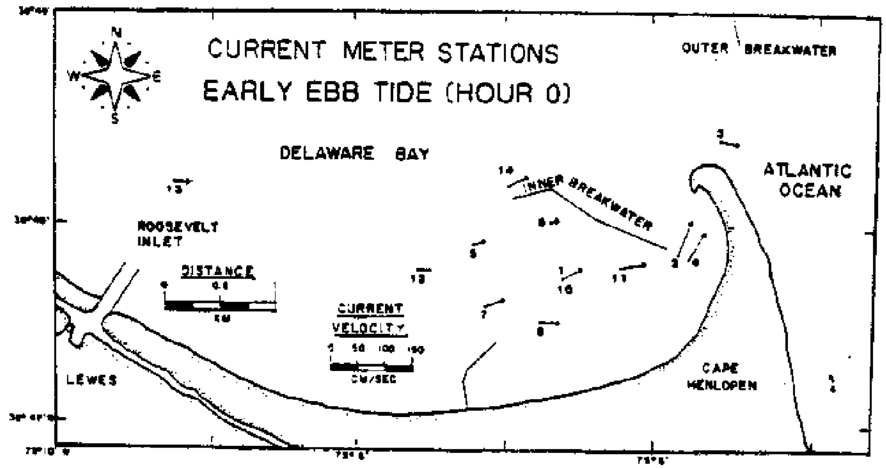


FIGURE I-4. Current vectors at fourteen stations during early ebb tide (Hour 0). Average of three tidal cycles. Length of arrows indicates current velocity in cm/sec (see current velocity scale).

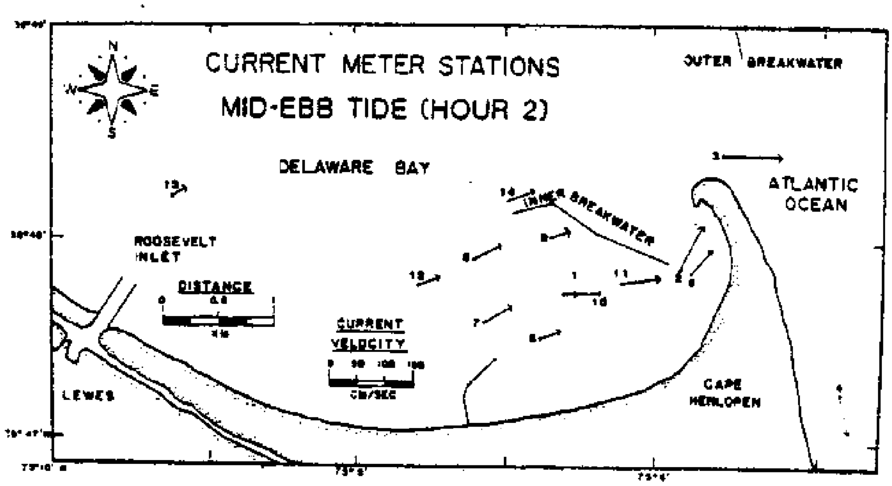


FIGURE I-5. Current vectors at fourteen stations during mid-ebb tide (Hour 2). Average of three tidal cycles. Length of arrwos indicates current velocity in cm/sec. (see current velocity scale).

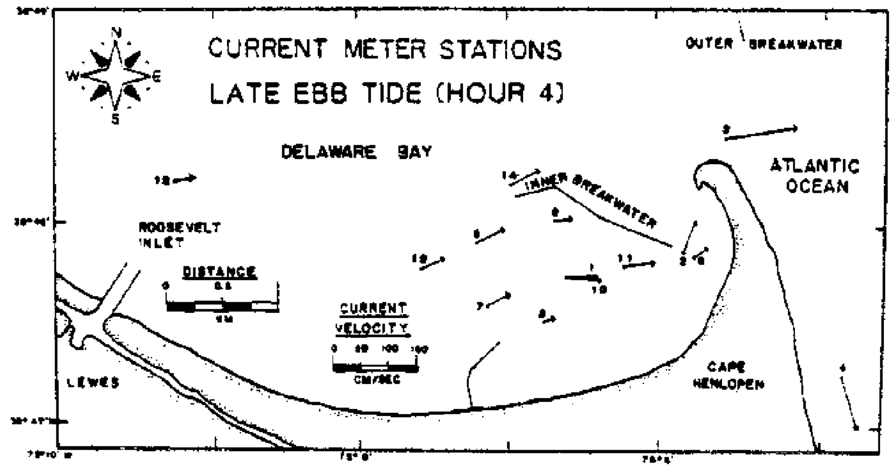


FIGURE I-6. Current vectors at fourteen stations during late ebb tide (Hour 4). Average of three tidal cycles. Length of arrows indicates current velocity in cm/sec (see current velocity scale).

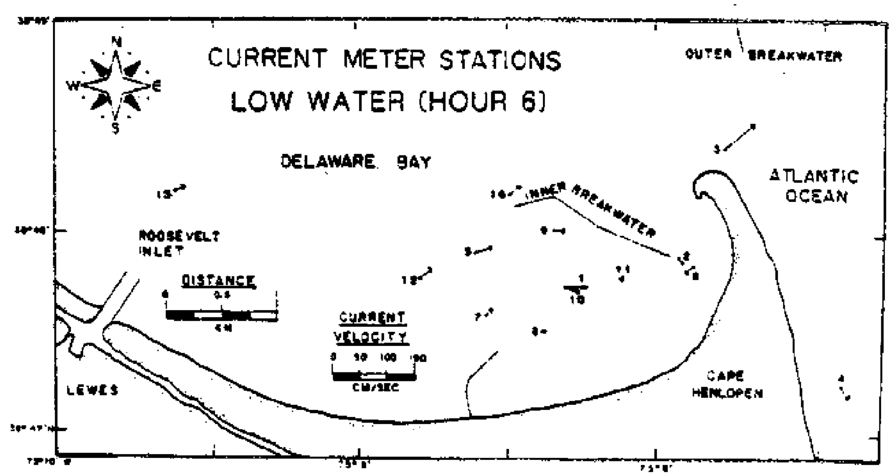


FIGURE I-7. Current vectors at fourteen stations during low water (Hour 6). Average of three tidal cycles. Length of arrows indicates current velocity in cm/sec (see current velocity scale).

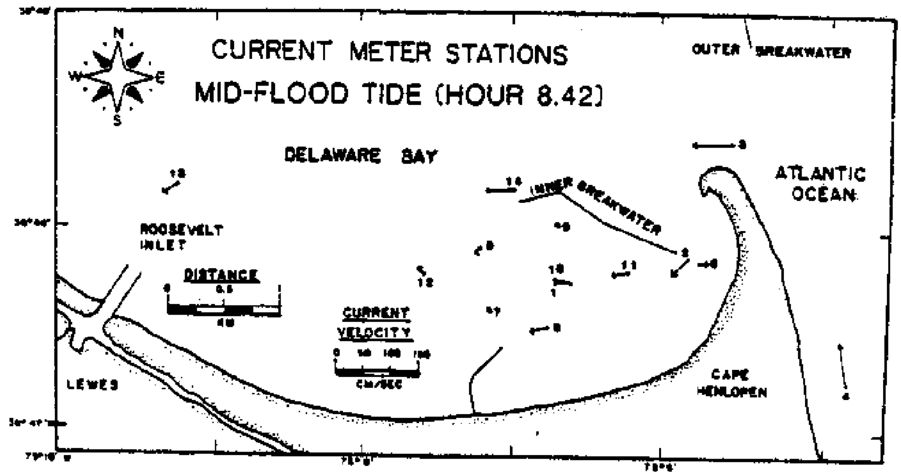


FIGURE I-8. Current vectors at fourteen stations during mid-flood tide (Hour 8.42). Average of three tidal cycles. Length of arrows indicates current velocity in cm/sec (see current velocity scale).

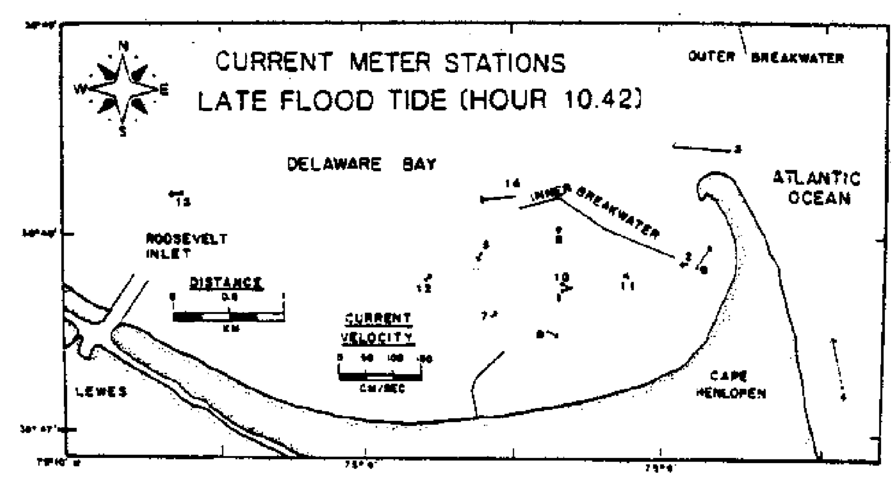


FIGURE I-9. Current vectors at fourteen stations during late flood tide (Hour 10.42). Average of three tidal cycles. Length of arrows indicates current velocity in cm/sec (see current velocity scale).

harbor's funnel shape. Northerly flow of water at Station 4 east of Cape Henlopen shows that currents sometimes move to the north here, even during ebb tide out of Delaware Bay (Station 3). Use Station 13 off of Roosevelt Inlet as representative of regional flow outside of the harbor.

Later in the tidal cycle during mid-ebb tide (referred to as Hour 2), current velocities are everywhere faster averaging about 50 cm/sec throughout the harbor and increasing to 80-90 cm/sec at the narrow eastern end (Figure I-5). The tendency for the water to flow toward the northeast is apparent at the stations in western Breakwater Harbor. Eventually, the water must turn to the east in order to exit the east end. In this and all the remaining "snapshots," current velocities at Station 3 due north of Cape Henlopen are the fastest (110 cm/sec here). Indeed, the currents are so swift there that a large sand wave partially buried the current meter. Station 4 shows the typical southerly direction of ebb flow out of Delaware Bay down the Atlantic coast.

During late ebb tide (referred to as Hour 4--Figure I-6), current velocities have begun to decrease in the harbor (50 cm/sec), although they are still very strong off Cape Henlopen to the north and east (110-120 cm/sec).

At the time of predicted low water (Hour 6--Figure I-7), currents are still ebb-oriented, albeit at a much lower velocity in the harbor (20-30 cm/sec). However, notice that flood-oriented vectors now appear at the eastern end of the harbor at Stations 2, 6, and 11.

Flood velocities are weak, though persistent (10-30 cm/sec) throughout the harbor during mid-flood tide (Hour 8.42--Figure I-8). Velocities outside of the harbor at Stations 3 and 4 are rapid (80 cm/sec). This further quantifies a fact that has been known for many years: flood velocities in the harbor are very low when compared with normal flood velocities in adjacent areas of Delaware Bay. This is due to the simple geometry of Breakwater Harbor with a narrow eastern entrance, but more importantly, due to the harbor's position in the flood-tidal "leeward" of Cape Henlopen (Demarest, 1978). Swift flood-tidal currents rush past the spit tip and bypass Breakwater Harbor. This condition obviously presents an opportunity for sediment deposition during low current velocities. This will be discussed in detail in forthcoming chapters.

Finally, completing the average tidal cycle for this area with late flood tide (Hour 10.42--Figure I-9), velocities are low (10-20 cm/sec) and directed irregularly throughout the harbor. Several small and complex gyres exist in the harbor during this phase. Similar gyres mapped by Klemas and others (1974) included one that brought water into the western entrance of the harbor on flood tide and out the eastern end of the harbor on ebb tide. Maximum sedimentation occurs during this near slack-water condition in the harbor. This occurs despite the fact that swift currents (100 cm/sec) are still flowing into Delaware Bay at Stations 3 and 4.

It should be pointed out that each of the stations was occupied during a <u>different</u> time period as outlined in Table I-2. An attempt was made at each station to choose three average tides of the lunar cycle. Data from spring tides and neap tides were not used.

The net water transport through the harbor is out the east end at an average rate of $2x10^6$ m^3/hour (Behnke, 1980). The average harbor volume is $8.6x10^6$ m^3, so it takes about 4.3 hours for one harbor volume to pass out of the eastern exit; this means that about three volumes are emptied out the east exit each tidal cycle (Behnke, 1980). Even though water and sediment have a tendency to move east through the harbor, some sediment apparently settles out sometime in the tidal cycle. Let us turn now to an examination of the principles affecting sedimentation in current-swept regimes.

Tidal Currents and Sedimentation Tendency

One of the basic principles of sedimentology is the relation between current velocity and the tendency for sediment of various sizes to be deposited, transported, or eroded. Such a graph is displayed as Figure I-10 and can be used to discuss the current velocity data in relation to sedimentation. Erosion of all cohesive and incohesive sediments up to pebble size occurs above 100 cm/sec, except for cohesive clays. However, in the silt and sand sizes typical of Breakwater Harbor sediments (see Chapters VI and VII), velocities of 30-100 cm/sec can erode cohesive and incohesive materials. This means that during nearly the entire ebb tide, erosional conditions exist throughout much of the harbor. During current velocities of flood tide in the harbor (less than 30 cm/sec), transportation and/or sedimentation of sands and silts

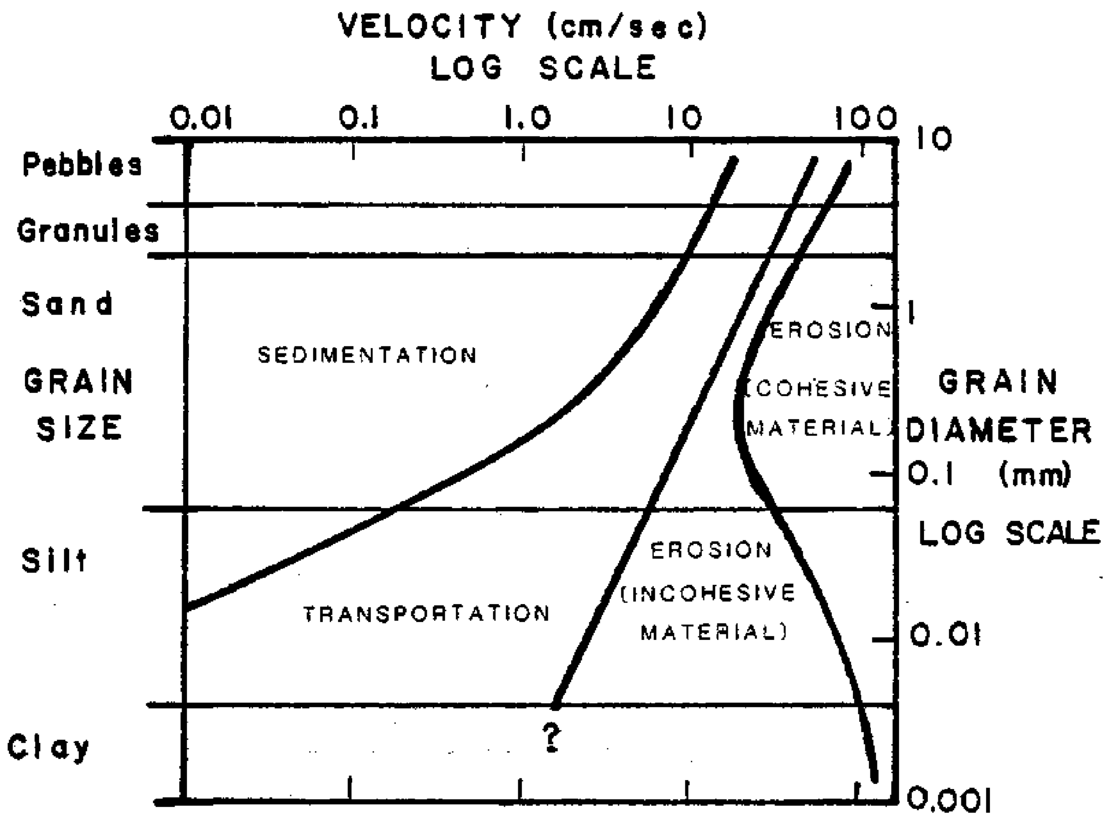


FIGURE I-10. Estimated current velocities for erosion, transportation, and deposition of different-sized particles. A velocity of 100 cm/sec = about 2 knots = about 3.6 km/hr (after Heezen and Hollister, 1964).

occurs. Apparently, the deposition during slack water or flood tide more than makes up for erosion of materials during ebb tide. This is deduced from the fact that historical shoaling has occurred in most of the area. Analyses of suspended sediment and mechanisms of deposition in the harbor area are presented in Chapters II, III, IV, and VII.

Thermal Aspects of Breakwater Harbor Related to Sedimentation

In a thermal analysis of Breakwater Harbor which predicts conditions under which icing might occur, Behnke (1980) collected much information on thermal properties of the water in the harbor. Since colder water becomes more dense and more viscous, it transports more sand in the surf zone, but deposits less in deeper water. Moreover, when ice covers the harbor and its shorelines, as occurred in the winters of 1976-77 and 1977-78, littoral processes are frozen in stop-action; little sediment transport occurs during these times. The winter of 1976-77 was the coldest on record in Delaware based on heating degree days (National Weather Service, Local Climatological Summaries, Wilmington, Delaware), and this severe icing condition was displayed in a very striking way: the Cape May-Lewes Ferry system was closed for 40 days, during which time the water temperature in shallow areas of the harbor dropped below -1°C. For salinities typical of Breakwater Harbor (26-32 $^{o}/oo$), this represents a marginal freezing condition.

Behnke (1980) concluded that solid harbor ice of monthly duration will occur, on the average, every 30 years. This condition would dampen waves in the harbor and therefore would result in sediments less disturbed by wave energy. Extensive shore ice, which would stop littoral transport, will occur about every six years (Behnke, 1980). Thus, although severe icing is rare, it may well be a significant factor in sedimentary history, both in the shore zones and in the deeper areas of the harbor.

In order to evaluate the effect of season (including water temperature) on sedimentation patterns, year-round sampling of suspended and bedload sediment was carried out throughout shore zones and deeper harbor areas (Chapters II, III, and IV).

Consideration of Wave Effects

It has been well documented that waves can cause modifications of both the sea bottom and shorelines (Bascom, 1964; Goldsmith and others, 1974). Qualitatively, the effect of waves on shorelines protected by breakwaters, capes, jetties, groins, and containing dredged channels can be quite complex. To have all of these occurring juxtaposed in an area of 20 square kilometers makes predicting wave effects enormously complex. The feasibility of quantifying wave effects by means of wave-refraction diagrams was evaluated in collaboration with C. Lozano (mathematician, University of Delaware).

All theories of wave refraction and diffraction involve several simplifying assumptions which must be approximately accurate in the natural setting, especially if the generation of wave paths is computer-assisted. Because of the complex and irregular shoreline trends, bottom slopes, and artificial structures, construction of any theoretical wave diffraction and refraction models for this area approaches the impossible, within the context of present wave theory (C. Lozano, personal communication).

One theory which was considered for the study area was the ray theory model. Assumptions which must be met are several, but specific failures of the assumptions in the study area are as follows:

. The bottom must be smooth, but such is not the case in the study area (e.g. Hen and Chickens Shoal, the deep scour hole east of the inner breakwater, various shoals and breakwaters exist);

. The shoreline must be relatively regular, with no focal points or caustics (sharp incisions);

. There can be only minimal wave refraction around emerged structures in the study area. With the three breakwaters and two jetties in the study area, fulfilling this condition is not possible.

The effects of waves on the study area are considered in qualitative and quantitative fashions in Chapters II, III, V, and VI. However, no wave refraction or diffraction mathematical models were constructed for this study.

CHAPTER II

SURF ZONE SEDIMENT MOVEMENTS

Introduction

The importance of measuring surf zone sediment transport in a quantitative fashion has been recognized for many years, but the ability to do so with reliability under all conditions has lagged behind the need. In proceedings of a conference concerning coastal sediment transport with emphasis on the National Sediment Transport Study (N.O.A.A.-Sea Grant), Dean (1978) commented:

> "The quantitative understanding of sediment transport processes has been elusive and today must be considered rudimentary in many respects. Aside from the major problem of quantifying the total transport in terms of wave and current parameters, numerous other problems must be resolved to provide a rational understanding of this process. These include: the transport partition into bed and suspended load for various particles and wave characteristics; the distribution of sediment transport across the nearshore; the effects of rip currents on the onshore-offshore transport; the modifying action of a longshore bar on transport; the mobilizing effect of onshore waves with no longshore component combined with relatively small oblique waves as compared to the effect of the oblique waves acting alone; and many other problems of equal importance. The present lack of understanding of these processes has been due, in part, to the difficulties of conducting accurate measurements in the energetic and abusive surf zone environment. Therefore, development of methodologies and instrumentation for surf zone application is essential to the understanding and quantification of these processes." (p. V)

Although the preceding statement identifies problems worthy of consideration in many new dissertations, it is my opinion that present techniques and equipment are adequate for measuring sediment concentrations in the surf zone, for purposes of this study. Both bedload and suspended load traps are important in assessing surf zone sediment movements, although it has been estimated that up to 90% of the sediment transport occurs in the bedload, that is, within several tens of grain diameters of the bed (Komar, 1978).

Devices for Measuring Bedload Activity

Problems of measuring bedload sediment concentrations have been plaguing researchers for centuries because devices inserted into the bedload flow can destroy or modify the environment that is being sampled. Consequently, several types of devices which remotely or indirectly measure grains have been developed, although all of them have reliability problems. Electro-optical systems, such as that described by Locher and others (1976), use the principle that light transmission drops off with increasing concentration of suspended sediment. However, positioning the probe at just the right elevation above the bed in a repeatable manner is very difficult. Moreover, the probe measures any opaque object (including bubbles), and so has a tendency to overestimate the sediment load. Finally, the system is sensitive to changes in ambient temperature and light levels. For the reasons discussed above, as well as for reasons of prohibitive cost, electro-optical devices were rejected for use in this study.

The other option in bedload sediment traps is that of an open-ended box placed on the bottom. Helley and Smith (1971) developed such a device which could be deployed in rivers, but it is much too cumbersome to hand-carry into the surf zone (it weighs about 70 pounds or 32 kg.). Also, that device collects materials on a flow-through mesh which transmits some particles and greatly interferes with the flow.

Finally, a design for a simple and efficient bedload monitoring device was found in Graf (1971). The design calls for a rectangular box with open ends. A modified version of this device was designed and manufactured for this study and is shown in a sketch (Figure II-1) and in a photograph (Figure II-2). All walls of the device were made of plexiglass to allow visual inspection of sediment moving through the trap. Doors on each end were hinged and spring-loaded with an elastic so that they could close on remote triggering command. The doors were held open in the horizontal position until the triggering shaft was lifted. Although this bedload monitoring device has not been calibrated in a laboratory flume tank, its reliability and the repeatability of measurements were evaluated in the field (results discussed later in this chapter).

The bedload concentrations reported in this study are valid only in a relative sense between samples. The absolute value of the bedload concentrations measured is subject to debate. For example, if I had chosen a trap height one-tenth that of the device I used, the resulting concentrations may have increased to be more representative of bedload (I take bedload transport to mean that transport which occurs within a

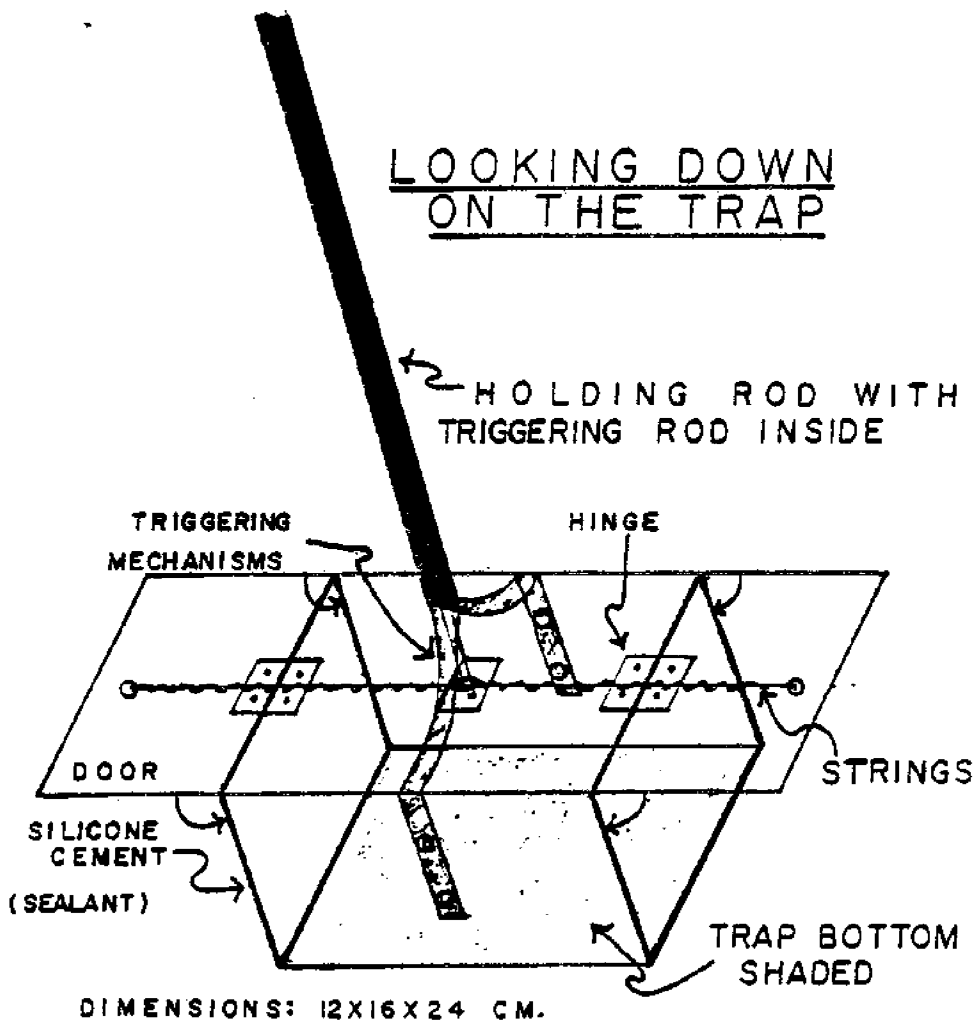


FIGURE II-1. General engineering sketch of bedload sediment trap used in this study.

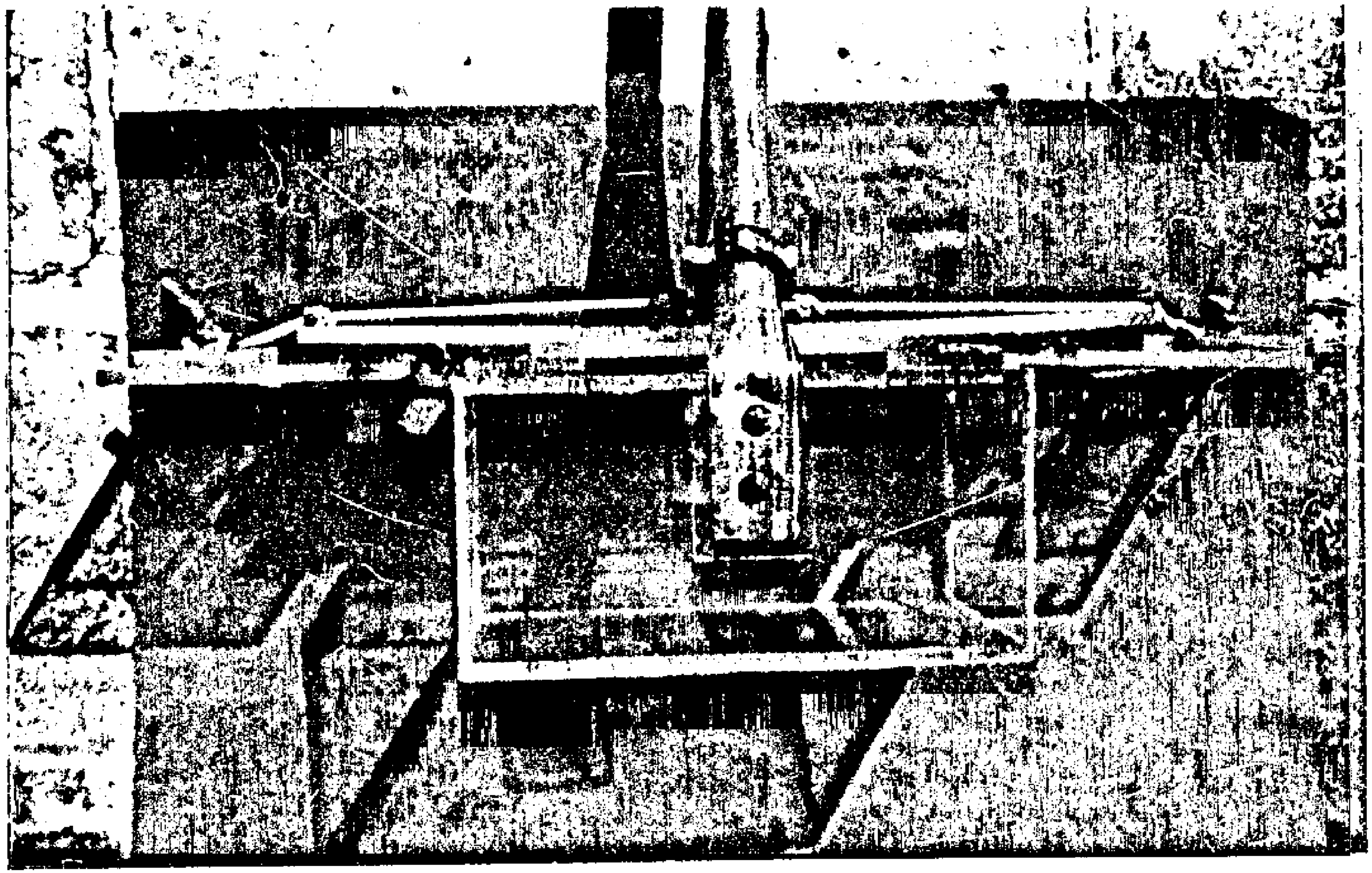


FIGURE II-2. Photograph of bedload sediment trap used in this study.

distance of several grain diameters above the bed). On the other hand, a smaller trap orfice such as this would tend to interrupt flow and create unwanted turbulence, thereby destroying the environment being measured. In conclusion, I chose my final bedload trap design so that it would impart a minimum of disturbance to the bed and also so that trap repeatability would be maximized.

Suspended Sediment Traps

Although suspended sediment is easier to measure than bedload, there was still a difficult choice to be made in which device to use. Problems with electro-optical systems discussed above also apply to suspended sediment traps, so they were rejected. Although other devices exist (e.g., Leatherman, 1979), the simultaneous water sampler described and extensively tested by Kana (1976, 1977) appeared to be the most transportable and reliable. Kana's device was used in this study and its repeatability tested in the field.

Field Collection and Laboratory Analyses

After completion of a series of pilot studies with the bedload and suspended load traps during February of 1977, a series of 16 stations which could be reoccupied was set up. Compass bearings and sextant angles were taken so each station could be relocated. The station locations are shown in Figure II-3 (Zones I, II, and III refer to energy distribution and will be discussed later). Samples were taken at each station along a line perpendicular to the shoreline. As the tide level changed, the sampling site was moved along the line until a water depth

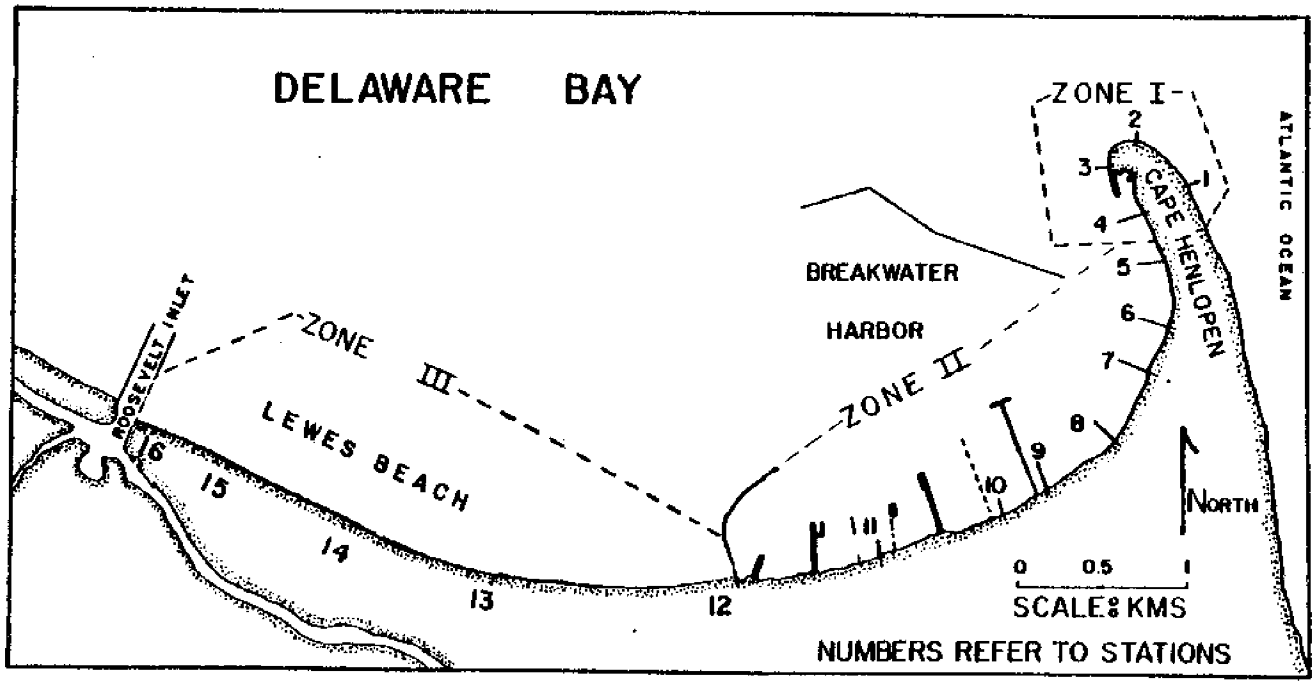


FIGURE II-3. Location map for surf zone sediment trap stations. The zones refer to different incident energy levels discussed in the text.

of one meter was reached. For this phase of the study, the limits were defined as from the eastern shore of Cape Henlopen to Roosevelt Inlet.

During 13 field sampling days between February 1977 and July 1978, suspended and bedload sediment concentrations were measured using the sediment trap devices. Dates, seasons, tidal conditions, and stations occupied are listed in Table II-1.

The purpose of these studies was to define and quantify the processes driving sediment transport. One question to be answered was: Which driving force(s) was(were) most important in controlling bedload and suspended load concentrations? These data, in conjunction with past sedimentation trends, could then be used to predict tendencies for the future (Chapters X and XI).

Appendix A identifies data which were collected at each sampling station for both bedload and suspended load traps. In addition to tidal stage data, wind velocity, wave heights and directions, water temperature, air temperature, and longshore current velocity were measured. Wind velocity was determined using a hand-held anemometer. Wave heights were measured using a wave staff. Longshore current velocity was measured by timing a neutrally buoyant object over a distance of 10 meters. Regardless of the tidal height, all trap samples were taken by wading out into a water depth of 100 cm. The bedload trap was placed on the bottom in the open position so that the long axis was parallel to the shore. At the passage of an average wave crest, the device was triggered to trap materials suspended by the wave. In a similar manner, the suspended

TABLE II-1. SURF ZONE BEDLOAD AND SUSPENDED LOAD SAMPLING CONDITIONS

DATE	SEASON	TIDAL CONDITION	STATIONS OCCUPIED	NOTES
5/14/77	SPRING	LOW SLACK	1-9	
6/7/77	SUMMER	HIGH SLACK	8-15	DATA LOST
10/14/77	FALL	STORM HIGH TIDE	1-5	STORM ON
11/13/77	FALL	EBBING-LOW	2-16 (EVEN)	
11/18/77	FALL	EBBING	9-15 (ODD)	
12/11/77	WINTER	LATE EBB	1-11	
1/14/78	WINTER	EBBING	2-6 (ODD)	ICE EFFECT
1/29/78	WINTER	EARLY EBB	1-15 (ODD)	
2/26/78	WINTER	LOW SLACK	2,6,10,14	
3/18/78	WINTER	FLOODING	1-15 (ODD)	
4/22/78	SPRING	EBBING	2,8,12,16	
5/21/78	SPRING	EBBING	1-15 (ODD)	
7/6/78A	SUMMER	LOW SLACK	2-16 (EVEN)	DUPLICATE
7/6/78B	SUMMER	LOW SLACK	2-16 (EVEN)	SAMPLES

sediment trap was triggered at the passage of an average wave in 100 cm of water. One sediment trap jar was set 20 cm above the bed and the second was set at 50 cm above the bed. In pilot studies using a third jar at 70 cm above the bed, it was discovered that the higher sample contained essentially the same concentration of sediment as the 50 cm sample.

Photographs of field collection techniques for the bedload sampler and the suspended load sampler are shown in Figures II-4 and II-5, respectively. In both cases, the full container was emptied into a plastic jug via a large plastic funnel. In most seasons, a wet suit was required in order to work in the surf zone all day. The wet suit also provided buoyancy in case of mishap. In the event that traps captured entrained air, a calibration scale on each jar allowed volume calculations.

Laboratory procedures consisted of filtering sediment through Whatman #114, wet-strengthened filter paper (5.5 cm in diameter) using a millipore-filter apparatus and a high-vacuum pump. The filters and sediment were weighed to the nearest 0.0001 gm using a Mettler Analytic Balance (Model H-51). The volume of the bedload trap was 3.6 liters (0.95 gal) and the volume of each suspended load trap was 1.9 liters (0.5 gal). The concentrations of bedload and suspended load materials are reported in gm/liter in all of the remaining figures of this chapter.

When the full jugs were brought in from the field, all sand and dirt was washed off the outside of the containers. Then, the jars were

FIGURE II-4. Photograph of bedload trap during use in the field.

FIGURE II-5. Photograph of suspended load trap during use in the field.

allowed to set for about 48 hours to allow settlement of sands, silts, and clays. The clear water was then carefully drawn off the top to reduce the volume of water that had to be filtered.

<u>Bedload and Suspended Sediment Concentrations of the Surf Zone</u>

Various environmental conditions were sampled in order to determine which parameters dominate littoral transport (Figures II-6 to II-18). Over a period of more than one year, occasional samplings of bedload and suspended load were undertaken in order to determine which factors dominate littoral transport (Figures II-6 to II-18). In general, the highest waves, most rapid longshore currents, highest bedload concentrations, and highest suspended load concentrations were recorded at Stations 1-4 on the Cape Henlopen spit tip. This area of highest energy is referred to as Zone I on Figure II-3. The lowest waves, slowest longshore currents, lowest bedload concentrations, and lowest suspended load concentrations were recorded at Stations 5-11 behind the inner breakwater. This area of lowest energy, protected by the inner breakwater, is referred to as Zone II on Figure II-3. Finally, Stations 12-16 generally recorded intermediate values of wave heights, longshore currents, bedload concentrations, and suspended load concentrations. This Lewes Beach area of intermediate energy is referred to as Zone III on Figure II-3. Depending on wind direction and resultant wave approach, Station 5 could become part of Zone I on Cape Henlopen. For example, during times of northwesterly winds (Figures II-6, II-12, and II-14), Station 5 appeared to be more similar to energy parameters of Zone I than those of Zone II.

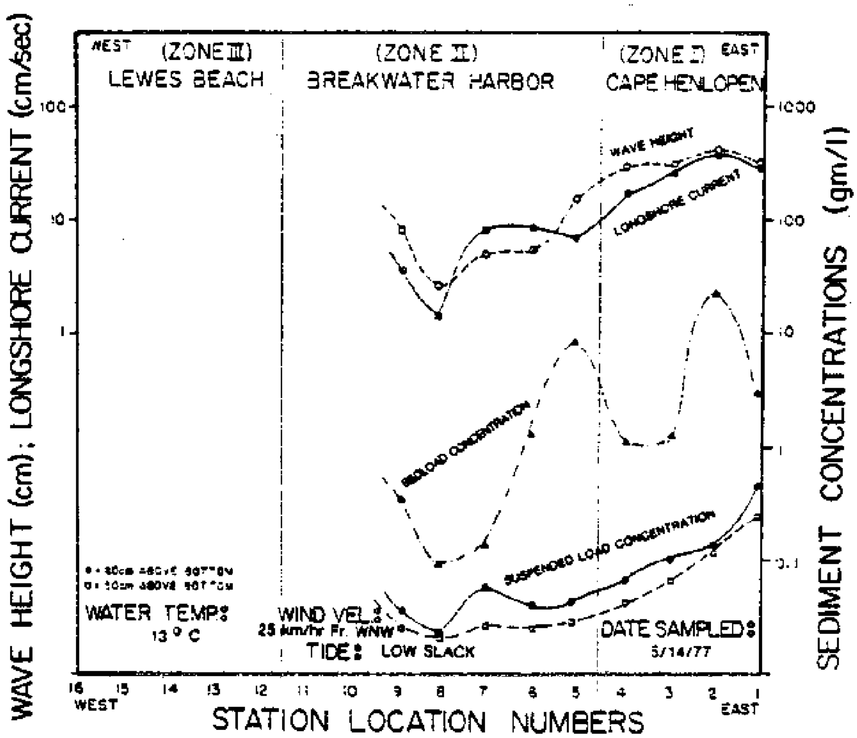


FIGURE II-6. Surf zone energy conditions and sediment concentrations on 5/14/77.

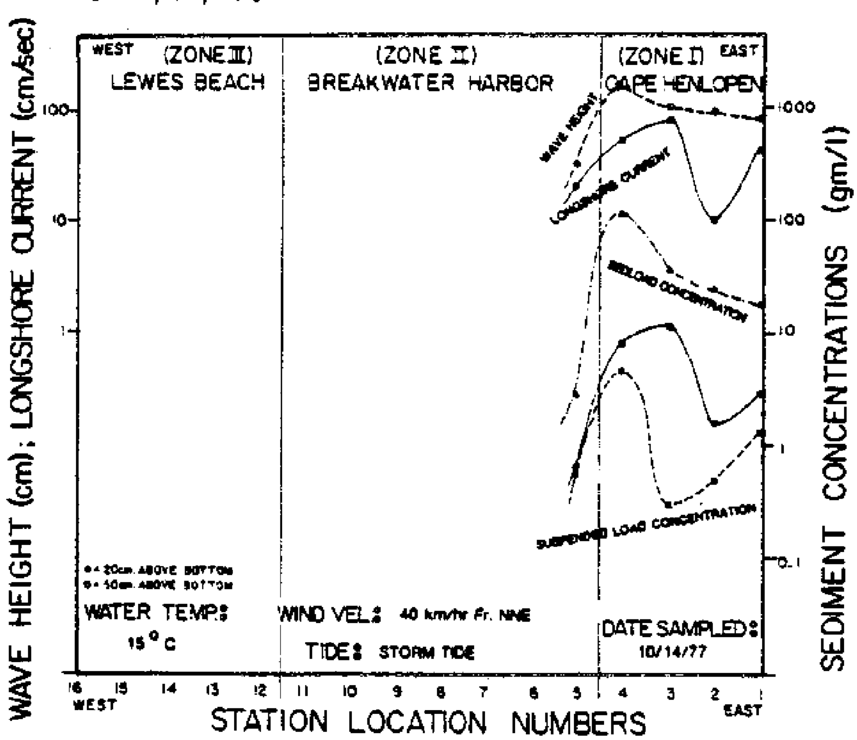


FIGURE II-7. Surf zone energy conditions and sediment concentrations on 10/14/77.

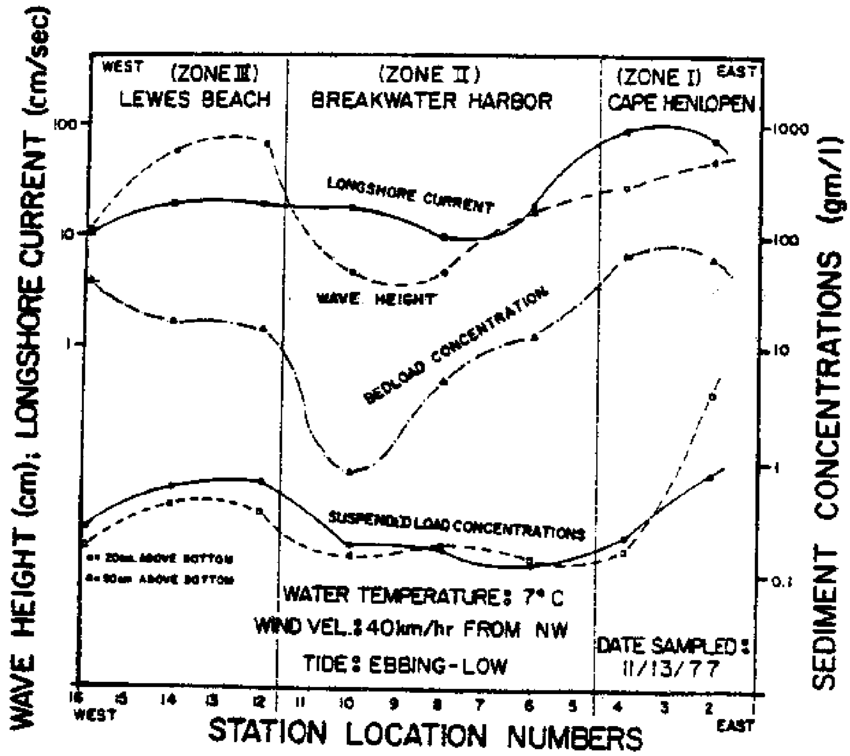


FIGURE II-8. Surf zone energy conditions and sediment concentrations on 11/14/77.

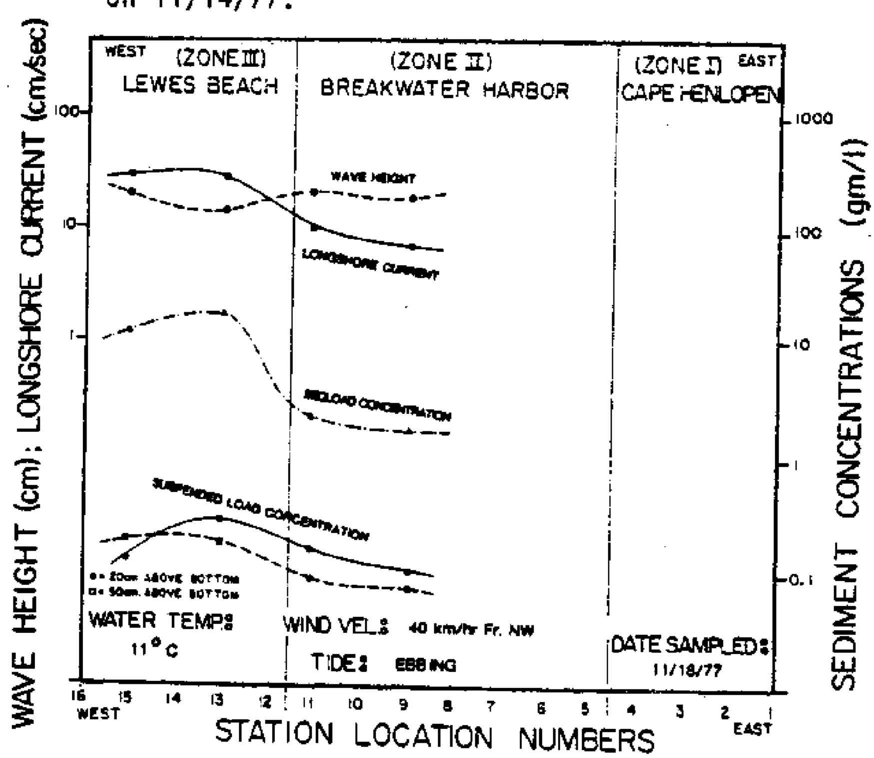


FIGURE II-9. Surf zone energy conditions and sediment concentrations on 11/18/77.

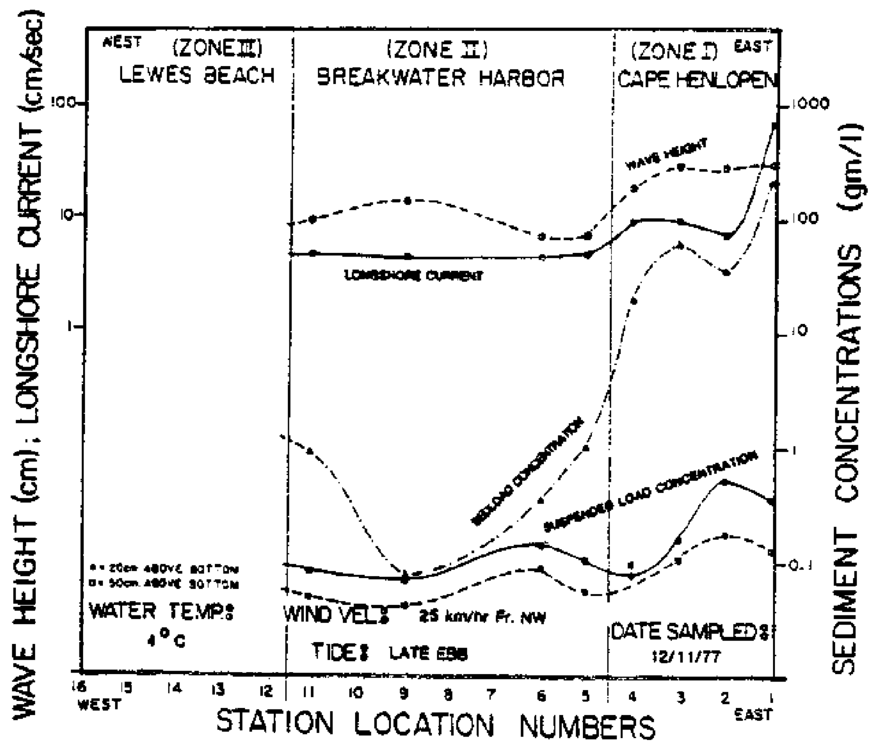


FIGURE II-10. Surf zone energy conditions and sediment concentrations on 12/11/77.

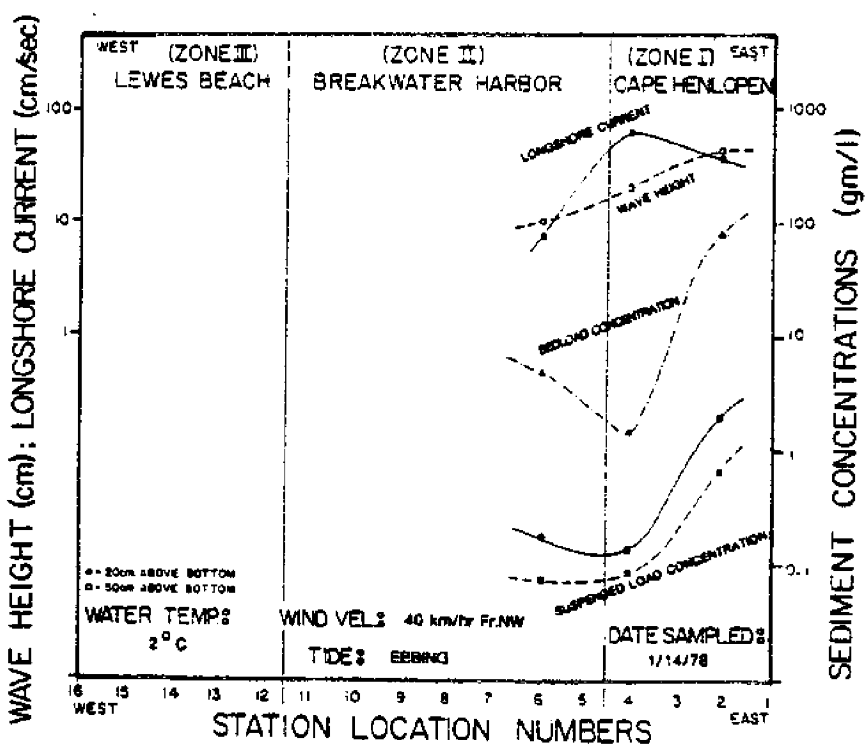


FIGURE II-11. Surf zone energy conditions and sediment concentrations on 1/14/78.

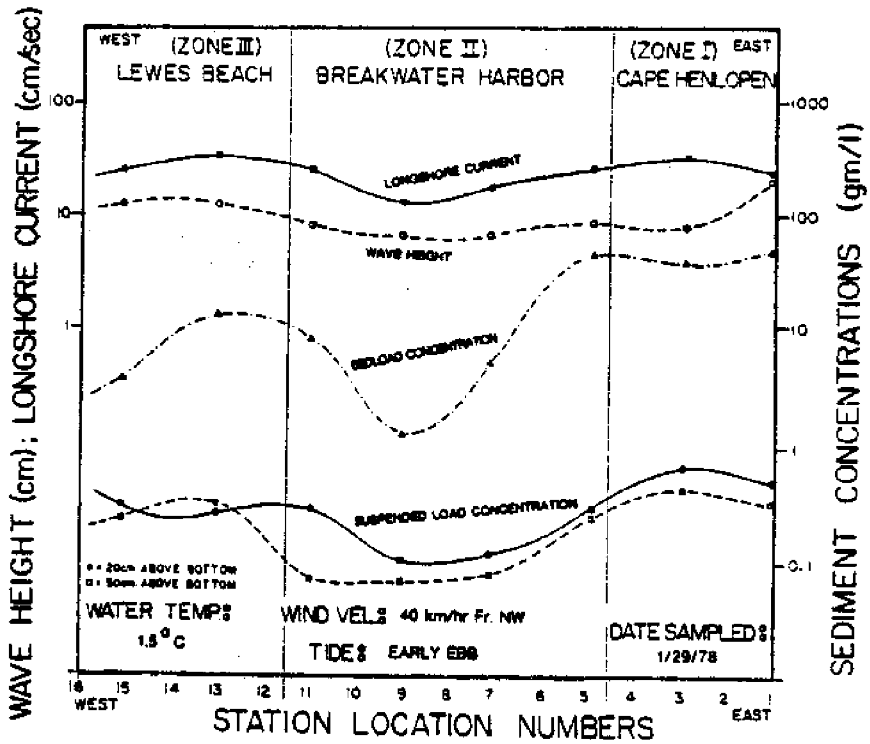


FIGURE II-12. Surf zone energy conditions and sediment concentrations on 1/29/78.

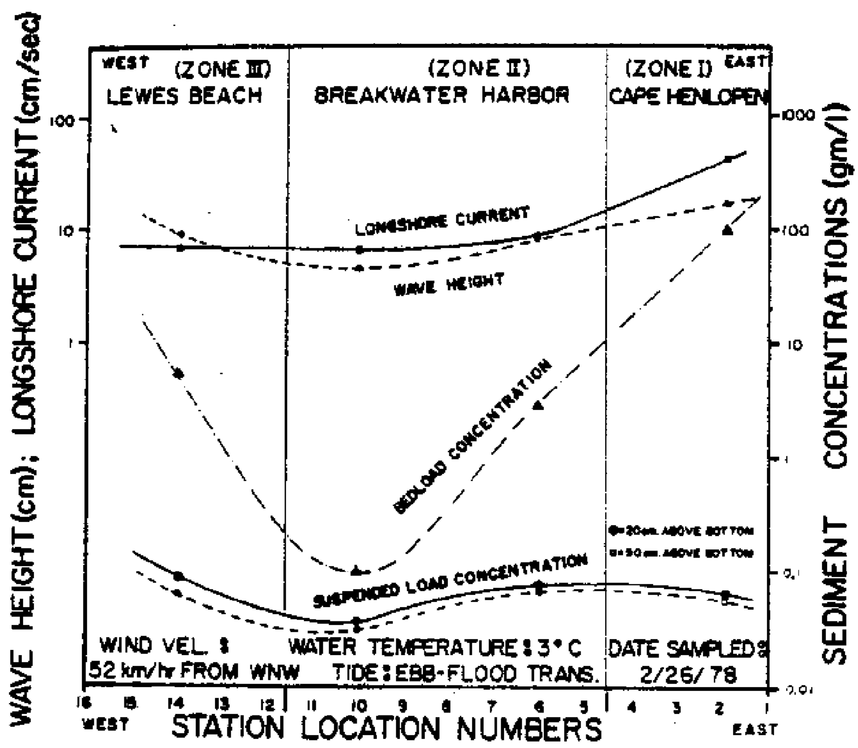


FIGURE II-13. Surf zone energy conditions and sediment concentrations on 2/26/78.

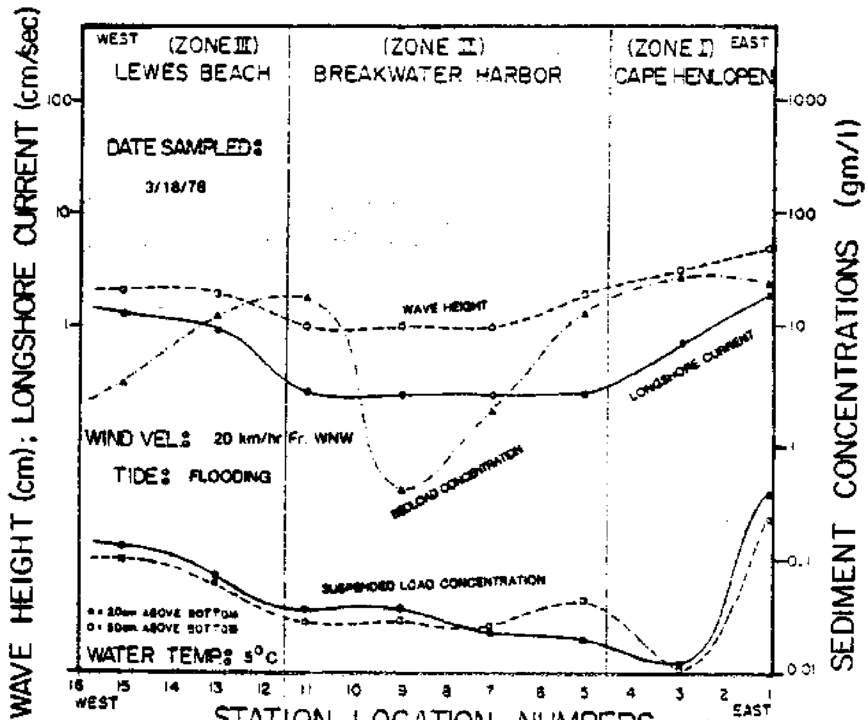


FIGURE II-14. Surf zone energy conditions and sediment concentrations on 3/18/78.

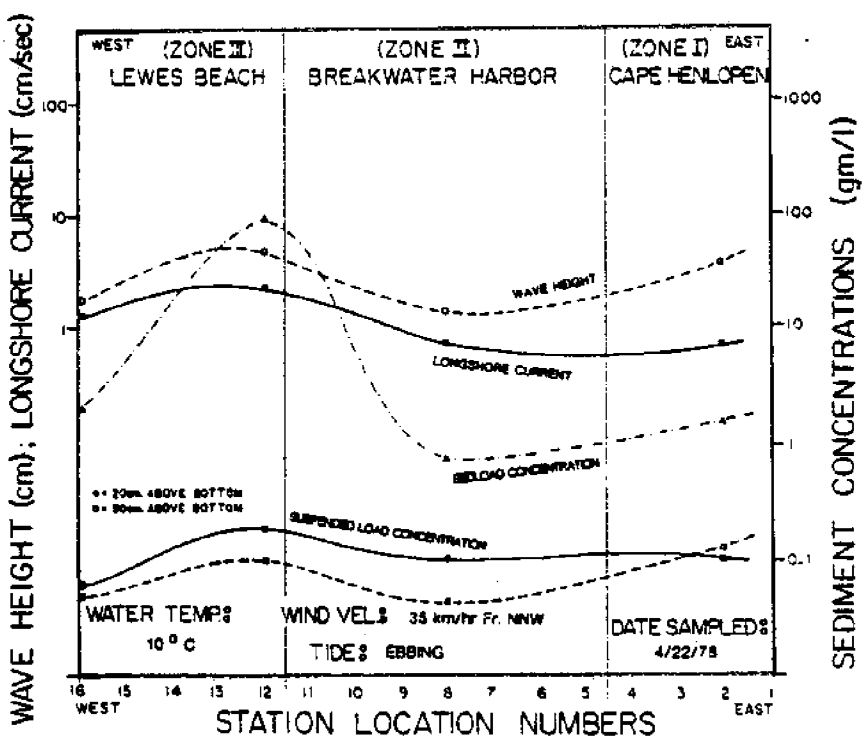


FIGURE II-15. Surf zone energy conditions and sediment concentrations on 4/22/78.

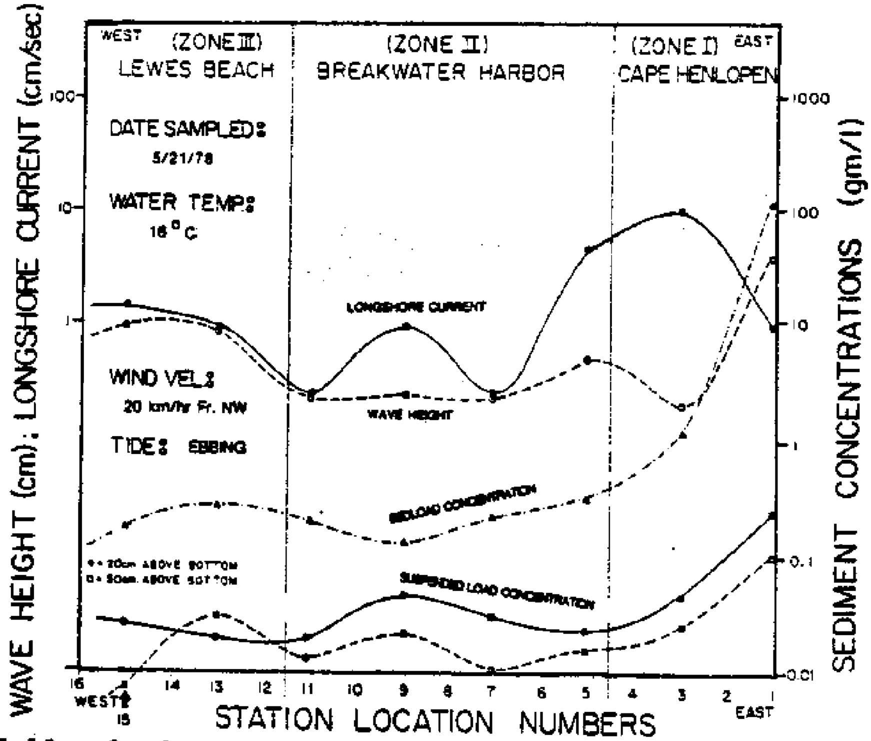


FIGURE II-16. Surf zone energy conditions and sediment concentrations on 5/21/78.

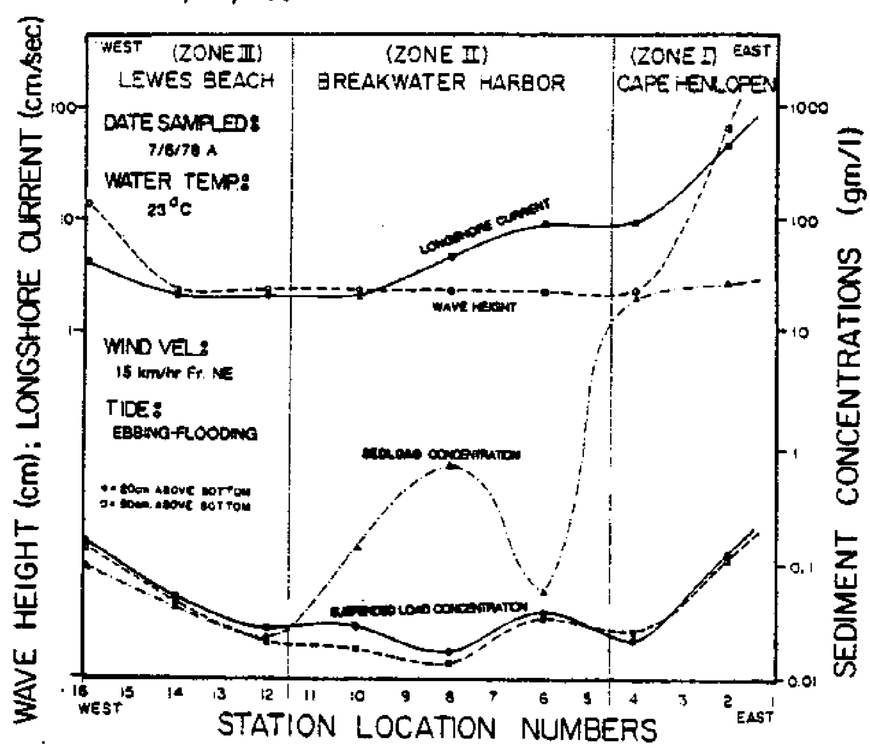


FIGURE II-17. Surf zone energy conditions and sediment concentrations on 7/6/78(A).

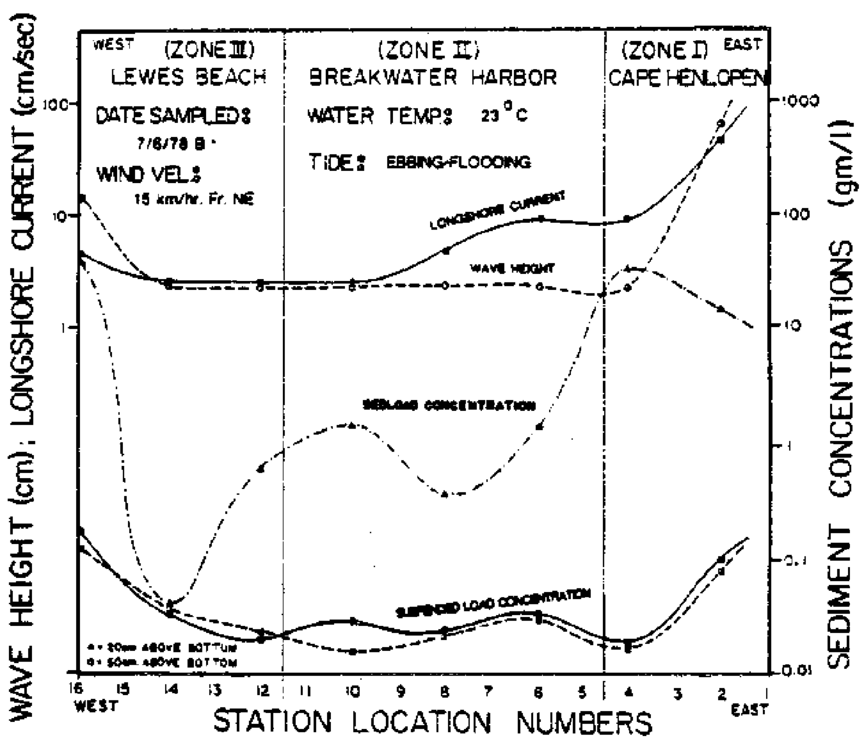


FIGURE II-18. Surf zone energy conditions and sediment concentrations on 7/6/78(B).

Except for minor anomalies displayed in Figures II-8, II-9, II-12, II-14, II-16, II-17, and II-18, the suspended load concentrations at 20 cm above the bed were higher than those at 50 cm above the bed by 10-20%. In most cases, bedload concentrations were an order of magnitude higher in concentration than associated suspended load values at the same station. This appears to agree favorably with earlier results stating that bedload accounts for some 90% of sediment transport in the shore zone (Komar, 1978). Although it is conceivable that bedload concentrations could be zero while suspended load could be large, such a condition was not found in this area. It should also be noted that the data on sediment concentrations presented in this study are not sufficient to calculate total littoral transport across the surf zone; I only measured transport at a water depth of one meter. Substantial drift is moved along the shore in water depths less than one meter and, to a lesser extent, in water depths of more than one meter.

During the northeast storm of October 14, 1977, a sampling program was undertaken to evaluate the effect of storm conditions on surf zone sediment transport (Figure II-7). Suspended load and bedload sediment concentrations during storms were about an order of magnitude higher than non-storm concentrations. During storms, sediment can be moved up to ten times farther as a result of longshore currents and wave heights about five times larger than normal conditions.

Even though colder water moves more sediment, the results of cold-water sampling (below 5°C) did not indicate that water temperature was a major factor in determining bedload and suspended load sediment concentrations. Instead, wave height and longshore current velocity (the latter driven by waves and tidal currents) dominate the response of bedload and suspended load sediment concentrations. In an indirect manner, wind direction and speed have a major effect on concentrations of suspended surf zone sediment: winds are the forces that drive the waves and most of the longshore current.

In order to test the repeatability of the bedload and suspended load traps, duplicate samplings were carried out on July 6, 1978 (Figures II-17 and II-18). Although the suspended load trap shows excellent agreement, the bedload trap shows only general agreement, with some anomalies (e.g., Station 16).

In conclusion, the results of the surf zone sediment movement studies show that the bedload component dominates sediment movement in the study area by about 9:1 over suspended load sediment. Moreover, sediments from Cape Henlopen and Lewes Beach are converging into the area behind the inner breakwater. This trend is consistent for many offshore breakwaters worldwide. Waves and associated longshore currents move sediment from areas of higher energy (Zones I and III in Figure II-3) to areas of lower energy (Zone II in Figure II-3). A well-known example of this is the Channel Islands Breakwater in California, U.S.A. (Bruno and others, 1979).

Cape Henlopen Beach Grain Size Trends

A general review of Delaware Atlantic coast grain-size trends is contained in Moody (1964). The sands along the Delaware Atlantic coast have an average median diameter of about 1.3 Ø (Ø = $-\log_2$ of grain diameter in millimeters) above mean high tide and 0.45 Ø at mid-tide zone (U.S. Army Corps of Engineers, 1956). Surface samples may contain up to 28% granules; pebble layers 8 to 15 cm thick occur at depths in the beach sediments of 0.5 to 1.5 m.

In the 2-3 Ø size class, about 2% of grains are heavy minerals (Schneider, 1962; Maurmeyer, 1974). Opaque minerals compose about 50% of the heavy mineral fraction in the 2 Ø to 3 Ø size class and give the sand a peppered appearance. Variable percentages of zircon, hornblende, garnet, staurolite, epidote, and sillimanite comprise the most frequently occurring non-opaque heavy minerals (Schneider, 1962). Schneider's results were confirmed for Cape Henlopen by results of an unpublished report (Hoyt, 1977).

The median diameter of beach sands collected at mid-tide zone (approximately 0.6 m above mean low water) decreases southward from Cape Henlopen (U.S. Army Corps of Engineers, 1956). The grain size of samples collected on the beach above the high-tide line show a similar trend. Moody (1964) interprets this trend as due to a decrease in "longshore tidal currents south from the entrance to Delaware Bay" (p. 71). This statement needs elaboration, but probably refers to the notion that flood- and ebb-tidal currents scour fine sediments from the spit area, leaving a coarse lag deposit there.

During two samplings of beach sediments on Cape Henlopen (2/5/77--Figure II-19 and 10/15/77--Figure II-20), grain size samples were

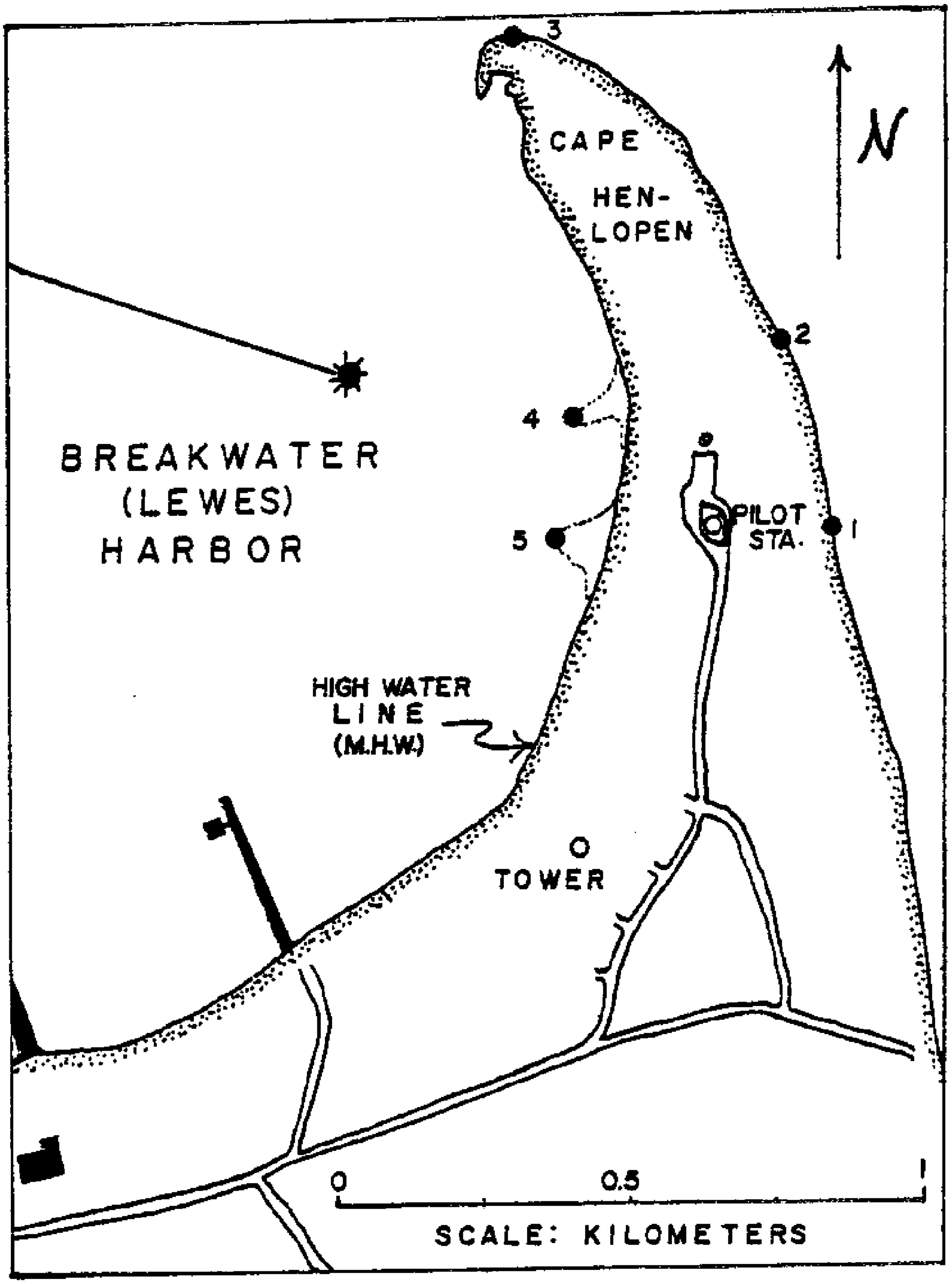


FIGURE II-19. Cape Henlopen beach and bedload trap sample locations used for grain-size comparisons.

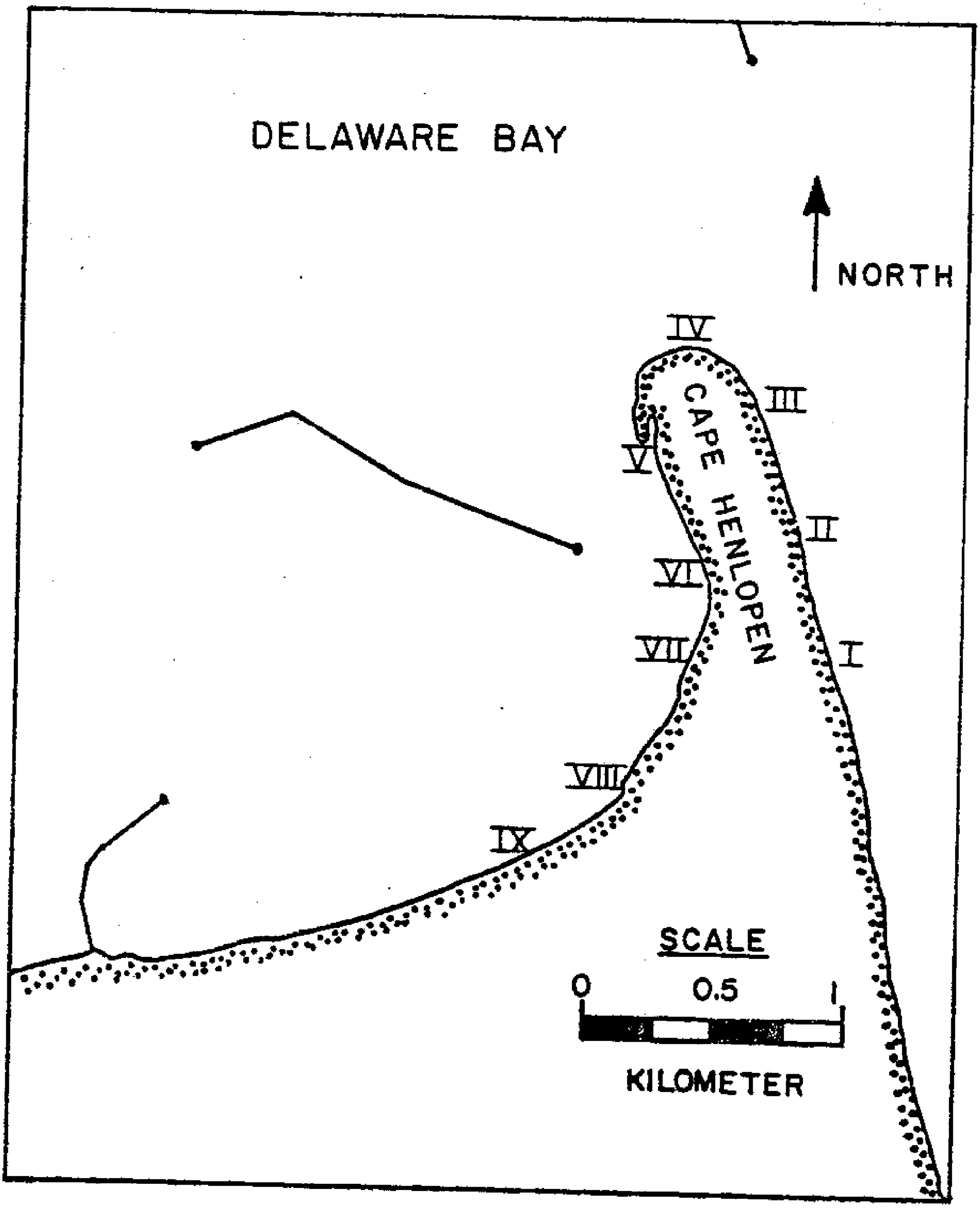


FIGURE II-20. Post-storm beach sample locations on Cape Henlopen and associated tidal flats used for grain-size comparisons.

collected and were found to display trends generally consistent with results of earlier studies (Halsey, 1971; Maurmeyer, 1974; and Demarest, 1978). Samples for the present study were analyzed by a sieve-shaking technique outlined in Appendix J. Stations 1-5, displayed on Figure II-19, each consisted of one sample taken at the high-tide line and one taken at a depth of 100 cm of water. In every case, the offshore sample is finer (Appendix B), indicating a lower-energy environment offshore. The grain size becomes coarser toward the spit tip in a manner similar to that found by the U.S. Army Corps of Engineers (1956). The grain size becomes finer on the west side of Cape Henlopen toward Breakwater Harbor. For comparison purposes, grain sizes at Roosevelt Inlet and at South Bowers Beach, Delaware Bay, were analyzed with the bedload trap during this bedload pilot study. At the much lower-energy locations found up Delaware Bay, the bedload grain sizes were appreciably smaller (fine sand instead of medium sand--see Appendix B).

The day after the October 14, 1977, storm, another set of sediment samples from the Cape Henlopen beaches and tidal flats was collected (Figure II-20). The nine samples collected at about the mid-tide line were coarser than samples taken earlier (Appendix B). Also notable was a fining of samples from the spit tip (Station V in Figure II-20) south to the center of the Breakwater Harbor shoreline (Station IX in Figure II-20). This fining southward on the tidal flats of western Cape Henlopen is a good indication that less energy is available to move sediment as one moves southward. This finding agrees with trends observed by Halsey (1971) and Demarest (1978). The sand samples collected for this study were also analyzed by the sieve-shaking technique outlined in Appendix J.

In order to evaluate the grain-size character of the beaches and offshore zones at each of the 16 surf zone sample locations (Figure II-3), four samples were taken along the profile. The first sample was taken at the high-tide line with a hand trowel and the second was taken at a depth of 100 cm during high tide with a clear plexiglass tube 6 cm in diameter to a depth of 10 cm. The third sample was taken at the low-tide line and the fourth was taken at 100 cm depth during low tide (Appendix C). Although a general offshore trend of fining occurs below the low-tide shoreline, the low-tide shoreline often shows a coarser character than the high-tide shoreline. This is due to the fact that large waves break at the toe of the beach near the low-tide line and winnow fines away. It can be seen that very coarse sands and gravels are accumulating in the areas of Stations 12 and 13 adjacent to the Ferry Breakwater. It can also be seen that the sample taken 100 cm below low tide at Station 16 is very fine sand. This is because it is associated with an organic-rich marsh outcrop in the eroding surf zone. Erosion and accretion trends in the study area will be discussed in detail in the next chapter.

CHAPTER III

BEACH AND NEARSHORE PROCESSES--ACCRETION AND EROSION TRENDS

Introduction

Beach and nearshore processes from Cape Henlopen to Roosevelt Inlet were studied by means of a variety of techniques. These included field observations, water- and sand-dye experiments, time-lapse photography, and extensive beach profile measurements over a three-year period. Surf zone energy conditions were described in the previous chapter.

Previous Studies

Previous work on beach processes in the area has been undertaken in many studies (U.S. Army Corps of Engineers, 1956; Halsey, 1971; Kraft and others, 1976; Kraft and others, 1978; Demarest, 1978; Maurmeyer, 1974, 1978; DuBois, 1978; and Hoyt, 1981). All of these studies reported that a net littoral transport flowing toward the north has supplied Cape Henlopen with a net sand accretion yearly.

Halsey (1971), Kraft and others (1976), and Demarest (1978) all agree that the sand tidal flats on the west side of Cape Henlopen have been created by littoral transport of sands brought around the spit tip. The mobility of the "sand ridges" (Demarest, 1978) or "swash bars" (Halsey, 1971) was measured by Halsey with 35 permanent metal stakes, many of which are still there. She found the summer movement of these "swash bars" to be minimal, but their movement during the winter to range from 53 m in the north to 23 m or less due south of the eastern end of the inner breakwater. Strong northwesterly winds during winter months (Maurmeyer, 1978) create the wave regime capable of moving sand. Although Halsey noted no significant effect due to the action of tidal currents, she did find that spring high-tide levels allowed waves to move the sand in the bars as much as 2.3 m perpendicular to sand bar crest movement in one tidal cycle. Throughout one winter season, waves built the elevation of the tidal flat up an average of 15 cm over the area represented by her 35 stakes deployed in four, widely spaced grid systems. Halsey explained the difference in shape of the bars by their position relative to the eastern end of the inner breakwater. Bars on the northern part of the tidal flat experienced full wave energy coming around the spit tip. South of the breakwater, the bars experienced diminished wave energy because of diffraction around the breakwater and refraction on the bottom. Consequently, these bars are lower in profile and finer in grain size than those farther north.

Although Halsey (1971) did not speculate on the reasons for the differences in orientation of these tidal flat features, Demarest (1978) did so. He pointed out that the orientation of these ridges changes from coast-parallel in the north to coast-perpendicular in the south (Demarest, 1978, his Figure 5). The coast-parallel bars in the north are built into the area by strong littoral transport. During storms, bars can be built farther south than they would be during quiescent periods. After the passage of a storm, the sediments in the coast-parallel bars are reworked landward by smaller waves which are allowed to propagate south of the eastern end of the inner breakwater. This reworking, as proposed by Demarest (1978), acts to dissect the bars and move them gradually shoreward to form coast-perpendicular bars. According to the classification scheme of Greenwood and Davidson-Arnott (1979), the bars on west Cape Henlopen would be bar-type sand waves in the northern part of the spit (first described by Sonu, 1968) and nearshore crescentic bars in the southern part of the spit (originally described by Evans, 1940, and later by Niederoda and Tanner, 1970).

Erosion and accretion trends along the Breakwater Harbor shoreline have been observed by Kraft and others (1976). They noticed that littoral transport was entering Breakwater Harbor very slowly from the east due to a lack of wave energy behind the breakwater. In addition, the construction of the Ferry Breakwater in 1964 slowed down sand from entering the harbor along the shoreline from the west. Consequently, the shorelines of the harbor are "sand-starved" and therefore experience erosion.

Farther west along Lewes Beach, the U.S. Army Corps of Engineers (1956) has shown that erosion has occurred downdrift (east) of Roosevelt Inlet, since the construction of the inlet in 1938. About one kilometer east of the inlet, a null zone exists which displays no accretion or erosion (U.S. Army Corps of Engineers, 1956). From the null zone east to the Ferry Breakwater, a zone of accretion exists because the littoral drift has built out the shoreline there. A detailed figure displaying these trends is presented in Hoyt (1981). Also in that publication, a tabulation of ten beach-nourishment projects east of Roosevelt Inlet is presented. This type of beach-replenishment project takes sand from the west side and inside of Roosevelt Inlet and pumps it onto the beach east of the inlet to prevent erosion damage to shoreline structures. Also, the Federal and State Governments have emplaced a total of nine groins along Lewes Beach since 1940, two of which have been visible along western Lewes Beach during short intervals of time in the last five years (U.S. Army Corps of Engineers, 1968).

Beach Profile Results and Related Studies: 1976-1979

Eight beach profile stations were set up and reoccupied at several intervals over a one-and-a-half to three-year period. The locations of these stations are shown in Figure III-1. All beach profiles, except those taken along the axis of the Army Pier (AP in Figure III-1) were performed using a method modified after Emery (1961). This method uses a tangent to the earth's surface (the horizon on the water) as a level, and when it is employed carefully, it can be quite accurate (Emery, 1961). Important observations at or between the locations of the eight stations are also recorded in the following sections. Before making sweeping conclusions based on beach profiles, one must evaluate cautiously the overall cyclicity of beach processes. For example, a decade-long period of accretion may be followed by severe erosion. Moreover, it should be pointed out that the actual amount of sand moved past the profile sites during the time period studied was probably much greater than my numbers would suggest. This

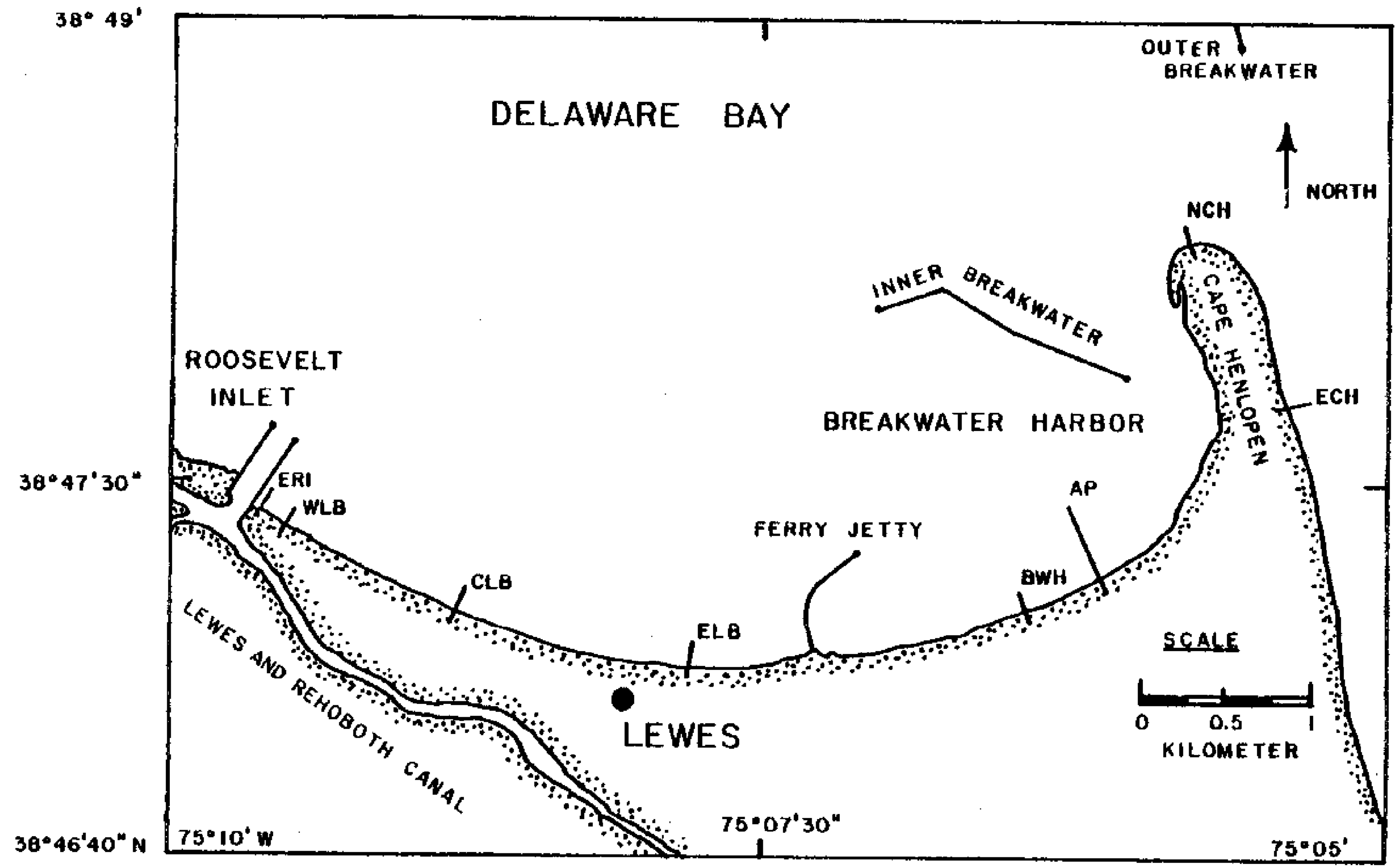


FIGURE III-1. Locations of beach profile transects in the study area. The abbreviations refer to the following: ECH-east Cape Henlopen; NCH-north Cape Henlopen; AP-Army Pier; BWH-Breakwater Harbor; ELB-eastern Lewes Beach; CLB-central Lewes Beach; WLB-western Lewes Beach; and ERI-east of Roosevelt Inlet.

is due to the fact that accretion and erosion can occur between the times of profiles. In addition to this, it should be made clear that I have only measured emergent transport (that above mean low water); much of the littoral transport occurs below the mean low water line in the form of submerged transport.

East Cape Henlopen (ECH). On the east side of Cape Henlopen, 11 profiles taken from August 1976 to September 1979 indicate that over 40 m of seaward (eastward) progradation has occurred (Figure III-2 and III-2 continued). This amounts to 126 m^3 of sand added per meter of linear beachfront, which is a very significant volume for any area on the east coast of North America (Shepard and Wanless, 1971). Thus, short-term records measured in the last three years show that east Cape Henlopen is growing seaward at rates of about 13 m/yr; this agrees with the trend shown by vertical aerial photographs taken during the last two decades (Chapter X), which show accretion north of the profile station and erosion south of there. This trend had not been reported earlier and has significant implications for future growth of the cape as discussed in Chapter X.

Between the times of the last profile and the first, several small storms first removed sand and then littoral drift and waves returned sand. A comparison of parts "C" and "D" of Figure III-2 shows a clear pattern of accretion and erosion in the earlier profile which was almost exactly reversed in the next month's profile. Also, during the winter of 1977-78, the elevation of the "beach" was built up artificially by snow and ice (Figure III-2-E). With the coming of

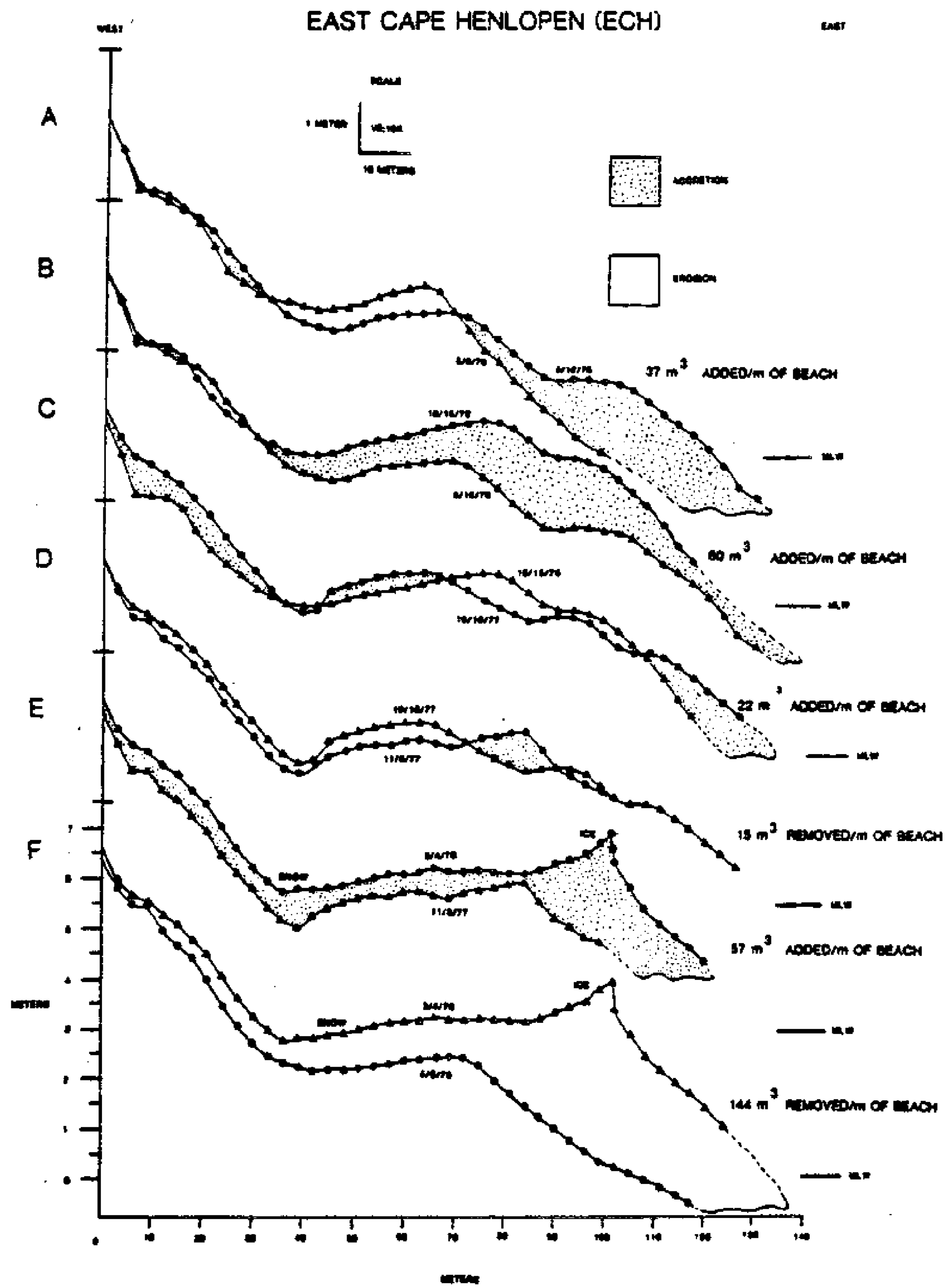


FIGURE III-2. Beach profiles from east Cape Henlopen.

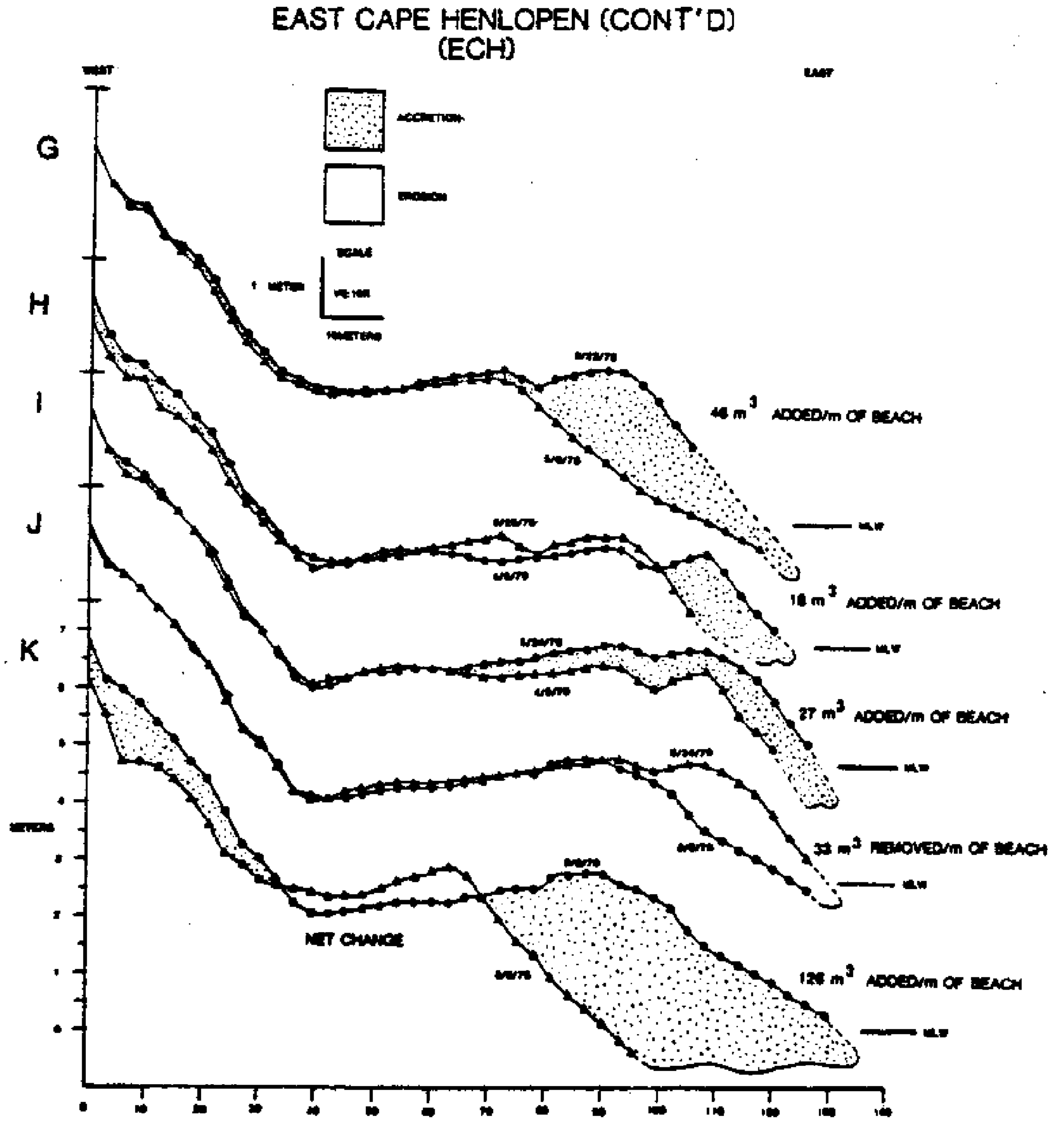


FIGURE III-2 continued. Beach profiles from east Cape Henlopen.

spring and several small storms, a major loss of sand to the profile (144 m^3/m of beach) was experienced (Figure III-2-F). Beach recovery and accretion dominated, so that the net change at the end of the study (Figure III-2-continued-K) was one of accretion, both in the lower reaches of the profile, as well as in the dunes. The slight erosion in the back-berm runnel in front of the dune was observed to occur during storms when northward-flowing water removed sand from this area.

This accretion of sand on the east side of Cape Henlopen may be related to the recent additions of large volumes of sand to the north side of Indian River Inlet, a locality which is about 25 kilometers south on the Atlantic coast. An example of the volume of sand removed from the beach and placed in the northerly littoral transport system was cited for the year 1978-79 by Hoyt (1981): in a one-year period, more than 200,000 m^3 of sand was placed into the northerly littoral transport system in the form of beachfill erosion from the north side of Indian River Inlet.

Although beach cusps and mega-cusps in the study area (Sallenger, 1979) do occur occasionally, longer-term accretion and erosion cycles appear unrelated to them. (A photograph of cusps and mega-cusps on Cape Henlopen is shown in the frontispiece.) The exact mechanism initiating beach cusps has not been adequately demonstrated (in this author's opinion); however, the sequence of events described by DuBois (1979) for Cape Henlopen generally fits my own observations. This sequential development of cuspate forms is outlined in detail by

Sallenger (1979), who thinks that "edge waves" initiate cusps by breaking through the berm at regular intervals.

North Cape Henlopen (NCH). On north Cape Henlopen, 13 profiles were taken from August 1976 to October 1979: the spit tip fluctuated back and forth so that a net 30 m eroded from the time of the first profile until mid-1978 (Figure III-3). During this period of time, several moderate northeast storms acted to remove material from northern Cape Henlopen. After that, accretionary ridges welded onto the tip so that the spit grew almost 70 m north by October 1979, for a net gain of about 40 m since August 1976. This accretion rate is only 12 m/year, about one-third the rates found by Maurmeyer for the 1973 year (Maurmeyer, 1974). These data show the effect of storm and littoral accumulation cyclicity that caused the spit tip to migrate back and forth nearly 100 m in three years. Also, during the winter of 1977-78, an ice berm some 3 m high had welded onto the northern spit tip area; these ice breakwaters, which are frozen onto the beachface at about the high-tide line, prevent normal littoral transport in the upper beachface and greatly alter those properties seaward of that. Although these massive ice bulwarks protect the sand in the upper beachface and beyond, they actually focus more wave energy on the lower beachface and offshore zone. However, because of the danger involved in working amongst large, floating ice blocks, a quantitative evaluation of this question could not be undertaken safely.

As in the case of east Cape Henlopen, the period from March 1978 to May 1978 resulted in major erosion of north Cape Henlopen

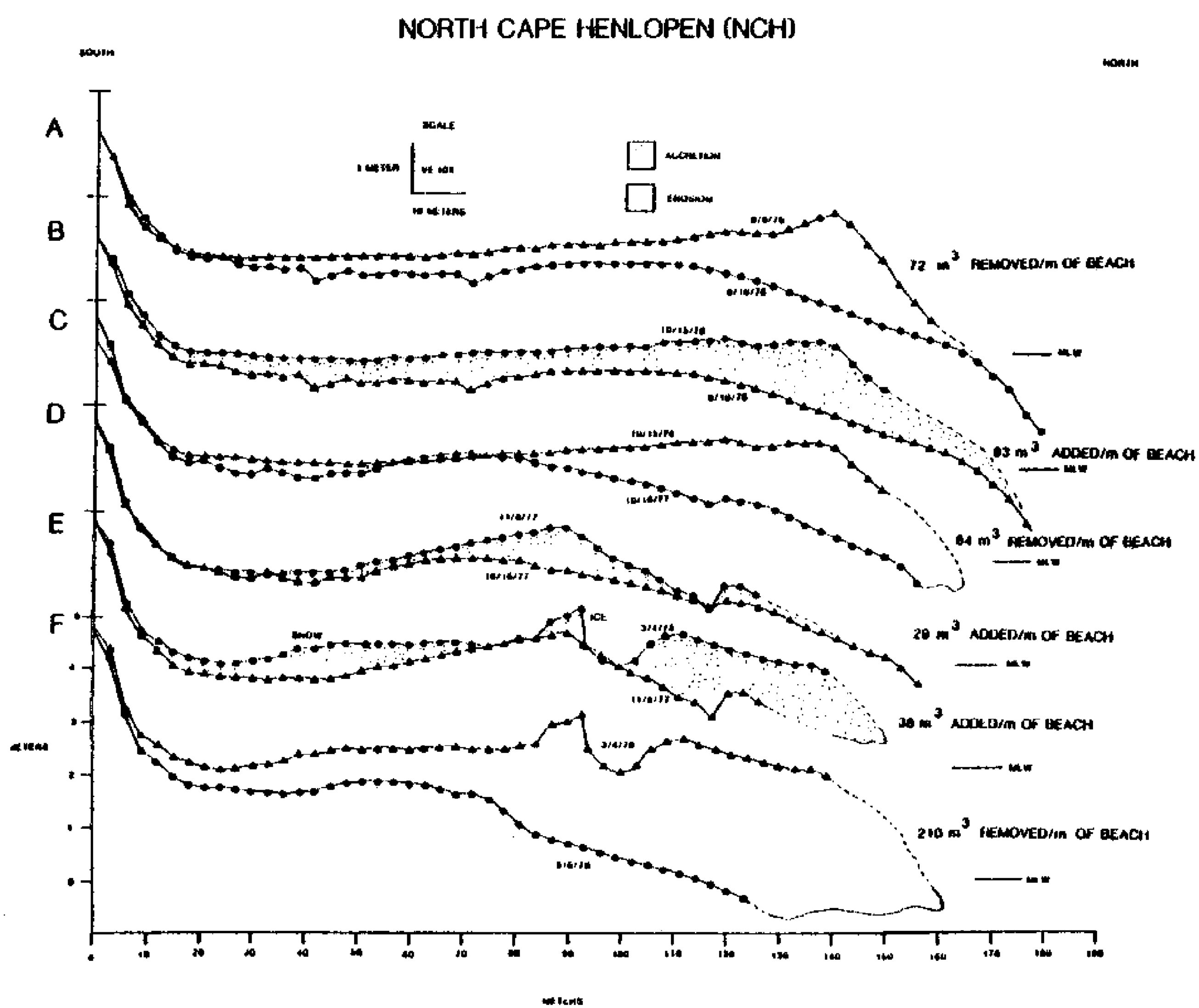


FIGURE III-3. Beach profiles from north Cape Henlopen.

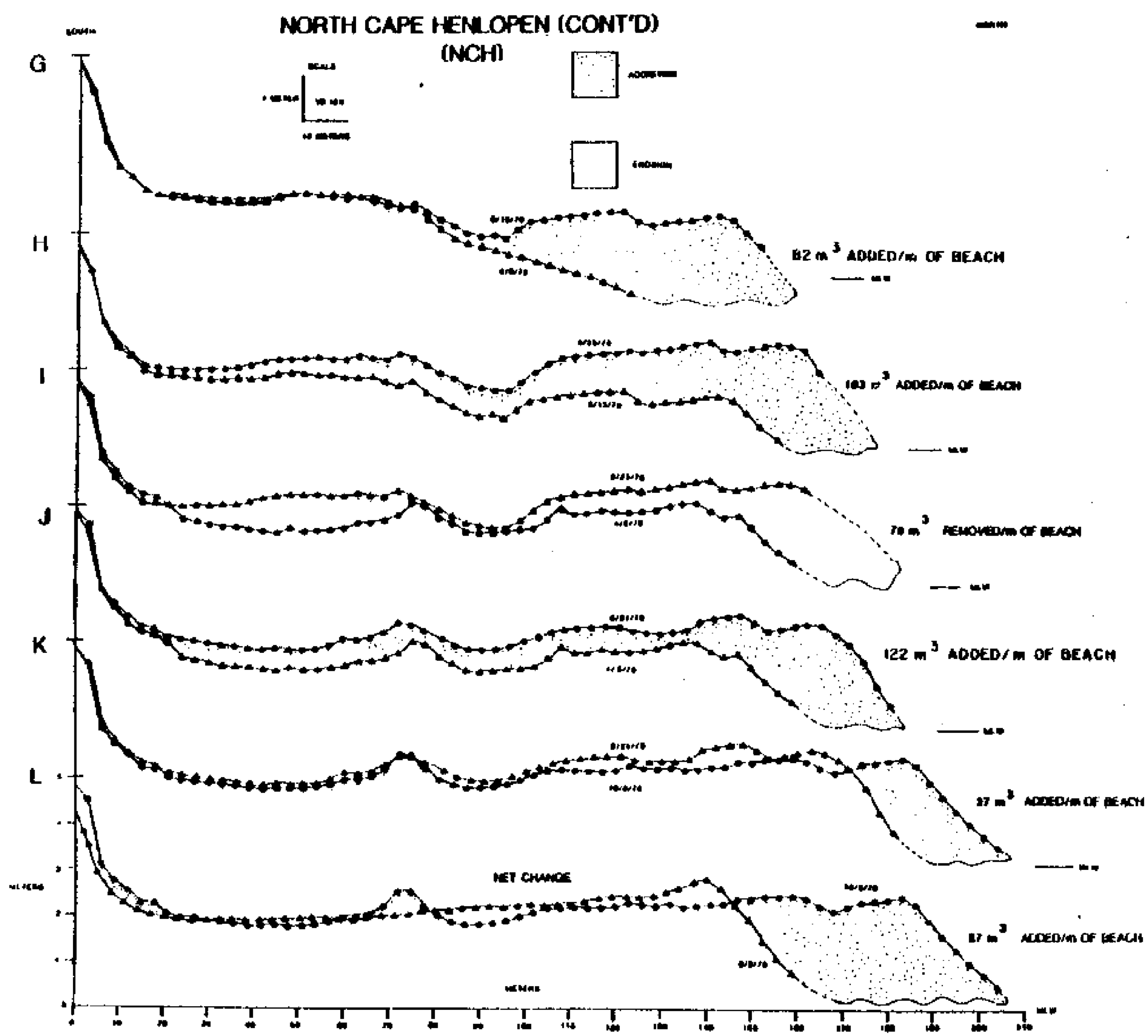


FIGURE III-3 continued. Beach profiles from north Cape Henlopen.

(210 m^3/m of beach--Figure III-3-F). After that, slow accretion was the rule, except for an erosive phase in the winter of 1978-79 (Figure III-3-continued-I). The net change (Figure III-3-continued-L) shows the establishment of a small incipient dune, a general lowering of the profile, and an accretion northward of some 40 meters. Longer-term (more than a decade) accretion trends will be addressed in Chapter X.

West Cape Henlopen (WCH). Although attempts to profile west Cape Henlopen were thwarted by an inability to use Emery's (1961) method, a series of substitute observations and time-lapse photographic studies provided much information on accretion and erosion trends there. Emery's method could not be employed because the horizon on the water could not be seen due to the presence of the Delaware Bay shoreline. Using a time-lapse photograph station set up on the pilot speaking station (location shown on Figure II-19), a 135 mm telephoto lens was used to take photographs of the west Cape Henlopen tidal flat areas on nine separate occasions from October of 1977 to April of 1979. Only minor changes were observed in the shoreline and offshore bars. One exception to this was 10-15 m of erosion seen in the dune line shoreward of the old fence on west Cape Henlopen. This erosion, which vertical aerial photographs (Chapter X) show has been going on for about 30 years, occurred primarily in the winter of 1977-78 when strong, gale-force winds from the northwest pounded this area for about 25 days (personal observations). The shoreline area due west of the pilot speaking station has been accreting in a series of beach ridges since about 1954 (based on vertical aerial photograph comparisons).

Other areas of the tidal flat shoreline and offshore zone remained very stable. Some areas between shore-perpendicular, tidal-flat ridges have been so stable that extensive algal mats have colonized there on the gravel lag surface. It is not known how long a period of time is required to develop these extensive algal mats, but I suspect that more than one summer season of stability is required.

Aside from ephemeral shore-parallel bars on the northwest side of Cape Henlopen and 1-2 cm ripple marks throughout the tidal flat, no major bar movement was noticed. A staked grid was emplaced in concert with M. Niedzielski (1978, unpublished). Time-lapse studies with photographs and subsurface, dyed sand plugs failed to show any measurable movement. The dyed sand was prepared by mixing one part water with two parts sand, two parts dye powder, and four parts powdered milk (the casein from the milk acts as a glue to bond the dye to the sand).

Profile on the Army Pier (AP). Using the top of the Army Pier as a stable datum, the relative elevations of the harbor bottom and beach were measured during three separate days in 1978 and 1979. These data were later referenced to the mean-low-sea-level datum using a United States Geological Survey Benchmark installed on the southern end of the pier (Figure III-4). The data show an essentially unchanged beachface and deeper than 1 m profile, but display some minor changes in the shallow offshore profile. The following generalizations characterize the patterns of deposition observed.

. Between the initial survey of 1/28/78 and the next survey of 8/9/78, a deepening along the profile was observed. This may have been

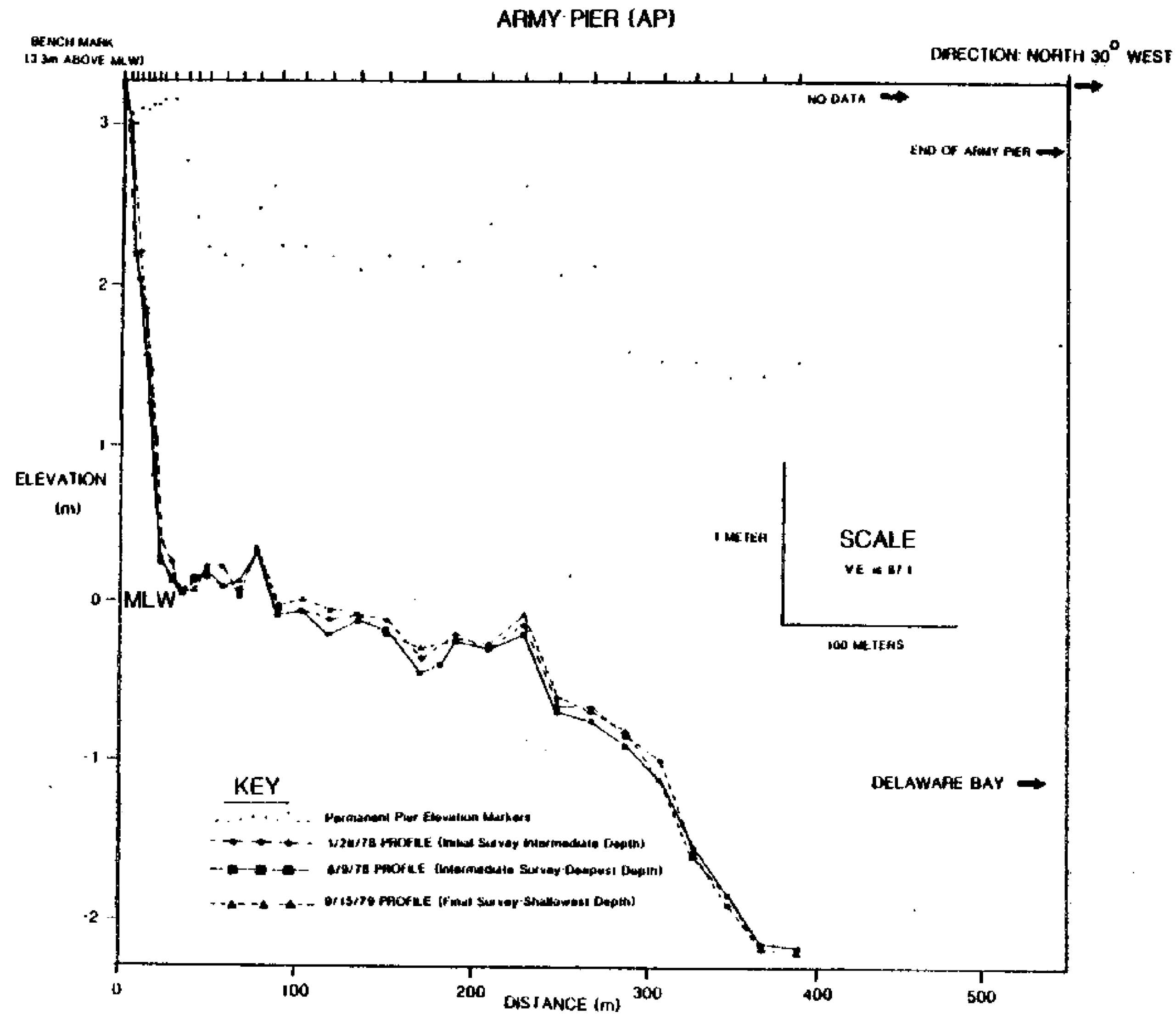


FIGURE III-4. Beach and nearshore profiles taken at the Army Pier.

associated with bed erosion caused by many storms in that period. However, it was expected that storms would accumulate materials in the offshore profile, not erode them;

. Between the intermediate survey of 8/9/78 and the final survey of 9/15/79, about one year later, significant shoaling of 10-15 cm occurred in several parts of the profile. These findings suggest a shoaling trend in this nearshore zone of several centimeters/year on the average; this additional material offshore appears to come mostly from beachface erosion. However, since the changes are so minor, it is not valid to suggest definite trends from these data.

During an extreme spring low tide, a series of seven offshore parallel bars was observed here under the Army Pier. These bars were of the type described by Zenkovitch (1967) as multiple parallel bars. This type of bar forms only under conditions of shallow offshore slopes with height and spacing nearly uniform and wave energy low to moderate. All of these conditions apply to the multiple parallel bars observed here.

Breakwater Harbor (BWH). The only major source of sand to the area around the Breakwater Harbor beach profile station (Figure III-1) is a small tidal creek emptying into the harbor from the south. Littoral transport is so low that any small volume of sand entering the harbor shorelines from the east or west would take a considerable period of time (years?) to reach the area. Consequently, the five beach profiles collected between March 1978 and September 1979 all show a gradual trend of shoreline erosion (Figure III-5). The net change

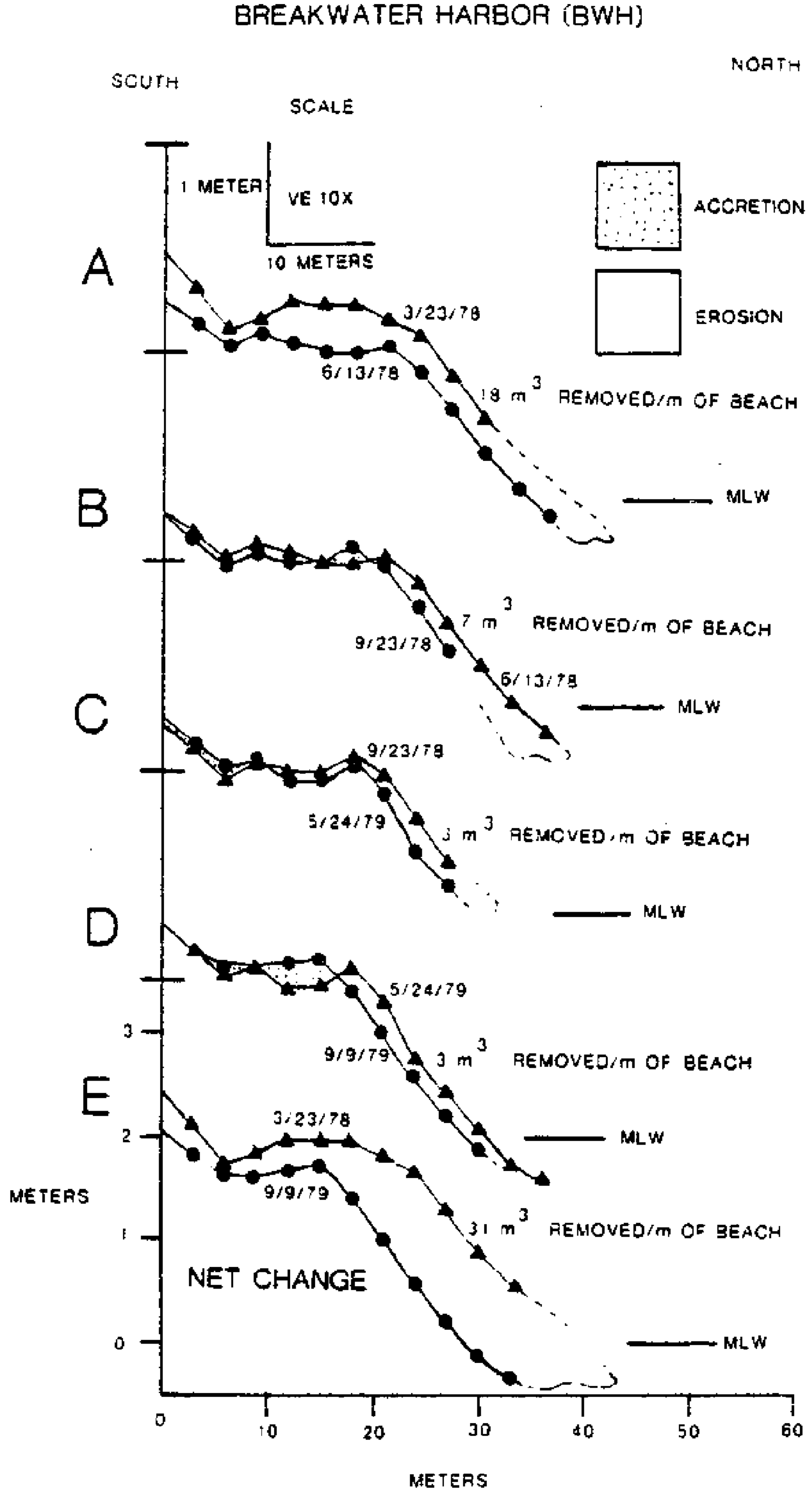


FIGURE III-5. Beach profiles from Breakwater Harbor.

over that 18-month period (Figure III-5-E) shows about 10 meters of shoreline retreat and a loss of 31 m^3/m of beach.

Eastern Lewes Beach (ELB). Several interesting beach features have occurred in the vicinity of profile ELB (Figure III-1). They appear to be related, in part, to the Ferry Breakwater, built there in 1964. The most obvious general feature is that of beach accretion on the west side of the breakwater. This results from the easterly littoral transport and has been noted previously by Kraft and others (1976) and Demarest (1978). Several lens-shaped offshore bars were found here in the spring of 1979. They were associated with the horns of giant or mega-cusps with a horn-to-horn distance of about 150 m. These features appeared after a period of strong easterly winds which may have set up wave refraction patterns around the Ferry Breakwater. Also noted at this location were frequently occurring water seepage features at the low-tide bench of the lower beachface. There may be a spring flowing out here or, more likely, an impermeable subcrop beneath.

Figure III-6 shows the accretionary nature of this locality with a net change from March of 1978 to September of 1979 of almost 10 m. This amounts to accretion of 22 m^3/m of beach at this spot (Figure III-6-E). It should be mentioned that this area has been accretional since 1940 (U.S. Army Corps of Engineers, 1968) and receives drift from beach nourishment farther west (Hoyt, 1981).

Central Lewes Beach (CLB). In the area of central Lewes Beach (Figure III-1) there was moderate accretion over the period from March

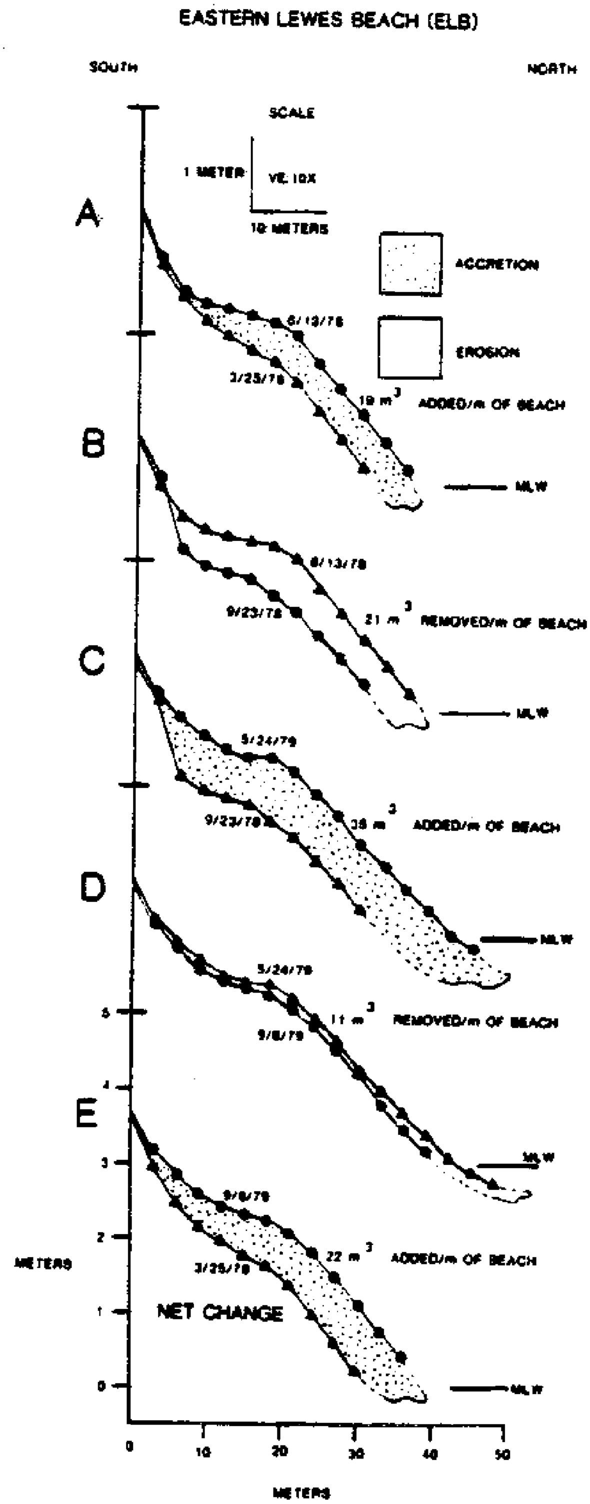


FIGURE III-6. Beach profiles from eastern Lewes Beach.

of 1978 to September of 1979. The accretion was exactly the same as that at eastern Lewes Beach (Figure III-7-E). The building of the beach here is consistent with historical trends mapped by the U.S. Army Corps of Engineers (1968).

Western Lewes Beach (WLB) and East of Roosevelt Inlet (ERI). Both of these localities are direct recipients of sand beachfill projects as outlined by Hoyt (1981). They both show strongly accretional profiles in direct response to the beach-nourishment projects (Figures III-8-C and III-9-C). Although minor periods of erosion exist between beachfilling operations, the recent trend has been toward net accretion (Figures III-8-E and III-9-E). If left alone, these areas would continue to experience the downdrift erosion typical of this inlet (U.S. Army Corps of Engineers, 1968; Hoyt, 1981). As one moves farther west toward the inlet, the beachfill operations become more volumetric, up to 76 m^3/m of beach adjacent to Roosevelt Inlet (Figure III-9-E).

Observations of occasionally exposed groins along western Lewes Beach demonstrate that short-term reversals in littoral transport occur; accumulations of sand have been found on the east side of groins instead of the normally expected west side. This occurs when northeast storms transport littoral drift to the west.

During storms, the beachfilled sand, which has been bulldozed, often displays unusual erosion patterns which can best be described as sawtoothed (Figure III-10). I suspect this results from differential

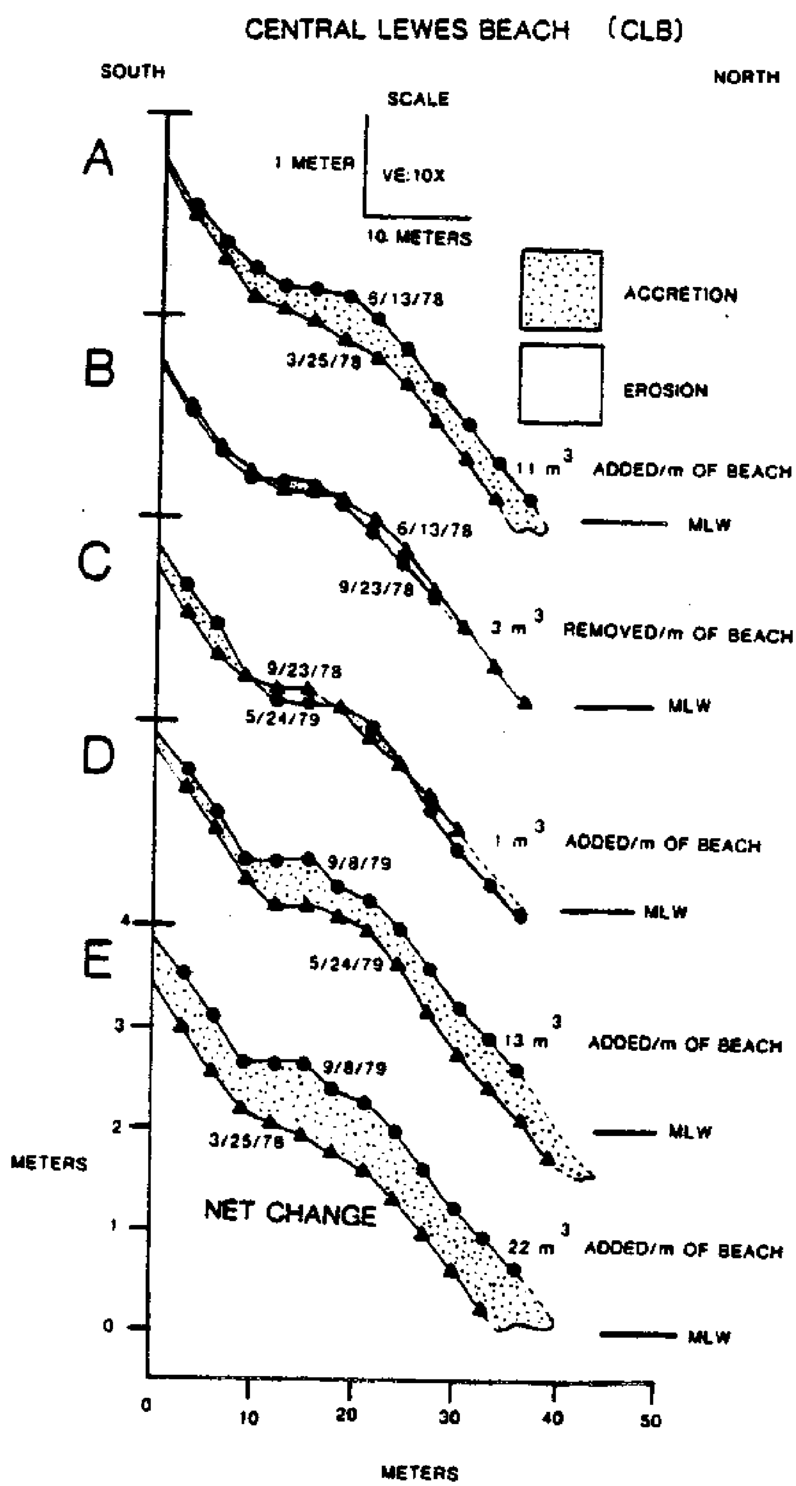


FIGURE III-7. Beach profiles from central Lewes Beach.

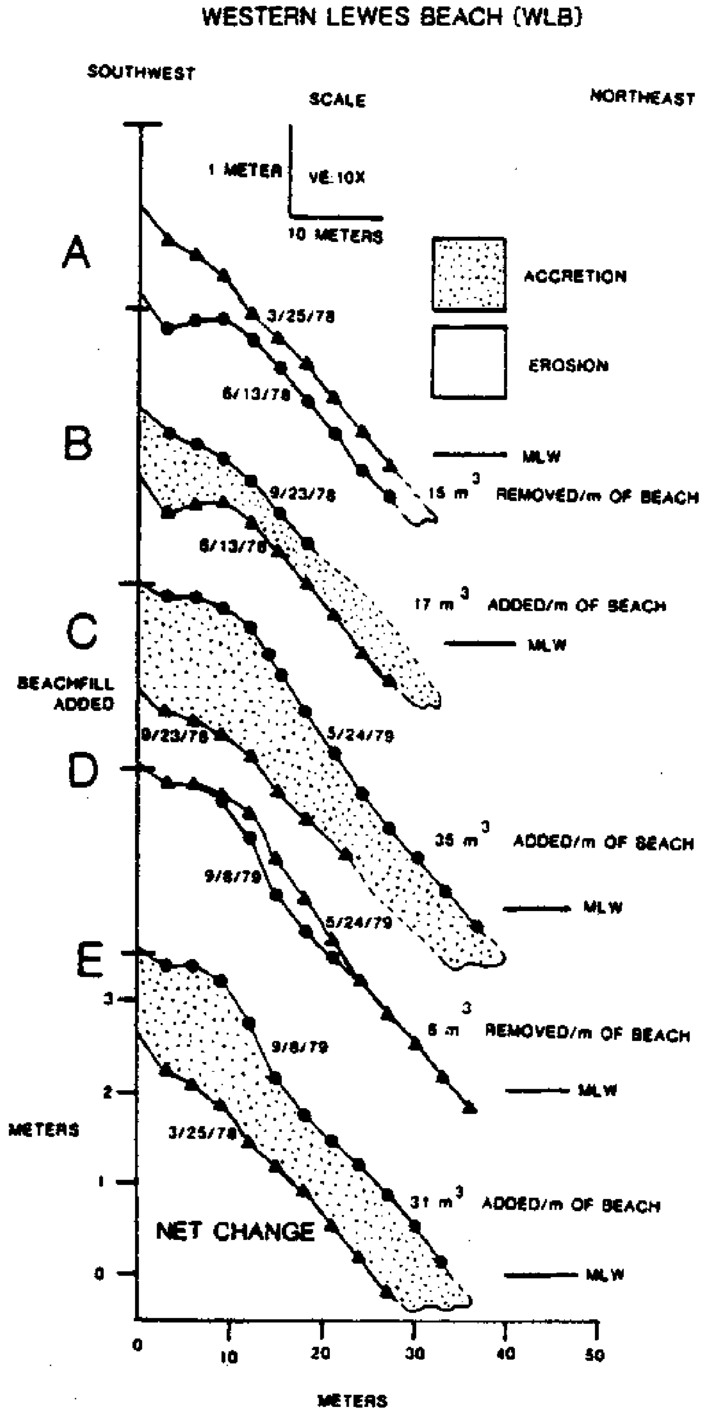


FIGURE III-8. Beachprofiles from Western Lewes Beach. Accretion shown in C was caused by beachfill operation.

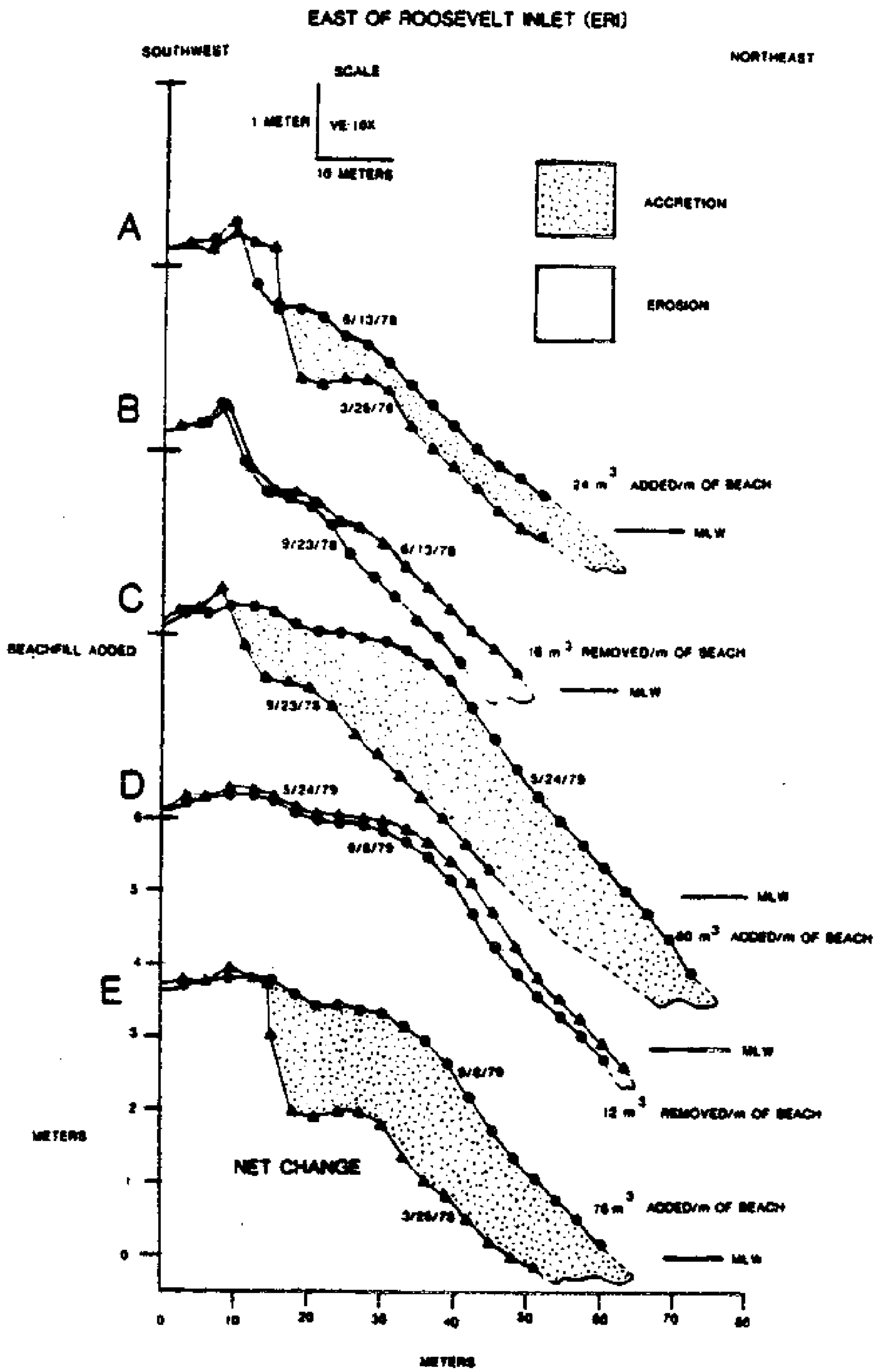


FIGURE III-9. Beach profiles from east of Roosevelt Inlet. The accretion shown in C was due to a beachfill operation.

FIGURE III-10. Unusual "sawtooth" erosion pattern on western Lewes Beach, created during storm of October 14, 1977. See text for explanation.

packing and cohesion created by the bulldozer track treads. During beach nourishment operations, bulldozers push sand up against the base of the dune, and the tracks of the tread differentially compact the sand.

CHAPTER IV

SUSPENDED SEDIMENT IN BREAKWATER HARBOR AND VICINITY

Introduction

Evaluating concentrations of suspended sediments for a wide variety of conditions is an important objective of this study. Once suspended sediment patterns were established over both the short term (tidal cycles) and longer term (months), it became feasible to propose mechanisms of fine-grained sedimentation and to test those models with evidence from subsurface cores (Chapter VII).

In their surveys of suspended sediments in Delaware Bay, Oo dam (1971) and Jordan (1968) found a dominance of quartz silt, with lesser amounts of clay minerals such as illite and chlorite. Oostdam noted that much of the suspended sediment passed the mid-estuary trap (concept proposed by Postma, 1967) and moved slowly throughout the bay as a high-concentration bottom layer. Oostdam (1971) surmised that this nepheloid layer was confined to within 50 cm of the bottom. In order to measure sediment concentrations for this study and evaluate modes of deposition, several avenues were pursued:

. SCUBA diving observations were made to ascertain first-order properties of suspended sediment;

. sediment trap jars were attached to drogues, which drifted with the current and collected sediment;

. bottom sediment traps were emplaced to collect sediment for periods of several months; and

. instantaneous, in situ sediment traps were used to collect sediment under a wide variety of situations.

SCUBA Diving Observations

During observations of five SCUBA dives in Breakwater Harbor, several aspects of modern geologic processes were noticed. The lower part of the water column, within about a meter of the bottom, always contained a nepheloid layer of concentrated, opaque mud. Usually, the upper boundary of the nepheloid layer was sharply defined. During various stages of the tide, these sediments were in modes of transportation, deposition, and erosion, although they never completely settled out. It appeared that this bottom suspension layer moved in and out with the tide and was created by bottom turbulence and by the addition of fine, organic-rich detritus, presumably from southwestern Delaware Bay marshes. These observations suggested that the harbor area was provided with a large and persistent supply of silts and clays with some organic material available.

A second major observation was the active bioturbation and tracks of crabs at the sediment-water interface during the summer months. During the winter months, however, this biological activity was largely absent and a smoother sediment surface was noted. Abundant shipwreck debris resting on the gravel-lag bottom indicated a long history of nondeposition in the deep hole east of the inner breakwater. Southwest of this scour hole in shallower areas of the harbor, a pair of olive-brown silt samples was collected from the sediment-water interface and was found to contain about 6% volatiles, which proved that the sediments are mostly mineral matter (Appendix E, after a method of the American Public Health Service, 1976). This method defines volatiles as anything that is evolved after heating the sample at 550°C for one hour.

Drogues With Attached Sediment Traps

Three different drogues with attached sediment trap jars were placed at three locations in the study area during flood tide to estimate normal settling rates of sediments in suspension. The dimensions of the ideal jar have been investigated in detail both in the lab and in the field (Gardner, 1978; Richardson and others, 1980). In cases where the jars are anchored in currents with a velocity less than 10 cm/sec, the amount of material settling through the trap jar accurately reflects settling rate (Richardson and others, 1980). All of the trap jars used in the present study were 13 cm long and 8.2 cm in diameter. The length-to-width ratio for these jars is 1.6:1, within the range identified by Gardner (1978) as accurate.

From each drogue, three jars were suspended at depths below the surface of 50 cm, 170 cm, and 300 cm. Some of the data were lost by jars impacting the bottom (2) or spilling their contents (2), but there were still some useful observations which could be made:

. quantities of sediment trapped in the jars showed a non-linear (logarithmic) increase toward the bottom (displayed qualitatively in Figure IV-1);

. accumulations of sediment in the jars throughout the study area appeared to be about the same (the photograph presented as Figure IV-2 shows the contrast of nearshore turbid water to the clearer water of central Delaware Bay channels);

. fluxes of sediment through the trap tops averaged about 44 mg/hour at 50 cm below the surface, about 132 mg/hour at 170 cm below the surface, and about 574 mg/hour at 300 cm below the surface. Converting these fluxes into grams/m^2/hour yields 8.3 gm/m^2/hr at 50 cm, 25 gm/m^2/hr at 170 cm, and 109 gm/m^2/hr at 300 cm;

. based on the above measurements during one day on flood tide (September 16, 1979), the weight of suspended sediments settling onto the bottom throughout Breakwater Harbor is 3.27×10^5 kg/hr or 327 metric tons/hr.

However, the sediment traps measure only flux through the water column, not sedimentation rate on the bottom. The actual accumulation rate on the bottom is undoubtedly less, but it is not known how much of this sediment is resuspended on ebb tide. A fuller analysis of this question is contained in Chapter XI.

Bottom Long-Duration Sediment Traps

In order to determine bottom sedimentation conditions in the

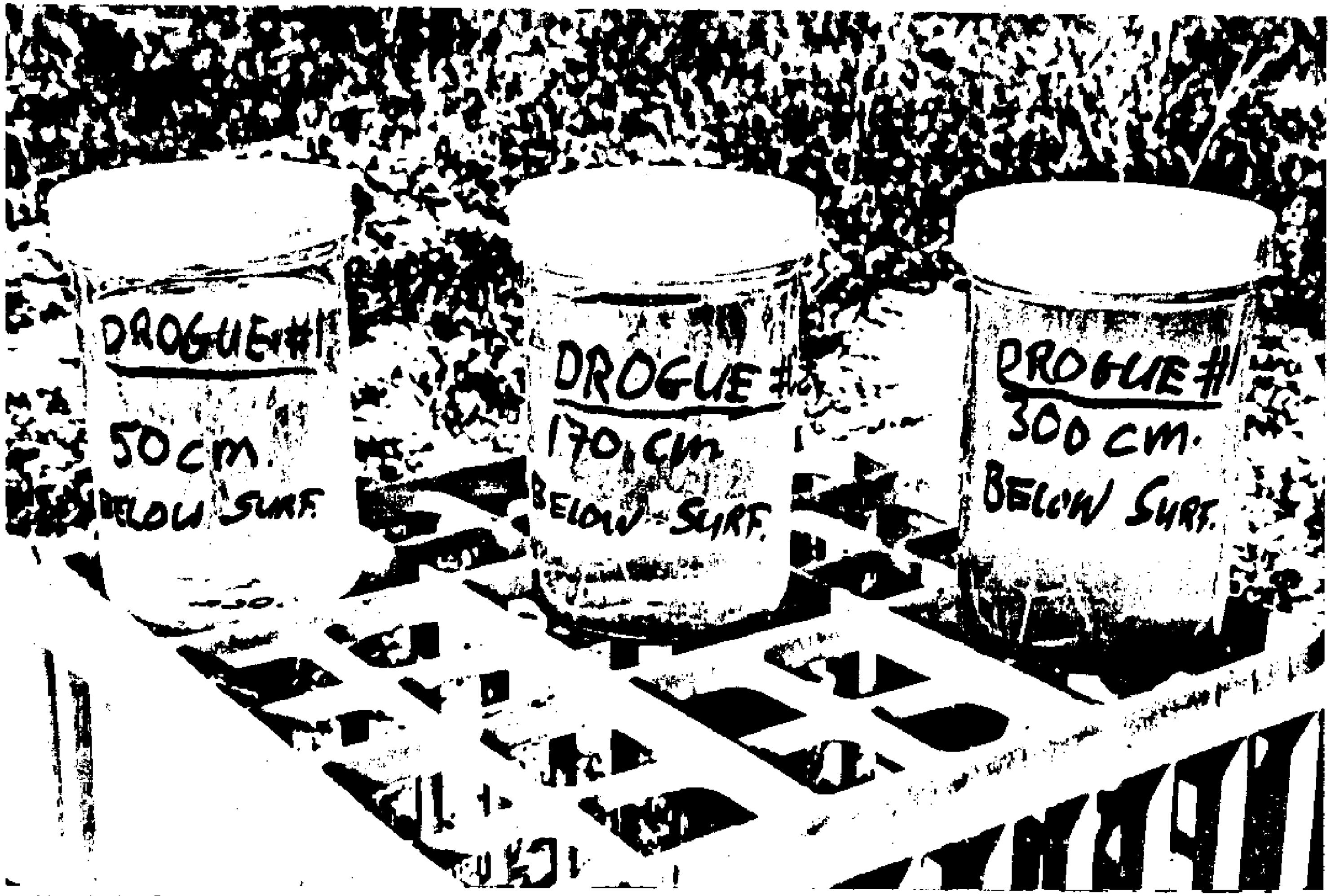


FIGURE IV-1. Photograph of drogue sediment trap jars which measured the bedward (downward) increase in sediment concentration.

FIGURE IV-2. Photograph looking west across the study area. The turbid water of southern Delaware Bay can be seen contrasted with clearer water of Delaware Bay channels (lower right).

study area, bottom sediment traps, which have been used successfully in lakes (Haupt, 1976) and on the submerged portion of the eastern North American continental shelf (D. Folger, personal communication), were deployed for this study. A photograph of an assembled trap ready to go overboard is shown in Figure IV-3. A simple engineering sketch of such a trap is presented in Figure IV-4. A total of eight trap jars was used on each trap, hung at 10 cm intervals up from the bed ranging from 20 to 90 cm.

The traps were deployed by filling and capping the jars prior to lowering the trap overboard. Once on the bottom, the traps were anchored with a cement weight on the end of a 30-meter (100-foot) line. A SCUBA diver then carefully swam down on top of the trap and removed the lids, being careful not to stir up bottom sediment. The location of the trap site was surveyed in using intersecting lines and sextant angles in the same manner the current meter sites were located (Chapter I).

To test the utility of these trap devices, one was emplaced in the central part of Breakwater Harbor (marked "PS" in Figure IV-5). This pilot study trap was emplaced in October of 1977 and recovered eight months later. As had been feared, biological fouling of the traps with barnacles, spider crabs, mud crabs, and algae was quite severe. It is probable that each trap jar was occupied by a crab during a substantial part of the eight months (three of the eight jars had residents on the date of recovery). Qualitatively, sediments found in the trap jars are representative of those which are actively suspended within a meter of the sediment-water interface. The trap jar which had

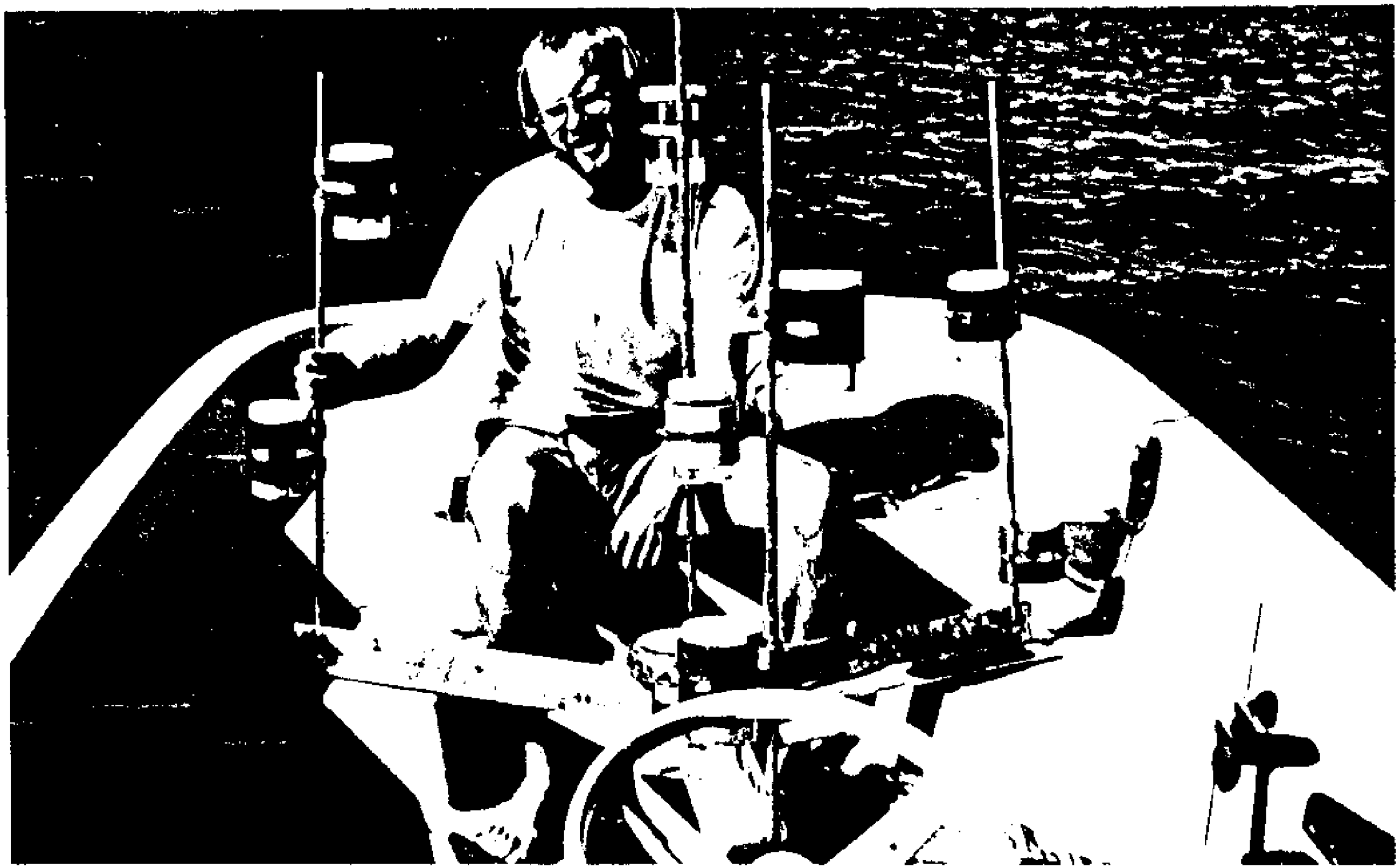


FIGURE IV-3. Photograph of long-duration bottom sediment traps used in this study. This one accumulated sediments on the bottom of Breakwater Harbor for eight months.

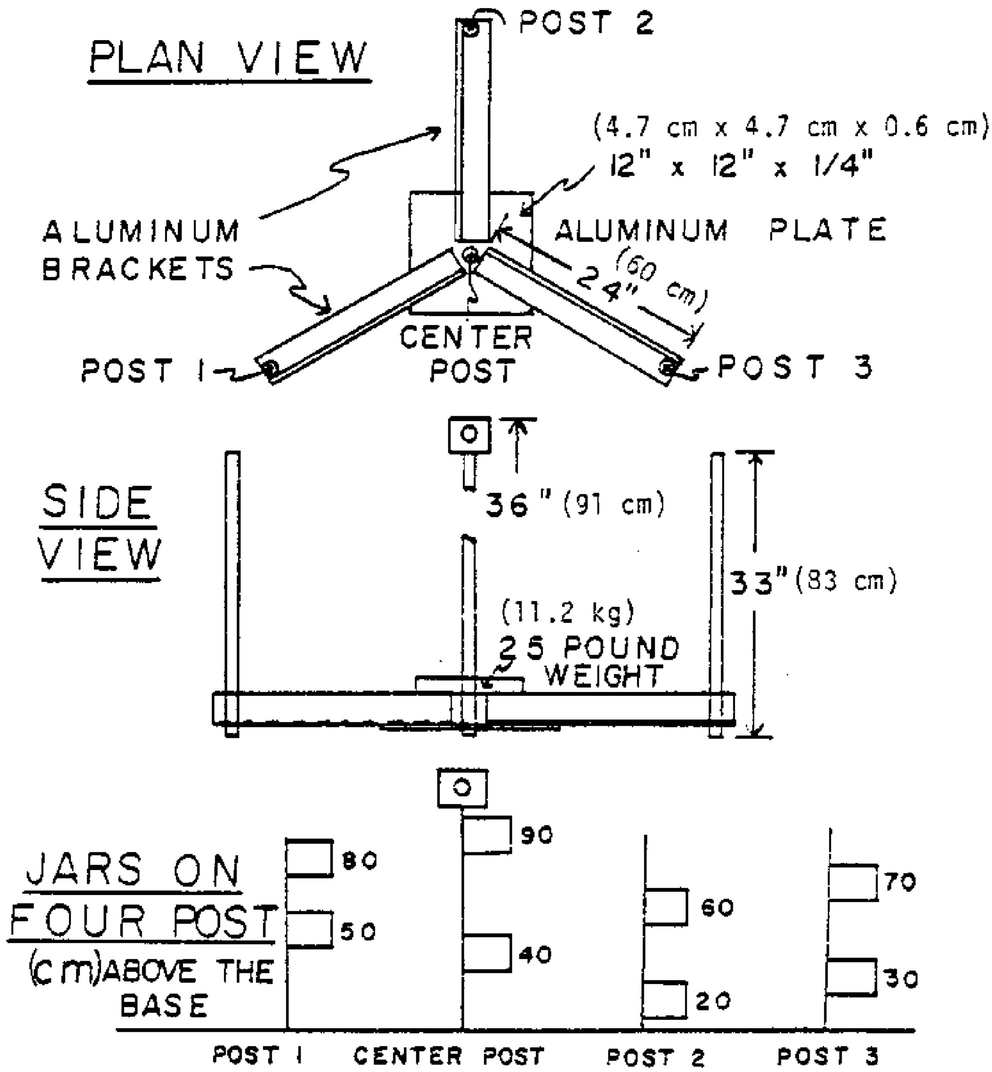


FIGURE IV-4. Simplified engineering sketch of bottom sediment traps, with elevations of the eight trap jars plotted (jars are 13 cm tall and 8.2 cm in diameter, which is a 1.6:1 length-to-width ratio).

been suspended at the 40 cm elevation had slipped down to 30 cm, so there are no data at 40 cm. Grain size analysis of all the trap contents showed that all of the sediments were sandy muds, according to the classification of Folk (1954). The data, presented in Appendix D, show an average of 41% sand, 34% silt, and 25% clay.

The sediments from the trap jars were also analyzed for their volatile solids content (Appendix E, after a method of the American Public Health Service, 1971). They all contained 9-12% volatiles, much more than the 6% collected by hand on the harbor bottom. One reason for this difference may be the organic residue left in the trap jars by flora and fauna which occupied them.

Another method of evaluating bottom sediment accumulations is to place a large, flat pan on the bottom; although this was done, current scour eddies around the pan eroded any sediment which was deposited. In addition, a metal stake was driven into the harbor bottom to evaluate shoaling, but, once again, scouring caused by the stake made this attempt fail. Information on shoaling rates would have to come from vibracores and historical bathymetric charts.

In an effort to improve upon the data collected in the bottom sediment trap pilot study, four more traps were prepared and painted with copper-based antifouling paint. They were deployed in the four locations (T1, T2, T3, and T4) indicated on Figure IV-5. Those sites were chosen to represent a variety of sedimentary regimes in the harbor area. The traps were emplaced in June of 1978 and a recovery

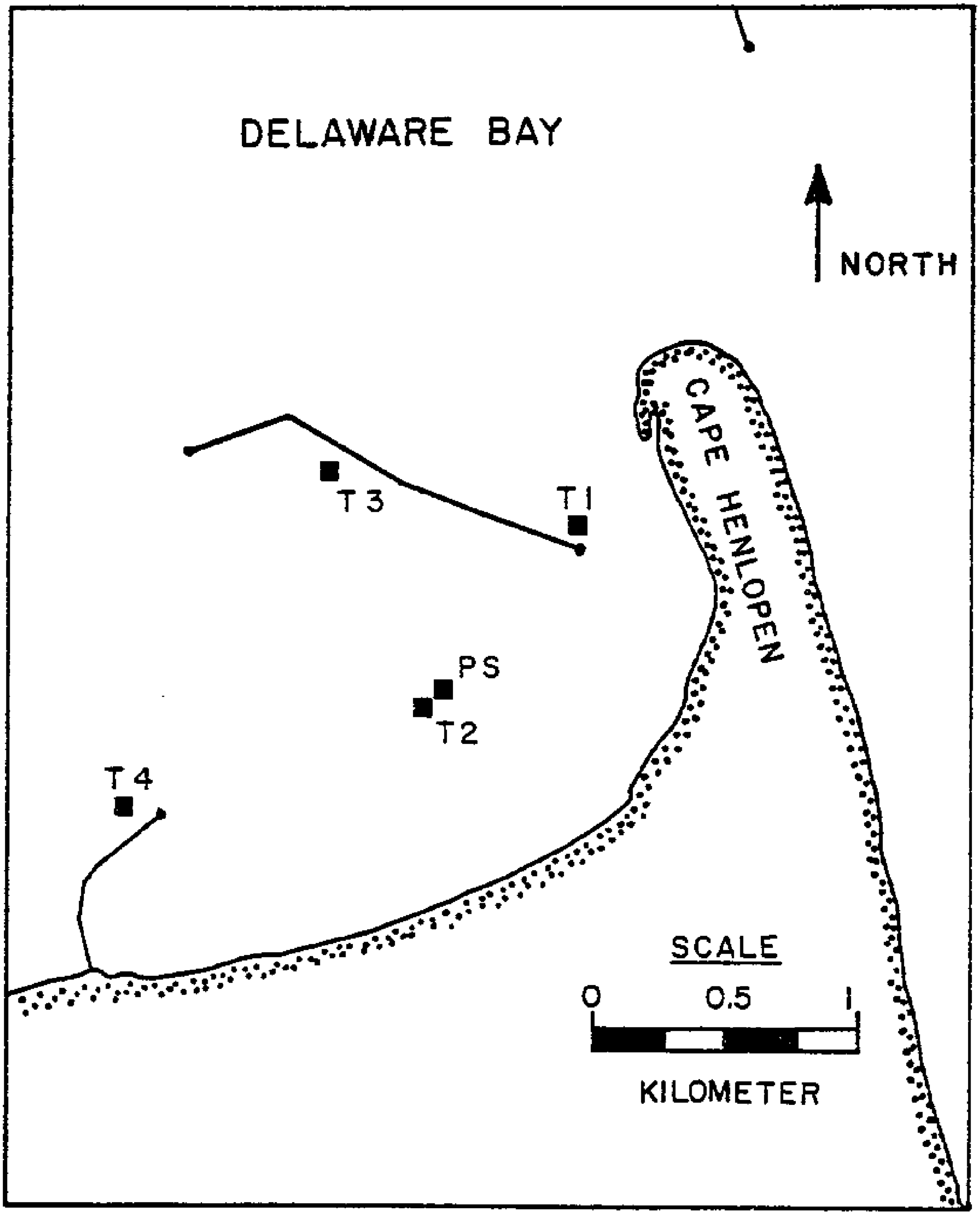


FIGURE IV-5. Locations of bottom sediment traps used in this study. Pilot study is designated as "PS."

attempt was made four months later. However, only T1 was found. The others had been displaced from their locations and/or stolen. Despite two other recovery attempts later in the year, no trace of the traps was found. Even more frustrating was the fact that T1 had been broken and overturned, probably by an anchor or fishermen. Moreover, the antifouling paint was found to be ineffective against biofouling. Fortunately, reasonably good data were obtained in the pilot study. Other conclusions on long-term trends in bottom sedimentation would have to come from analyses of vibracores and bathymetric changes (Chapter VII).

Sediment Trap Results

Various approaches can be used to collect suspended sediments for analysis. Two of these are:

. drawing water and sediment up through a hose and then centrifuging the sediment down (e.g. Jordan, 1968; Ootsdam, 1971); and

. collecting water and sediment *in situ* with a Nansen-type bottle.

Since I wanted to be able to measure sediment concentrations and salinity precisely, as well as analyze the sediment for grain size, mineralogy, and volatile solids determination, the second of these methods was used. Also, equipment and procedures required for drawing water up through a hose necessitate a larger and more expensive system than I had available.

The simultaneous water sampler (Kana, 1976), which was used to collect the surf zone data presented in Chapter II, was modified so that it could be used as a suspended sediment trap. In order to sample three depths within the water column, the device was made slightly negatively buoyant by the addition of weights (Figure IV-6). The device was then lowered carefully over the side of the boat with a line attached to the trigger rod. By approaching the bottom slowly and noting the line tension, it was easy to tell the instant the shoe contacted the bottom. At that instant, the operator (myself for all cases) pulled up sharply to release the trigger mechanism, closing all the doors simultaneously. Underwater observations of this procedure verified that the trap doors closed before any bottom sediment was stirred up.

Samples normally were taken at eight stations throughout the study area, one at the surface, one 190 cm above the bed, and one 50 cm above the bed. Samples were filtered using a millipore apparatus and a high-vacuum pump. Whatman #114 qualitative, wet-strengthened paper circles (5.5 cm in diameter) were used in the lab to collect sediments. Results of a pilot study on 3/14/79 demonstrated that samples taken in the water column between the surface and 190 cm above the bottom did not add substantial information to the profile. The vast majority of suspended sediment was almost always within 2 m of the bottom. Table IV-1 enumerates the dates and conditions of suspended sediment samplings. Harsh weather during the winter prevented sampling from a small boat during that season.

FIGURE IV-6. Photograph of modified simultaneous water sampler (Kana, 1976) used to trap suspended sediments at various heights above the bed.

TABLE IV-1. WATER COLUMN SUSPENDED SEDIMENT SAMPLING CONDITIONS

DATE	SEASON	TIDAL STAGE	NOTES
4/25/79	SPRING	EBBING	EXTRA STATIONS J & K SAMPLED
5/16/79	SPRING	FLOODING	
5/21/79	SPRING	LATE EBB	
6/5/79	SPRING	LATE EBB	
7/3/79	SUMMER	FLOODING	FERRY PROP-WASH SAMPLED
8/9/79	SUMMER	LATE FLOOD	
4/29/80	SPRING	EBBING	DUPLICATE SAMPLES TAKEN
4/29/80	SPRING	FLOODING	DUPLICATE SAMPLES TAKEN
8/22/80-I	SUMMER	SLACK WATER	SMALL N.E. STORM ON
8/22/80-II	SUMMER	MID-LATE EBB	SMALL N.E. STORM ON
8/22/80-III	SUMMER	EARLY FLOOD	SMALL N.E. STORM ON
8/22/80-IV	SUMMER	MID FLOOD	SMALL N.E. STORM ON
8/22/80-V	SUMMER	LATE FLOOD-SLACK	SMALL N.E. STORM ON

In general, the suspended sediment samples contained very high volatile solids (about 13.5% for harbor samples 50 cm above the bed, about 15% for a sample off of Roosevelt Inlet, and about 8.5% in the sediment stirred up by the propeller of the ferry). These high volatile solids compositions (in comparison with bottom samples) reflect the fact that less organic matter is incorporated and preserved in the bottom sediment (Appendix E). The high value off Roosevelt Inlet reflects drainage of marsh organics. Salinities as low as 14 $^{0}/oo$ were found off of Roosevelt Inlet during ebb tide. Normal salinities for the other stations ranged from 26 $^{0}/oo$ to 32 $^{0}/oo$.

The mineralogies of the suspended sediments were analyzed by means of x-ray diffraction of clays and silts (Appendix F). The mineral assemblage, dominated by quartz, feldspar, illite, and chlorite, appears to be essentially identical in bottom and suspended sediments.

Suspended sediment concentrations collected for this study are displayed chronologically in Figures IV-7 to IV-19. The upper line on the plots shows the height of water in the area during the one-hour sampling time required. The general trend of concentrations revealed by these plots is that they are higher during ebb tide when rapid tidal currents keep materials in suspension. By the time of late flood tide (high slack water), much of the suspended material has settled out again. Take, for example, the first two sampling dates displayed in Figures IV-7 and IV-8. During ebb tide (Figure IV-7), concentrations of suspended sediments in the harbor area range from about 10 to 100 mg/l, while concentrations at Stations J and K, outside the harbor area, are

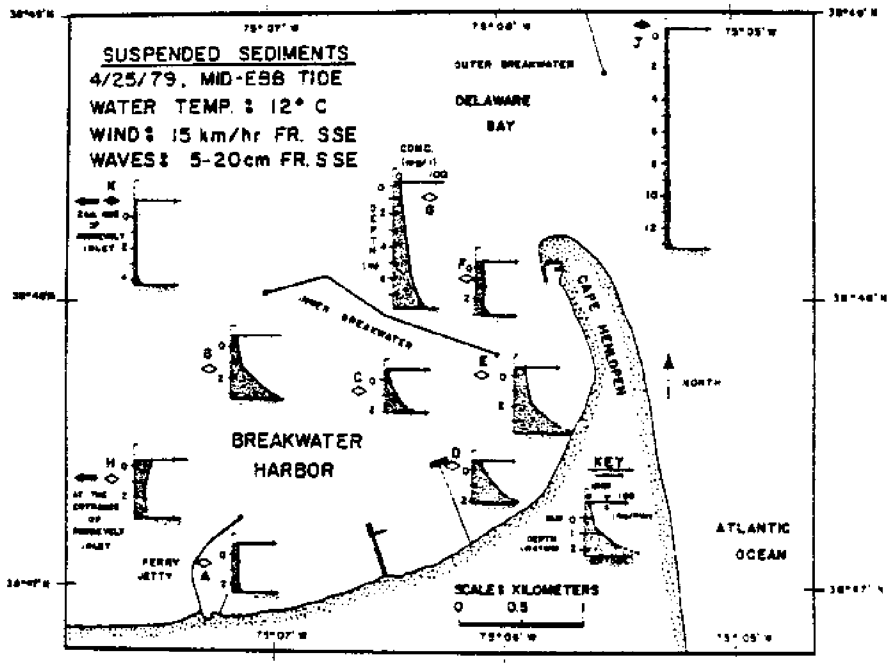


FIGURE IV-7. Plot of suspended sediments on 4/25/79. Stations J and K show background levels of sediment concentrations found in adjacent areas of Delaware Bay. Zero depth corresponds to mean low water.

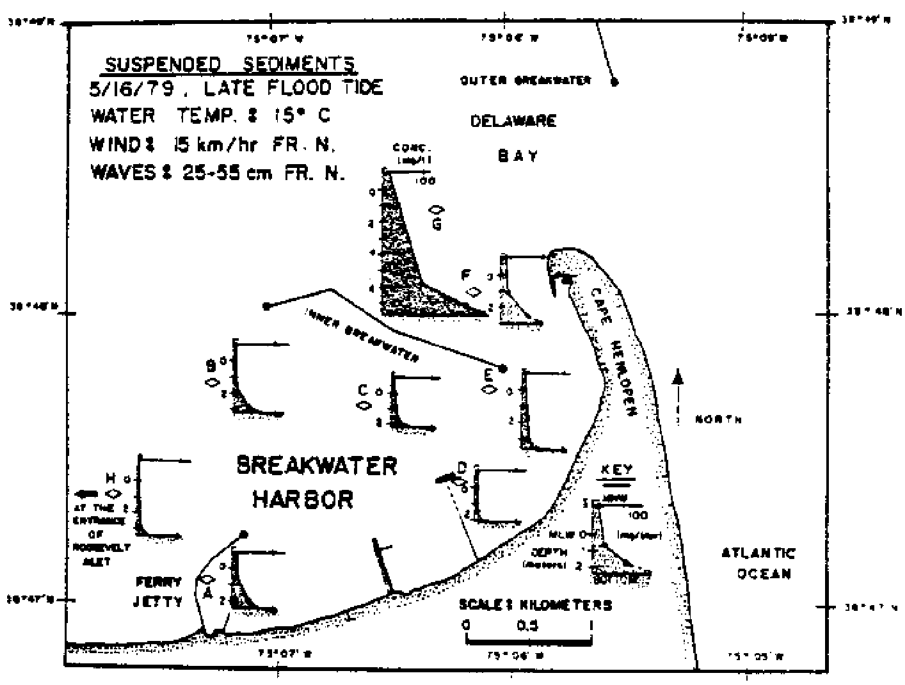


FIGURE IV-8. Plot of suspended sediments on 5/16/79. Zero depth corresponds to mean low water.

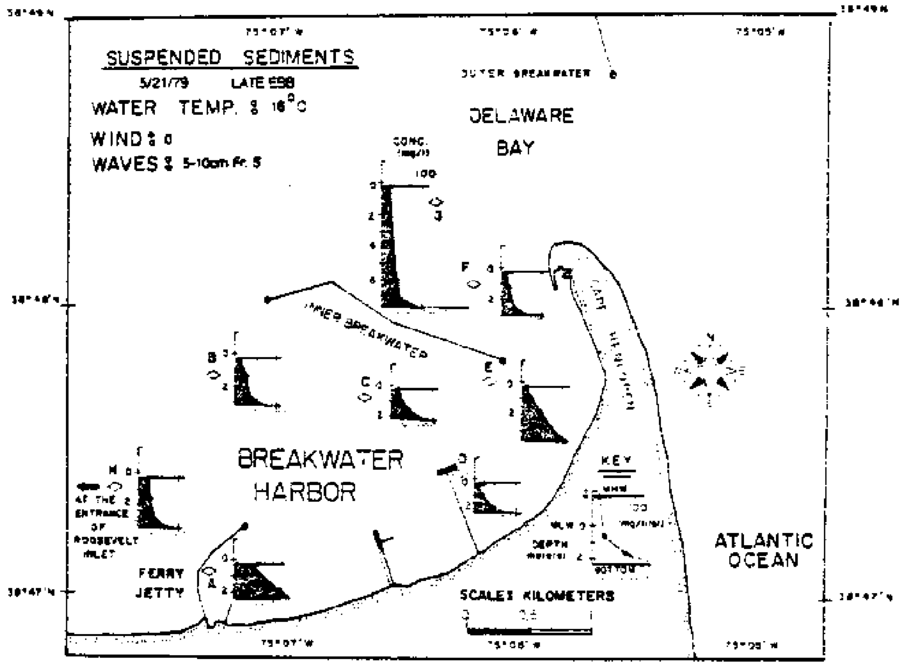


FIGURE IV-9. Plot of suspended sediments on 5/21/79. Zero depth corresponds to mean low water.

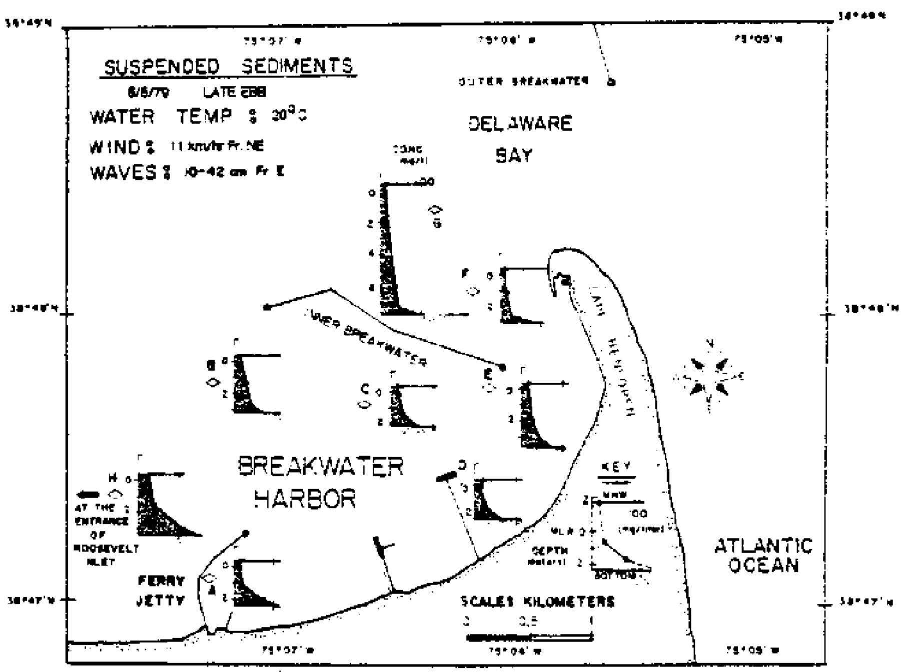


FIGURE IV-10. Plot of suspended sediments on 6/5/79. Zero depth corresponds to mean low water.

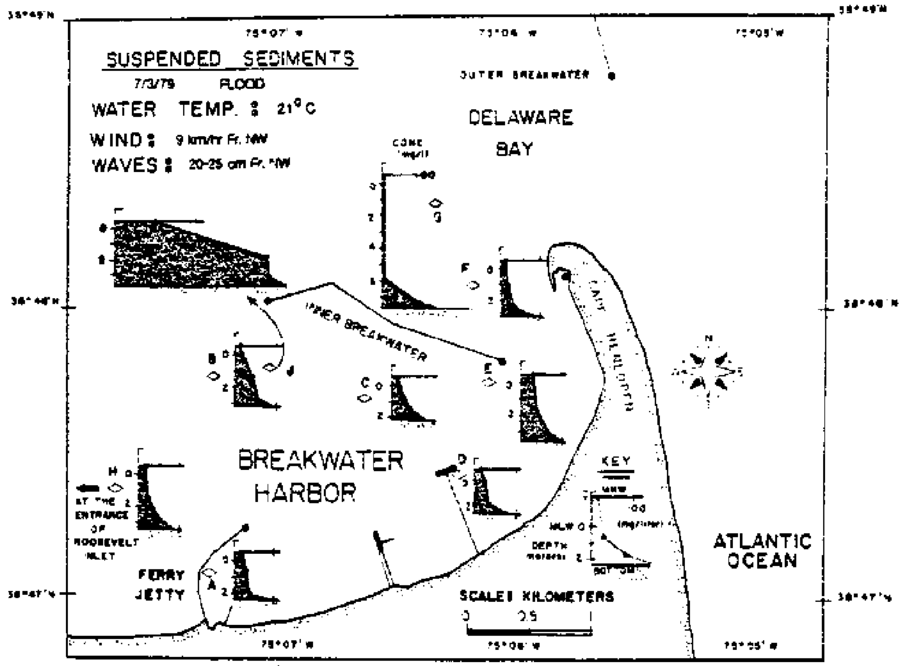


FIGURE IV-11. Plot of suspended sediments on 7/3/79. Station J is the location where the ferry prop-wash was sampled on this date. Zero depth corresponds to mean low water.

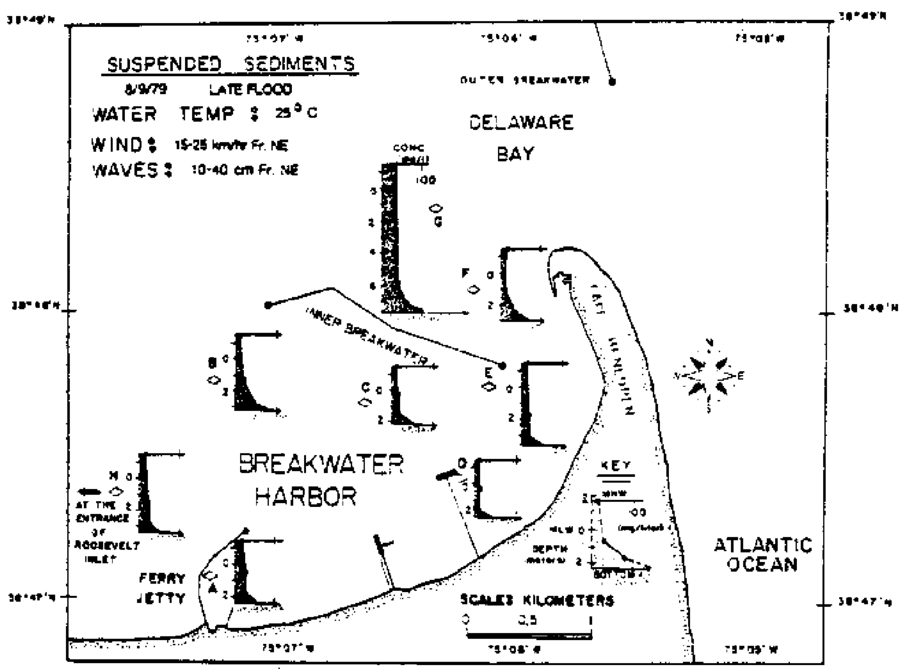


FIGURE IV-12. Plot of suspended sediments on 8/9/79. Zero depth corresponds to mean low water.

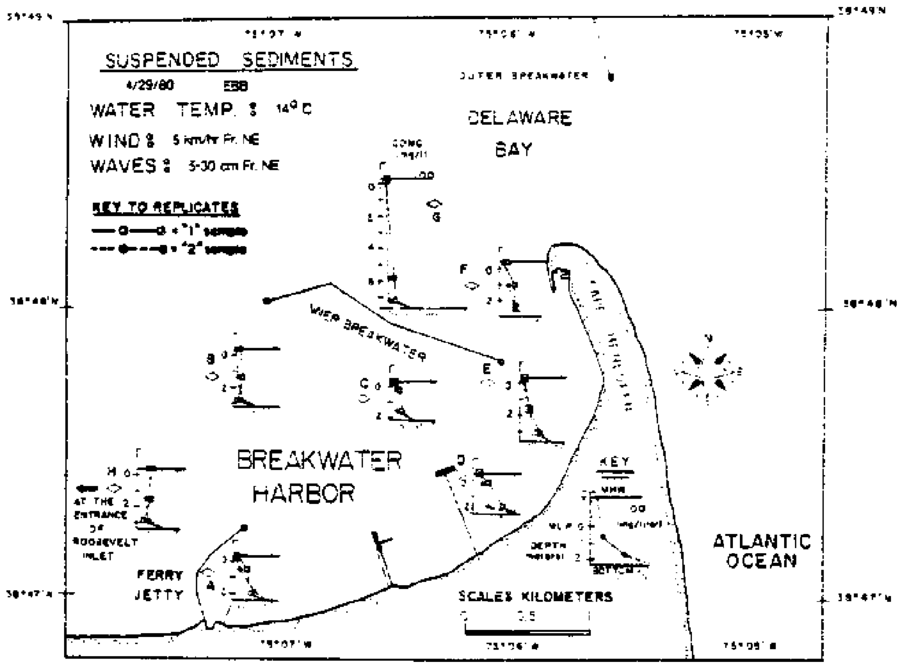


FIGURE IV-13. Plot of suspended sediments on 4/29/80 during ebb tide. The duplicate sample labelled "1" was taken first in each case.

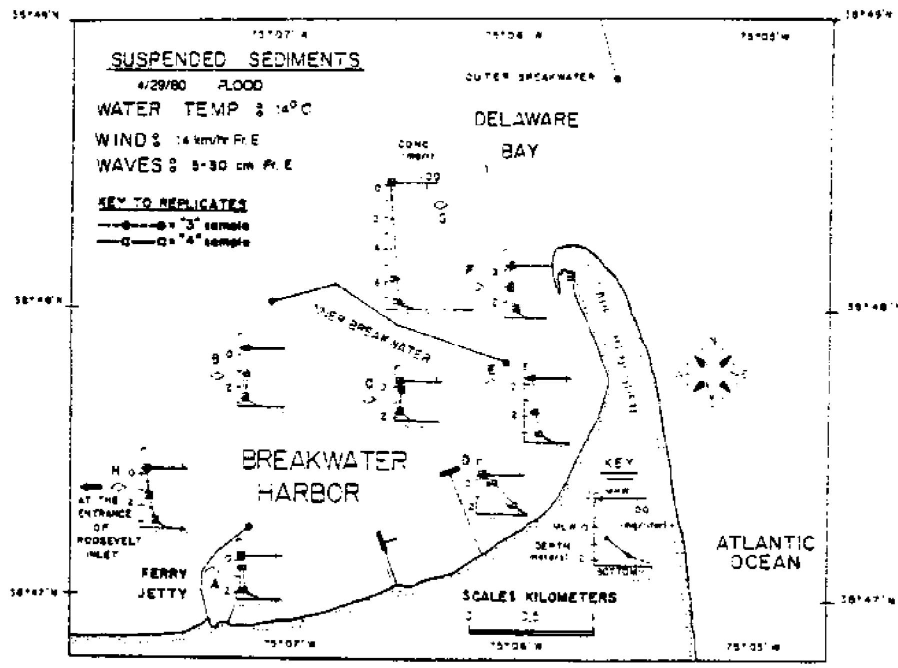


FIGURE IV-14. Plot of suspended sediments on 4/29/80 during flood tide. The duplicate sample labelled "3" was taken first in each case. Zero depth corresponds to mean low water.

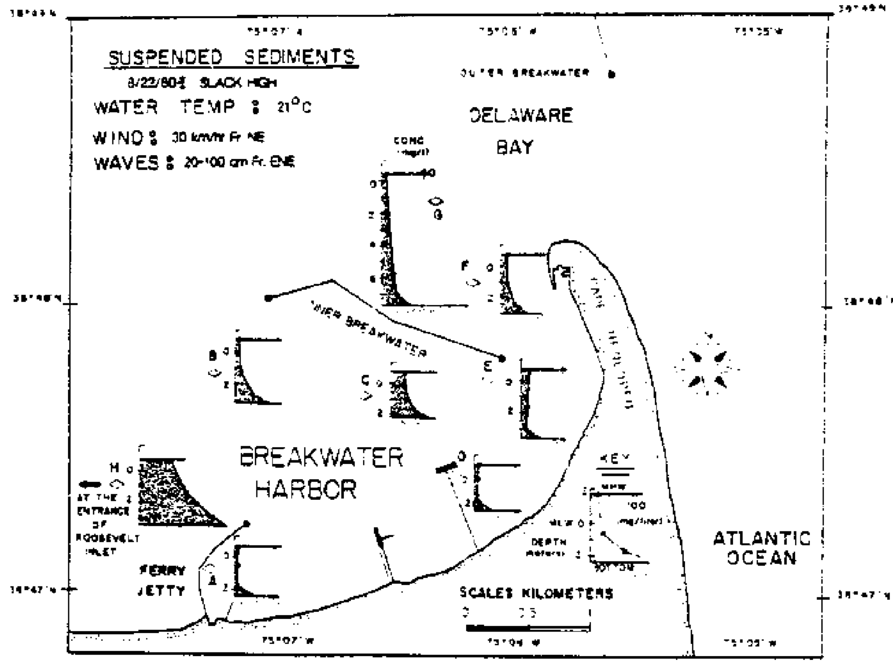


FIGURE IV-15. Plot of suspended sediments on 8/22/80-I, during a northeast storm.

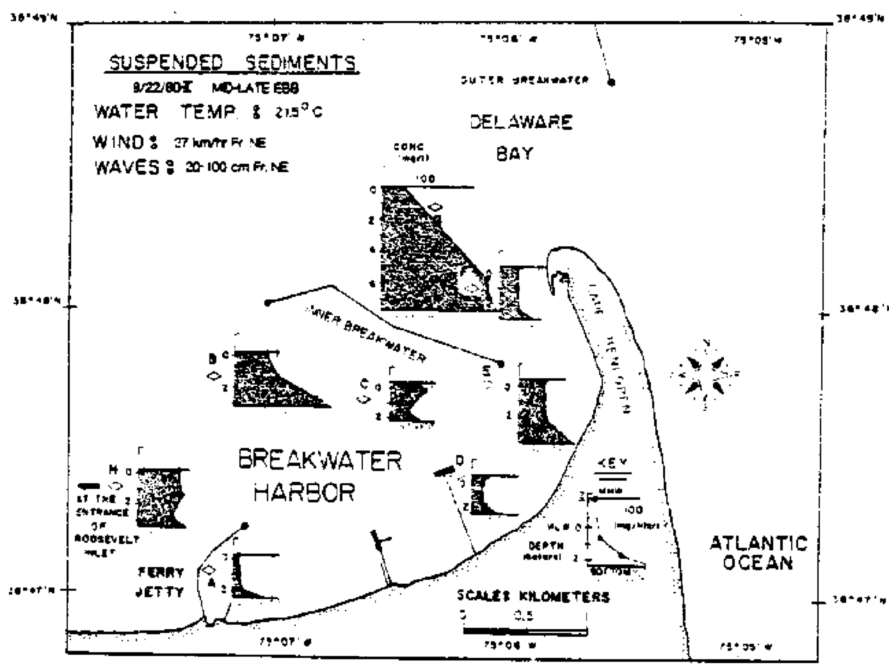


FIGURE IV-16. Plot of suspended sediments on 8/22/80-II, during a northeast storm. Zero depth corresponds to mean low water.

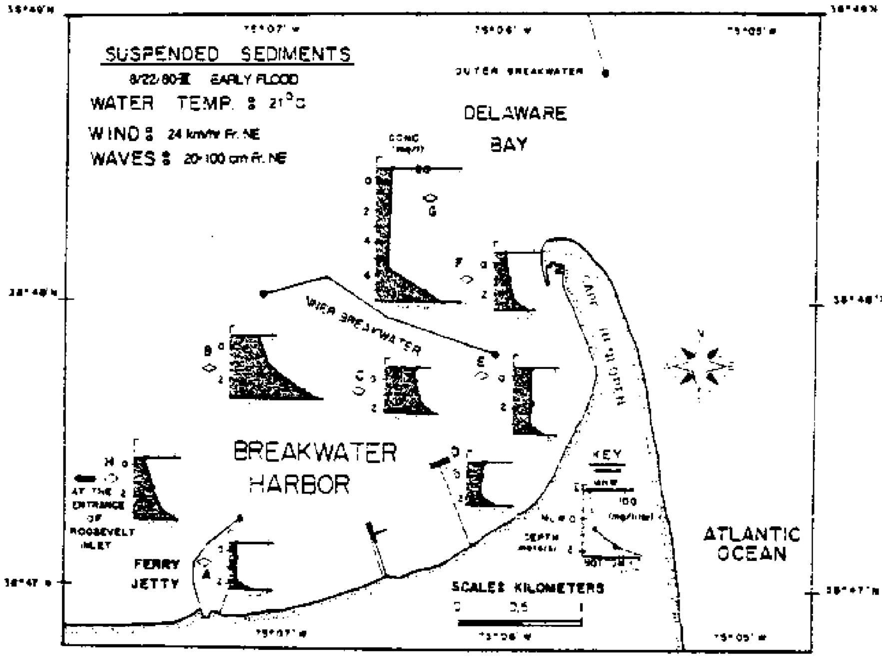


FIGURE IV-17. Plot of suspended sediments on 8/22/80-III, during a northeast storm.

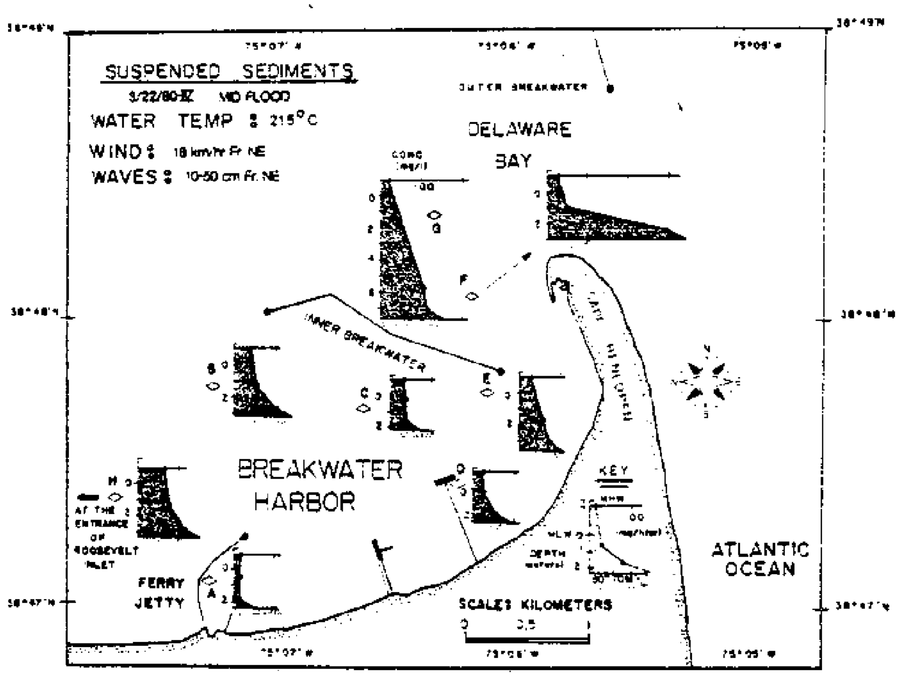


FIGURE IV-18. Plot of suspended sediments on 8/22/80-IV, during a northeast storm. Zero depth corresponds to mean low water.

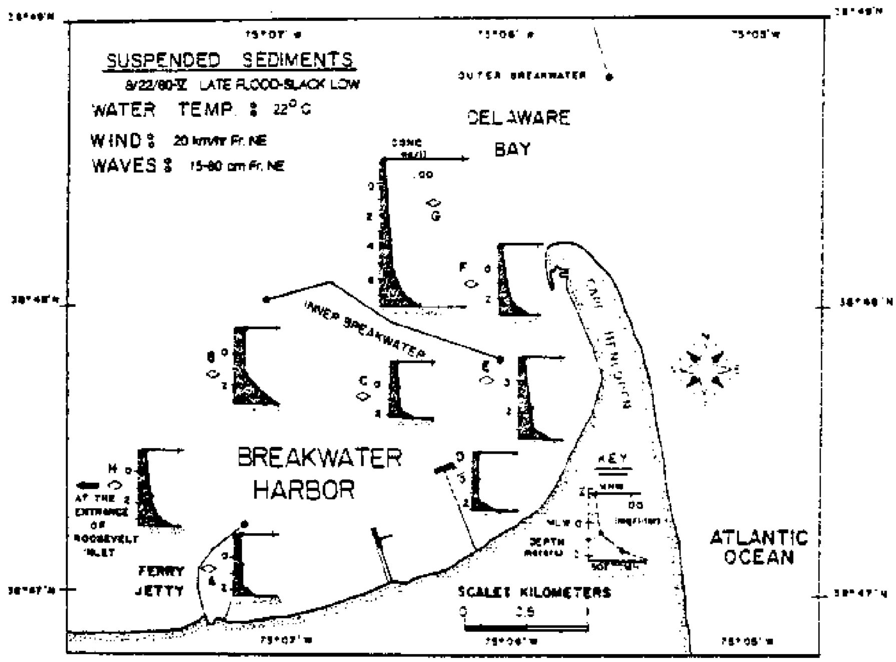


FIGURE IV-19. Plot of suspended sediments on 8/22/80-V, during a northeast storm. Zero depth corresponds to mean low water.

less than 10 mg/l. (Samples were taken from these two stations and a third station off the mouth of Delaware Bay for purposes of comparison with surrounding areas of Delaware Bay.) This information suggests that at least some sediments are resuspended from the harbor bottom and transported out of the harbor during ebb tide. Also, a plume of sediment-rich drainage water from the marsh can be seen coming out of Roosevelt Inlet (Station H). Clearly, much of the suspended matter is being transported into Breakwater Harbor from turbid waters of Delaware Bay.

In contrast with ebb tide, concentrations of suspended sediments on flood tide (Figure IV-8) are much lower in the harbor, about 5 to 30 mg/l. Stations G and F are exceptions: large volumes of sediment are suspended by the flood-tide eddies as they flow into Delaware Bay past Cape Henlopen. The low concentrations of suspended sediments in the harbor may be due partly to the cleaner flood-tide waters, but they are more likely a function of the low current velocities, which allow sediments to settle out of the water column. Thus, during ebb tide, fine-grained sediments are transported through the harbor, and during flood tide and slack water, most sediments settle to the bottom. The preservation and vertical accumulation of these sediments will be discussed in detail in Chapter VII.

<u>Resuspension of Bottom Sediment by Boats</u>. In general, data presented for the remainder of the sampling dates support the above observations. However, one major artificial factor was found to dominate the natural processes of sediment suspension in Breakwater

Harbor: resuspension of tremendous volumes of sediment by passage of ferry boats. An example of this phenomenon is plotted in Figure IV-11; concentrations of almost 400 mg/l were found near the bottom in the prop-wash of the ferry one minute after its passage.

A detailed analysis of the problem showed that it was by no means a trivial factor. The ferry terminal harbor in the southwest corner of Breakwater Harbor originally was dredged in 1963 to depths of about 4.5 m (personal viewing of original maps). Since 1963, the harbor has been deepened an additional 1-5 meters. Most of this deepening apparently is due to scour by the propellers of the ferry boats; little or no dredging has been performed in the last decade. The depths adjacent to the ferry pier are in excess of 30 feet in some places, especially west of the pier. The ferrys pin themselves into the berths for vehicle loading and unloading by means of throttling up the engines to hold the vessel fast. This creates considerable scour on the bottom, as evidenced visually and by suspended sediment measurements. As the ferry passes through the channel just west of Breakwater Harbor, large volumes of silt are suspended all the way out the channel. From repeated measurements of concentration of sediment in this prop-wash, a value of about 300 mg/l was found to represent the average sediment concentration in the water column about one minute after passage of the ferry.

The volume of sediment suspended with each passage of the ferry can be calculated for the west Breakwater Harbor channel (channel location shown in Figure 3 of Introduction). The distance from the ferry berths to the western end of the inner breakwater is 1,220 meters. From observations of the sediment plume width at the surface and assumed larger width at the bottom, an average of 30 m is estimated. Finally, the average water depth in the channel is about 5 m, as taken from the 1975 U.S. Army Corps of Engineers' unpublished survey. Thus, the volume of water in which sediment is suspended by the ferry is about 183,000 m^3. This volume multiplied by 300 mg/l equals 5.5×10^7 kg. This converts to 56,342 metric tons. Compared with the upper limit of 327 metric tons per hour which settle out of the harbor naturally (presented earlier in this chapter), this is 172 times more sediment during every single pass of a ferry!

Therefore, each passage of the ferry boat suspends about 5.6×10^4 metric tons. Annually, the ferry passes through Breakwater Harbor about 4,000 times (personal communication, Lewes Ferry Terminal). This figure has remained about the same since the opening of the ferry line in 1964. Each year about 2.24×10^8 metric tons of sediment are suspended in Breakwater Harbor by the ferry. From 1964 to 1981, some 4.03×10^9 metric tons have been suspended. The fate of this material and its implications for future shoaling will be considered in predictions presented in Chapter XI.

Trap Repeatability. In order to demonstrate the repeatability of duplicate sequential samplings, two sets of duplicate samplings were collected on 4/29/80 (Figures IV-13, IV-14). If the trap were to reproduce exactly presumed constant concentrations (which may never exist), then the two sets of lines plotted at each station should coincide exactly. The fact that the lines generally overlap demonstrates the good reproducibility of these results.

A second purpose of the samplings on 4/29/80 was to sample an ebb tide and the successive flood tide. Although the flood tide concentrations are slightly lower, the differences are minor. This probably is due to the fact that mid-ebb and early-flood tide were sampled; perhaps the sediments had not had enough time to settle out. Another nagging possibility is that abberations frequently are created by the passage of the ferry boat, which causes major sediment plumes to be stirred up.

Storm Sampling. The final sampling program for this phase of the study was carried out on 8/22/80 in five successive data collections (Figures IV-15 to IV-19). A mild, northeast storm was underway, which did allow acquisition of information on storm suspensions. Concentrations were generally higher than non-storm values by about a factor of two. The storm intensity was approximately constant throughout the day, so differences in concentrations could be attributed to tidal effects. As earlier samplings had shown, concentrations on ebb tide were much higher than those on flood tide. Although one might jump to the conclusion that a storm which hits during ebb tide will result in a net export of suspended material, it should also be remembered that material suspended up Delaware Bay, perhaps in even greater volumes, will be imported into the area.

CHAPTER V

CAPE HENLOPEN DEPOSITIONAL ENVIRONMENTS

Introduction

Depositional environments on modern Cape Henlopen have been outlined generally by Halsey and Kraft (1971) and Kraft and others (1976, 1978). The internal sedimentary structures associated with depositional environments on the spit have been studied in detail by John (1977), Hoyt and others (1979) and Hoyt and Kraft (1980b). These earlier studies, the latter two associated with the present work, will be reviewed in this chapter. In addition, other observations since the time of my earlier work will be discussed.

Depositional Environments and Associated Sedimentary Structures

Auger drilling and coring of the Cape Henlopen spit have established that coarse sands and gravels recently have been building out into a 20 meter-deep tidal channel (Kraft, 1971a, b; Kraft and others, 1976, 1978). Cores R-4107 and R-4109 taken by Shell Development Co., Houston, Texas, were located on the spit tip and provide clear evidence that the spit overlies thinly interbedded and bioturbated estuarine sands and silts deposited earlier in the Holocene Epoch (Kraft and others, 1978). Sedimentary layers of sands and gravels are visible, often dipping at about 30°.

In the spit deposits above the mean low water line, different processes created the layering and in many cases, excellent sedimentary structures are preserved. Figure V-1 shows a vertical aerial photograph of Cape Henlopen which displays the great variety of surficial depositional environments. The sedimentary structures associated with these environments are sketched in Figure V-2 (from Hoyt and others, 1979). The Atlantic beach system, which we know to be accretionary (Chapter III), consists of many sets of subparallel laminations truncated by erosional events and underlain by depositional events. Many of these depositional phases are in the form of shore-parallel bars which periodically weld onto the cape. The spit-tip beach system is similar to the Atlantic beach except that a more vigorous wave and current regime with the resultant coarser sediment are found there. Incipient and mature dunes exist throughout the central areas of the cape and are characterized by thin beds of long, sweeping foresets. Incipient dunes form as the spit advances to the north and east. Incipient dunes form on the berm when marsh and dune grass debris (bearing seeds and roots) is buried slightly under the surface. This can foster a small dune, which can be built higher by winds blowing material from the northwest. Moody (1964) has pointed out that northeast storms do not create dunes, because rain commonly associated with these winds prevents sand from blowing. A variety of tidal flat environments exists, most of them characterized by a burrowed substrate overlain by migratory swash bars (discussed in Chapter III).

The last major depositional environment to be discussed is the

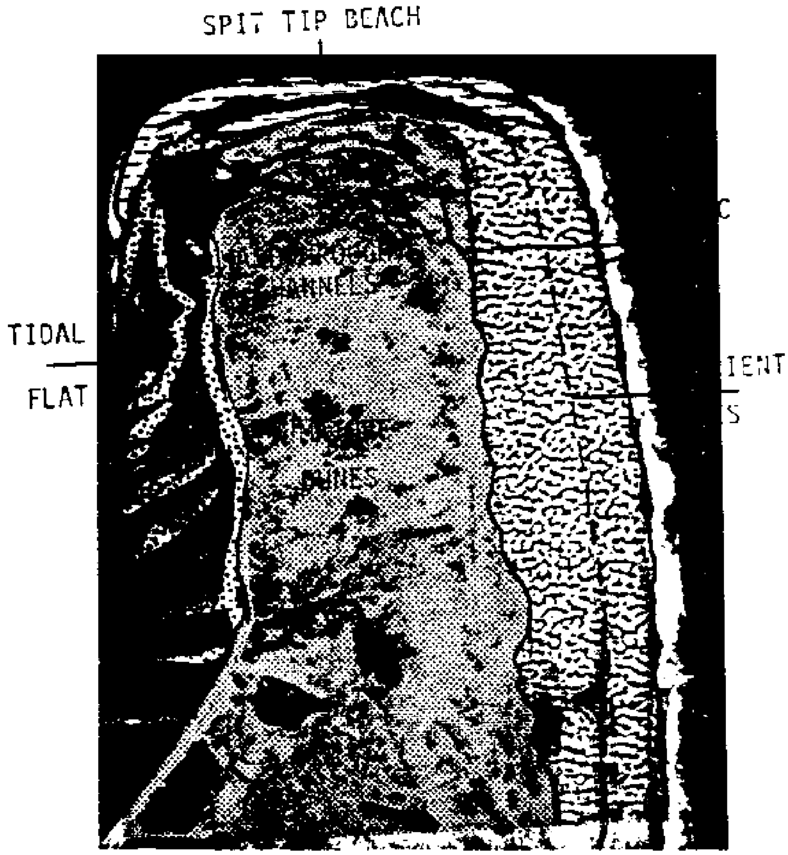


FIGURE V-1. Vertical aerial photograph of Cape Henlopen (1979) showing the variety of surficial depositional environments. For scale, the spit is about 500 m wide. After Hoyt and others, 1979.

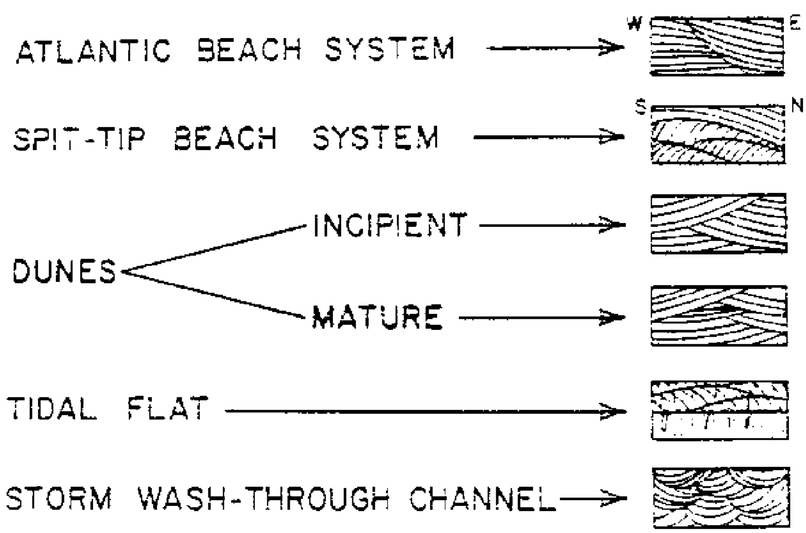


FIGURE V-2. Cape Henlopen surficial depositional environments and associated sedimentary structures (after Hoyt and others, 1979).

storm wash-through channels and associated festoon cross-bedding. These features had not been described previously in the literature for this or any other spit until they were described by Hoyt and others (1979). Festoon cross-beds are deposited by a uni-directional current and typically are associated with rivers. These sedimentary structures, if found in an ancient rock, would suggest a fluvial depositional environment. One of the purposes of the work of Hoyt and others (1979) was to point out that festoon cross-beds can be associated with spits. Festoon cross-beds are formed on Cape Henlopen in the following manner. During northeast storms, water flows from the back-berm runnel toward lower elevations in the north. Since the west side of the spit is lower than the east side, the water tends to flow from east to west across the spit. The water flows into one or two active wash-through channels which terminate in the northwest area of the spit in delta lobes. In one recently active channel, the gradient is down to the northwest (1:1320); the change in elevation from the Atlantic berm to the western storm delta area of the channel is 0.9 m (Hoyt and others, 1979). After passage of a storm, the surface of the channel contains irregularly spaced megaripples up to 50 cm high and 1-5 m long.

In the winter of 1979-80, the western end of the active channel (marked C in Figure V-3) was closed off by a dune which migrated in from the northwest. The channel no longer actively passes large volumes of water from east to west during storms. This pattern of development has been repeated many times in the past, as can be seen in Figure V-3. It appears that the older channels (marked A, B, and C)

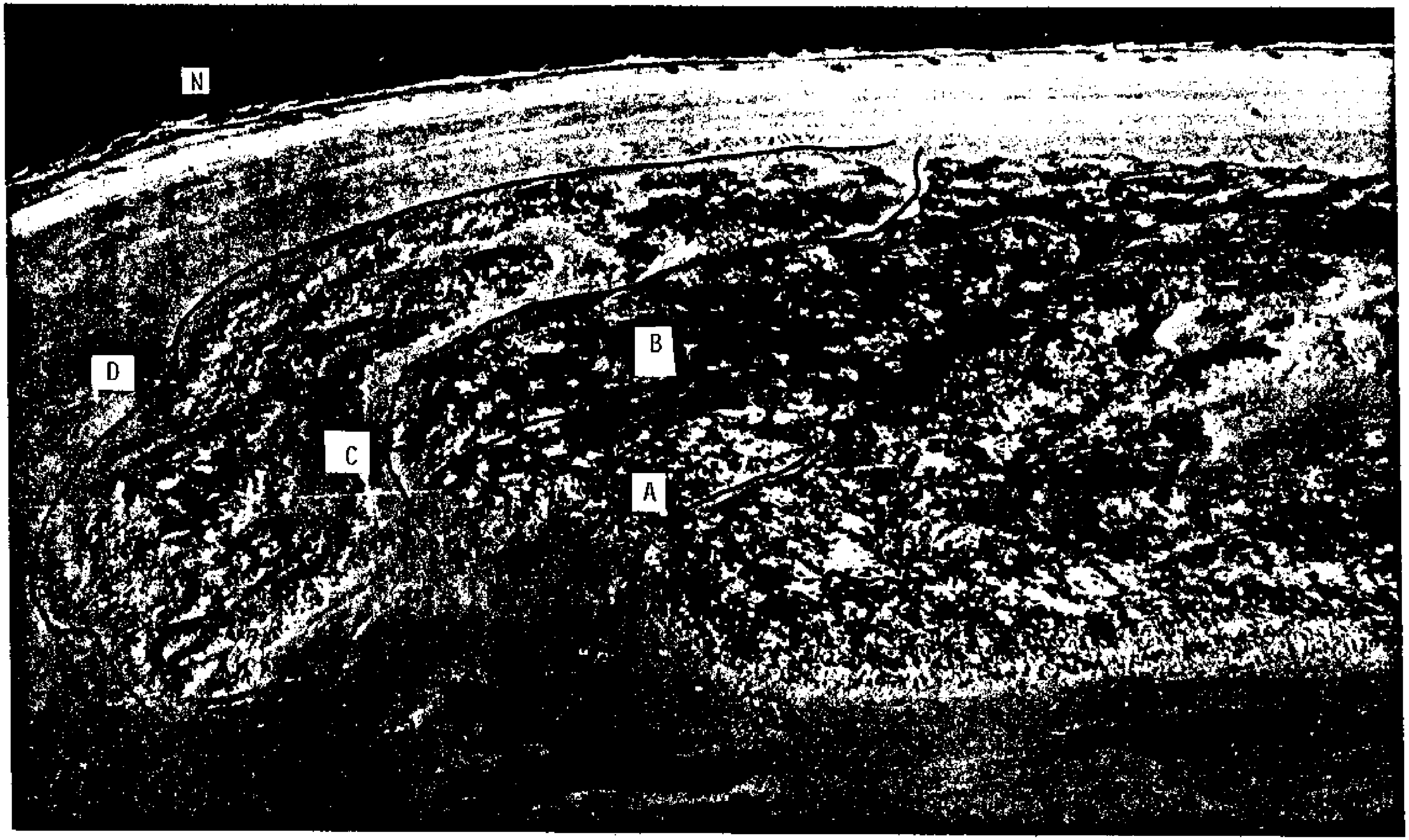


FIGURE V-3. Oblique aerial photograph of Cape Henlopen showing locations of storm wash-through channels. Channel A is the oldest one identified and D is presently active. For scale, spit is about 500 m across.

formed in the same way as the presently active one (marked D): ponded water during storms excavated its own channel in the back-berm runnel. According to recent growth trends of Cape Henlopen (Chapter X), wash-through channel C was formed at the site of a back-berm runnel in the early 1960's. Channels A and B probably formed in the 1940's and 1950's.

Shallow Cape Henlopen Cross-Sections

Based on drilling records, extensive trenching, and the preceding discussion, schematic cross-sections to a depth of about one meter below mean low water were constructed by Hoyt and others (1979). Figure V-4A shows a spit cross-section from south to north. Note that some storm channels have been overrun by dunes and buried. An east-west spit cross-section is shown in Figure V-4B. The accretionary character of the Atlantic beach is also displayed and the crossing of a storm wash-through channel is noted.

The application of these results to future growth of Cape Henlopen will be discussed in Chapter X.

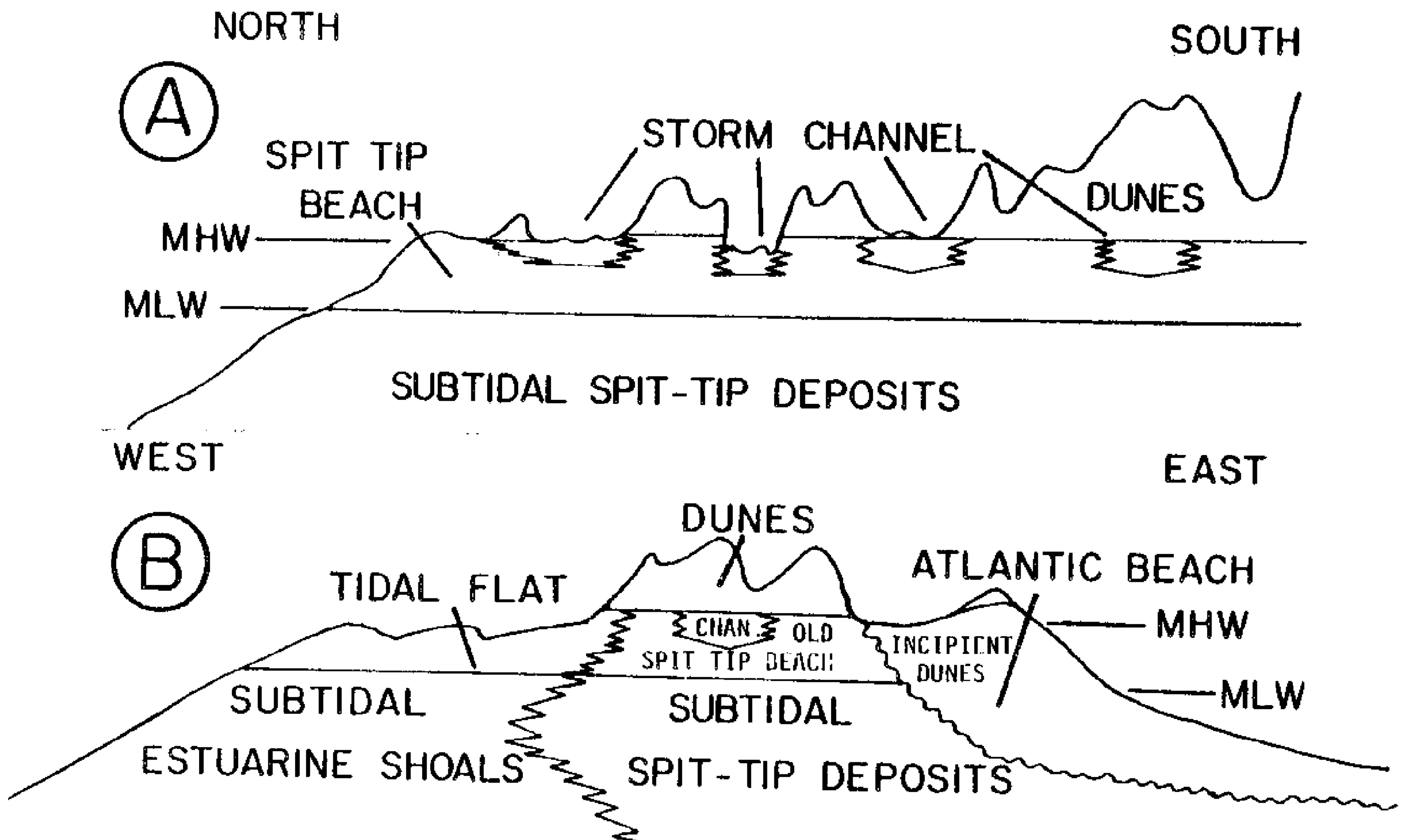


FIGURE V-4. Shallow, schematic cross sections of Cape Henlopen. Section A runs south to north and B runs east to west. Vertical scale is indicated by the tidal range of 1.4 m and the horizontal scale is indicated by the 500 m width of the spit in an east-west direction. Modified from Hoyt and others (1979).

PART TWO

GEOLOGIC HISTORY OF THE AREA

CHAPTER VI

BOTTOM SEDIMENT CHARACTER

Introduction

Bottom sediment characteristics such as grain size, mineralogy, and bedform will be considered not only for offshore of Cape Henlopen, but also for Breakwater Harbor.

Breakwater Harbor Bottom Sediment

Based on 35 bottom sediment samples collected with an anchor dredge, Demarest (1978) constructed an excellent map of bottom sediment grain size. Figure VI-1 is this map showing the bottom sediment verbal classifications (according to Folk, 1954) of the grain size data presented by Demarest (1978, his Figure 10). A very narrow zone of transition exists between sandy, nearshore sediments and silty, deep harbor sediments. This line approximately corresponds to the 1.8 m contour. However, some sands and gravels are also known to exist in the deep scour hole east of the inner breakwater (SCUBA diving observations). The muddy sediments found in this area have as their main component relict estuarine silts which have been eroded as the hole has deepened.

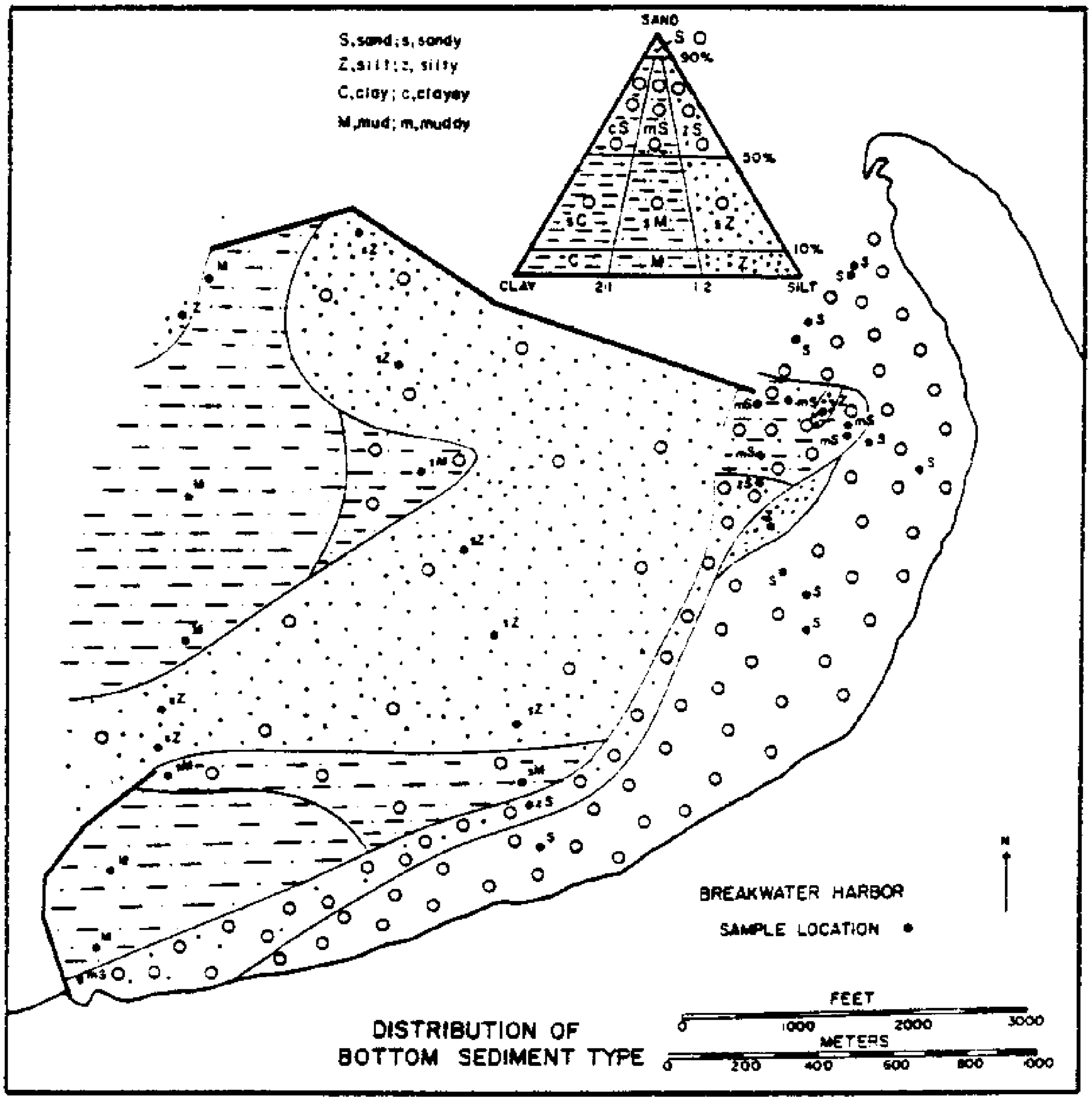


FIGURE VI-1. Bottom sediment types in Breakwater Harbor (from Demarest, 1978). The key to the patterns used is presented in a ternary diagram with end members sand, silt, and clay (from Folk, 1954).

Selected sediment samples used by Demarest (1978) from Breakwater Harbor were analyzed by x-ray diffraction for their silt and clay mineralogy. The locations of these samples are shown in Figure VI-2 and the minerals found in these sediments (quartz, feldspar, chlorite, and illite) are recorded in Appendix F. These minerals are similar in assemblage to suspended sediments from Breakwater Harbor (Chapter IV, Appendix F), as well as for subbottom sediments from Breakwater Harbor (Chapter VII, Appendix F). This assemblage is also similar to that found in coastal waters along the east coast of the United States (Griffin and others, 1968).

In order to double-check the validity of Demarest's (1978) bottom sediment map, and in order to construct a more accurate mud/sand interface line in the harbor (for purposes of choosing core sites), another sampling of bottom sediments was undertaken in August of 1978. Instead of an anchor dredge, which collects a sample from a wide area, a small, 10 cm-long core sampler was used to obtain a more precise spot-location sample. Samples of sediment were analyzed for percentages of sand, silt, and clay according to methods outlined in Appendix J. Figure VI-3 shows locations and Appendix G records grain-size data. These data generally agree with those of Demarest (1978), except that the mud/sand interface line should be drawn more landward in some localities.

Maurer and others (1974) and Kinner and others (1974) have studied benthic invertebrates in the area and report some additional

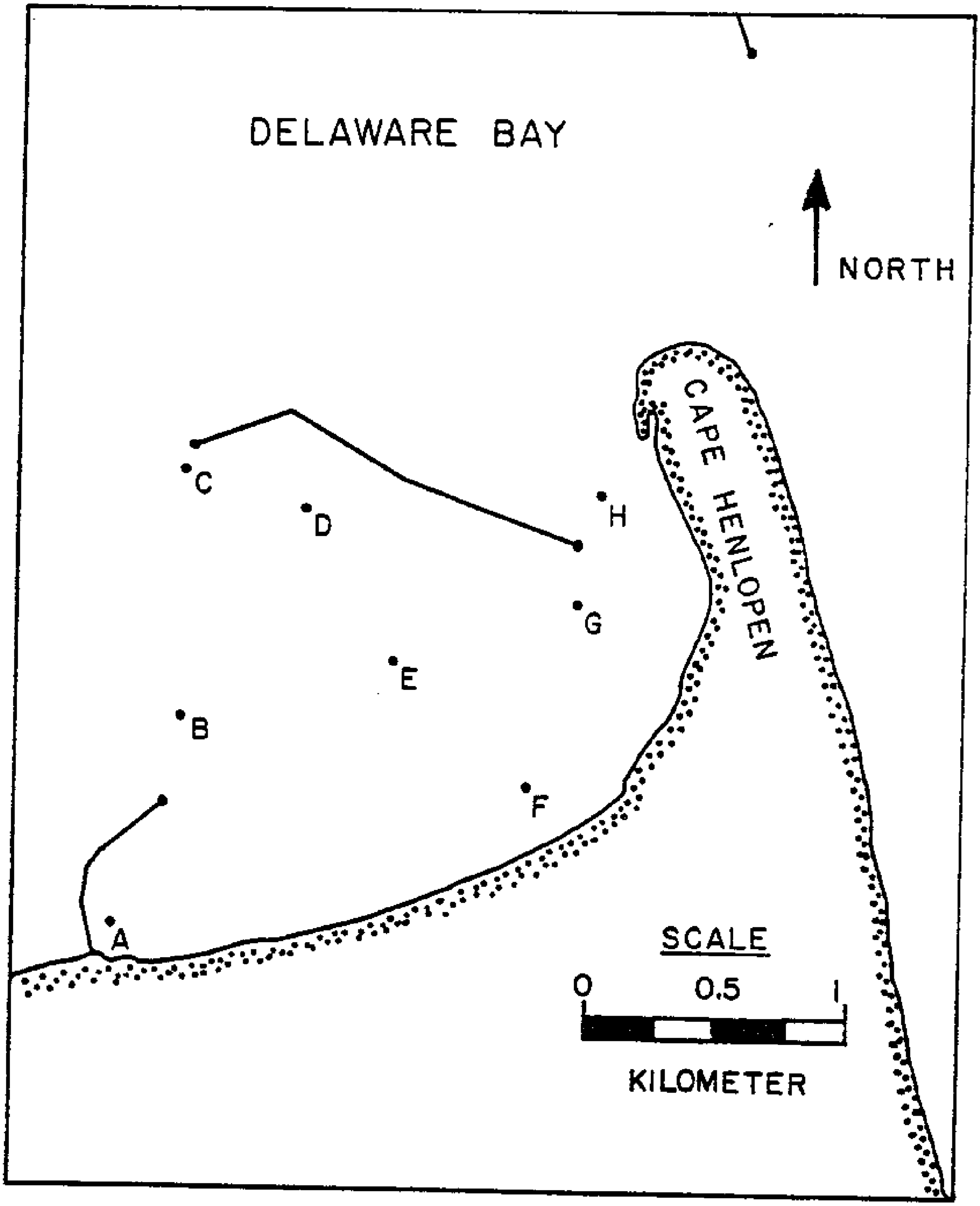


FIGURE VI-2. Location of samples from which x-ray diffraction of clays and silts was determined.

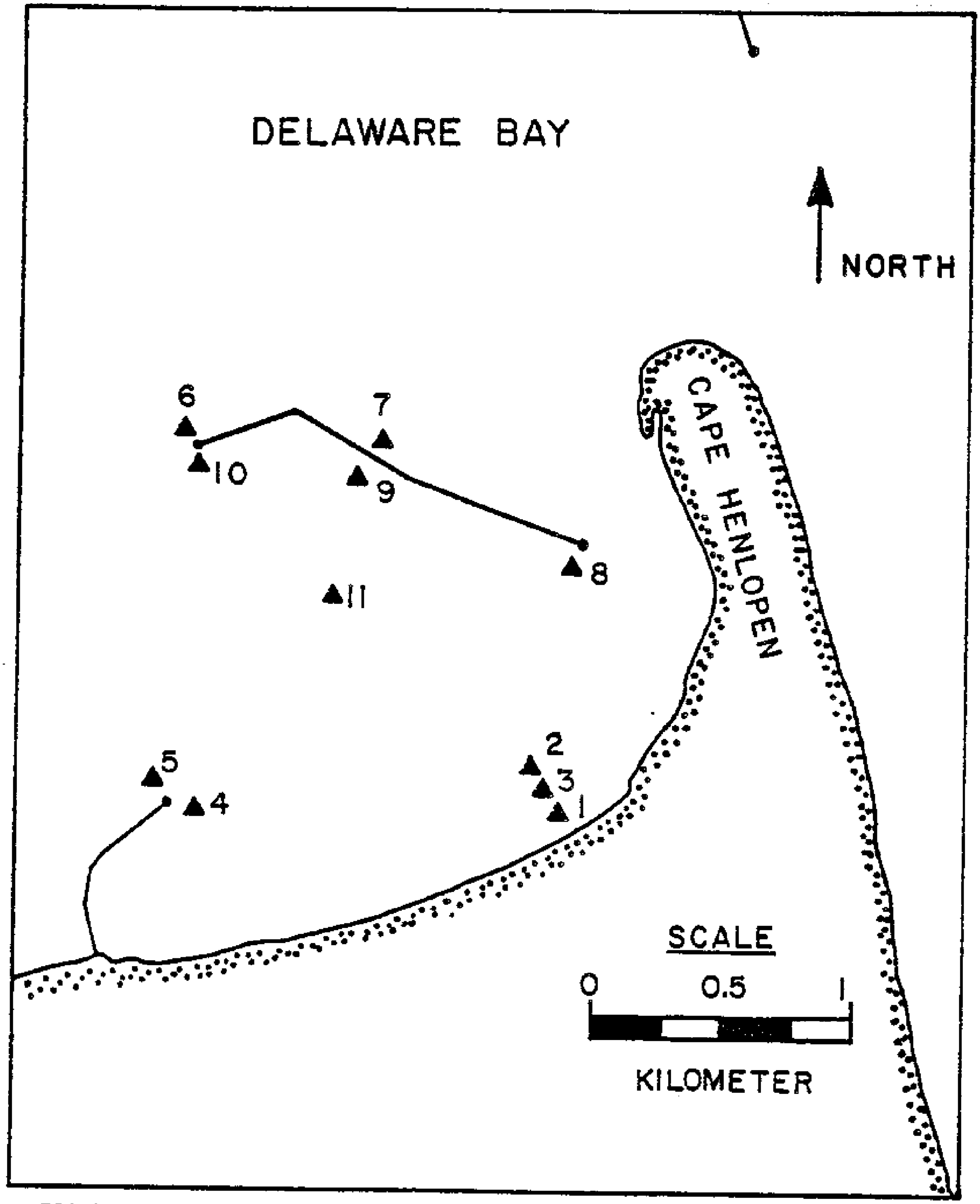


FIGURE VI-3. Location of selected bottom sediment samples for which grain size analyses were performed. Some of these samples helped determine the mud/sand interface between sands of Cape Henlopen shorelines and muds of Breakwater Harbor.

background information on sediment grain sizes in the surrounding area.

Bottom Sediment Character Offshore of Cape Henlopen

Grain-size data and a preliminary bottom sediment map from Demarest (unpublished data) were used to construct a more detailed map. I added information from samples I took so that the area covered by the map would be larger (Figure VI-4). A total of 20 samples was analyzed. Grain sizes and sorting of these samples are presented in Appendix H and are also shown in Figure VI-4. Based on these grain-size data and on seismic profiles presented in Chapter IX, approximate zones of sediment type were drawn. These zones generally parallel the directions of tidal currents in and out of Delaware Bay, and they consist of silts to gravels with intermediate grain sizes of various mixtures. This map is highly idealized, but the general notion of sediment zones paralleling the tidal currents is supported by seismic profiles. These samples were analyzed by means of the sieve-shaking technique and the pipetting of silts and clays described in Appendix J.

Geomorphic Features of the Sea Floor

Grain-size information and detailed seismic profiles of the region offshore of Cape Henlopen and in the Harbor of Refuge (Chapter IX) allowed construction of a map showing geomorphic features of the sea floor (Figure VI-5). Zones of flood-oriented sand waves and ebb-oriented sand waves were found on seismic profiles. This lends credence to the idea proposed by Moody (1964); he suggested flood channels were separate from ebb channels.

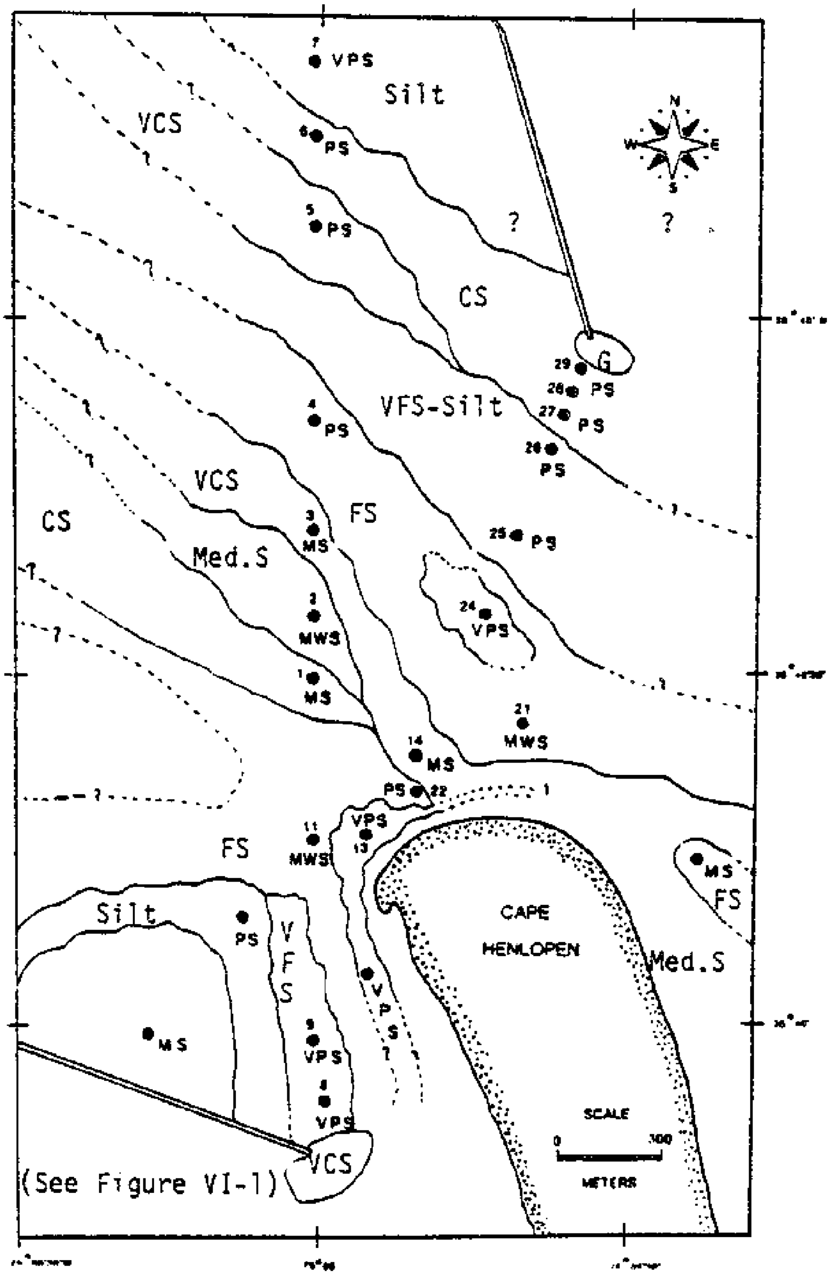


FIGURE VI-4. Bottom sediment grain size and sorting trends offshore of Cape Henlopen and in the Harbor of Refuge. The larger letters refer to grain sizes and the smaller letters refer to sorting indexes as follows: G=gravel, VCS=very coarse sand, CS=coarse sand, Med. S= medium sand, FS=fine sand, VFS=very fine sand; VPS=very poorly sorted, PS= poorly sorted, MS=moderately sorted, MWS=moderately well sorted. Grain sizes in Breakwater Harbor are displayed in Figure VI-1.

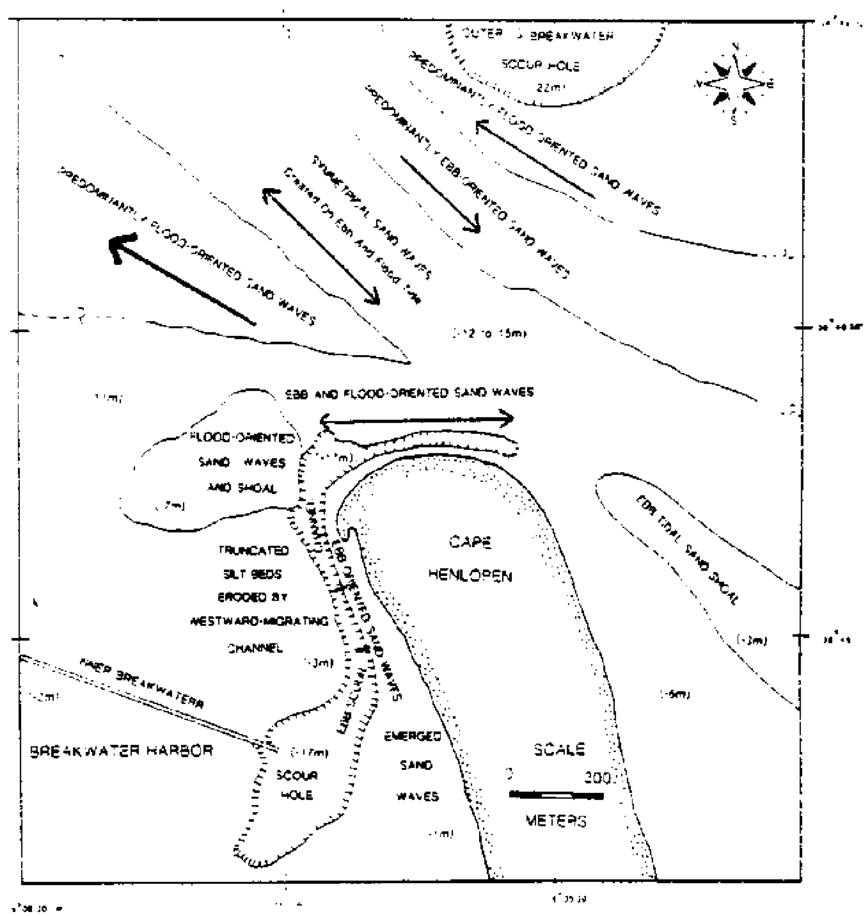


FIGURE VI-5. Geomorphic features of the sea floor off Cape Henlopen and in the Harbor of Refuge. Data from seismic profiles (Chapter IX) helped in constructing this map.

On the west side of Cape Henlopen, at a depth of -1.0 m to -6.0 m, ebb-oriented sand waves are found. According to the work of Boothroyd and Hubbard (1975) on the genesis of bedforms in mesotidal estuaries, this type of sand wave is formed by flow in the upper part of the lower flow regime. This inference is supported by current measurements in the region (Chapter I, current meter station 6). Ebb current velocities at this locality normally reach 65 cm/sec.

Based on bathymetric and seismic reflection records presented in Chapter IX, there are several deep depressions and channels surrounding the north and west side of Cape Henlopen. The tidal current velocities measured in these areas (presented in Chapter I) demonstrate that non-deposition and scouring would be occurring. Indeed, sediment samples from the scoured areas (e.g., 13 in Figure VI-4) consist of either relict sediments which are being eroded or lag deposits of coarse material.

An ebb-tidal shoal (Hen and Chickens Shoal) has long been associated with the spit. More recently, however, a noticeable flood-tidal shoal has begun to build up to the west of the spit tip (Demarest, 1978). This tidal shoal on the north side of the inner breakwater consists of silt in the area immediately adjacent to the breakwater and becomes gradually sandier to the north. The future implications of these trends will be discussed in Chapters X and XI.

CHAPTER VII

SUBSURFACE INFORMATION BASED ON VIBRACORES

Introduction

Although detailed subsurface analyses of Cape Henlopen, surrounding areas of Delaware Bay, and the Atlantic Coast have been undertaken (Kraft, 1971b; Sheridan and others, 1974; Kraft and others, 1976; John, 1977; Maley, 1981; and Marx, 1981), no such detailed coring analysis for Breakwater Harbor has been carried out. Before undertaking this study, there was no coring system available in this country or abroad which could take cores inexpensively in the shallow depths of Breakwater Harbor through the entire Holocene section. Therefore, a land-based vibracoring system was adapted to perform a similar function offshore using a shallow-draft barge.

A total of 26 vibracores was collected in Breakwater Harbor and the surrounding area. Analyses of these sediments included grain-size determinations, volatile solids determinations, x-ray diffraction of clays and silts, and x-radiographs of core sections.

Discussion of data from the vibracores includes methods of dating and the relationship of these data to the history of sea-level rise in Delaware Bay. Although sedimentation rates in Breakwater

Harbor are discussed, analyses of future shoaling patterns in Breakwater Harbor are reserved for Chapter XI.

Development of Shallow Marine Vibracoring

In the spring of 1978, I was asked to travel to the University of South Florida and the University of South Carolina in order to evaluate coring technologies which might be employed in the University of Delaware's Department of Geology coastal program. I recommended purchase of a vibracoring system which was later described by Lanesky and others (1979). The system built at the University of Delaware employed a 5 h.p. cement vibrator attached to 40 feet (12 m) of aluminum irrigation pipe, which is three inches in diameter (7.6 cm). The low-amplitude standing wave set up in the pipe (0.1-1.0 mm) acts to liquify the sediment within about 2 mm of the pipe wall. The pipe often will descend under its own weight without the necessity of adding more weight. At 3,600 r.p.m. engine speed, the vibrator head turns at 10,000 r.p.m. with a centrifugal force of about 80 kg. Recovery of the cores by hand winches or electric winches yields a core encased in an aluminum pipe. The pipe then can be sawed open and split to reveal a 2.9 inch- (7.4 cm-) diameter core with undisturbed sedimentary structures.

In order to obtain vibracores in areas of Breakwater Harbor deeper than about one meter, it was necessary to adapt the coring operation to a shallow-draft, twin-pontoon barge of the Department of Geology (R/V PHRYNE). Outfitting was completed by August of 1978, and the 26 vibracores were taken in September and October of that year.

The vessel is shown in use in Figure VII-1. It was used to take cores in water depths ranging from 0.5 m (1.5 ft) to 6.7 m (22 ft).

Instead of going into a detailed description of coring methods and procedures of core description, I would like the reader to refer to a detailed manual which covers methods of coastal vibracoring, procedures for core descriptions, as well as detailed instructions for coring from the R/V PHRYNE II, a new version of a twin-hulled barge owned by the Department of Geology (Hoyt and Demarest, 1981b). A shorter description of the barge is contained in Hoyt and Demarest (1981a).

Vibracore Locations and Descriptive Logs

The locations of the 26 vibracores collected for this study are indicated on Figure VII-2. Geologic cross-sections through these core sites are presented in the next chapter. Other core sites were attempted (e.g. Hen and Chickens Shoal, north tip of Cape Henlopen, channel west of Cape Henlopen, etc.), but recovery was thwarted by loss of sample and/or inability to core safely. The vast majority of desired core sites were occupied, however, and the locations, latitudes, longitudes, core lengths, water depths, elevations of core bases, approximate age of bases, and percent recovery for these cores are listed in Table VII-1. Cores collected in the nearshore sandy environments are generally less than 2 m in length, whereas those from central Breakwater Harbor are between 3 and 10.7 m long. The elevations of the core bases range from 1.1 m below mean low water in the shore zones to 13.1 m below mean low water in the south-central area of the harbor.

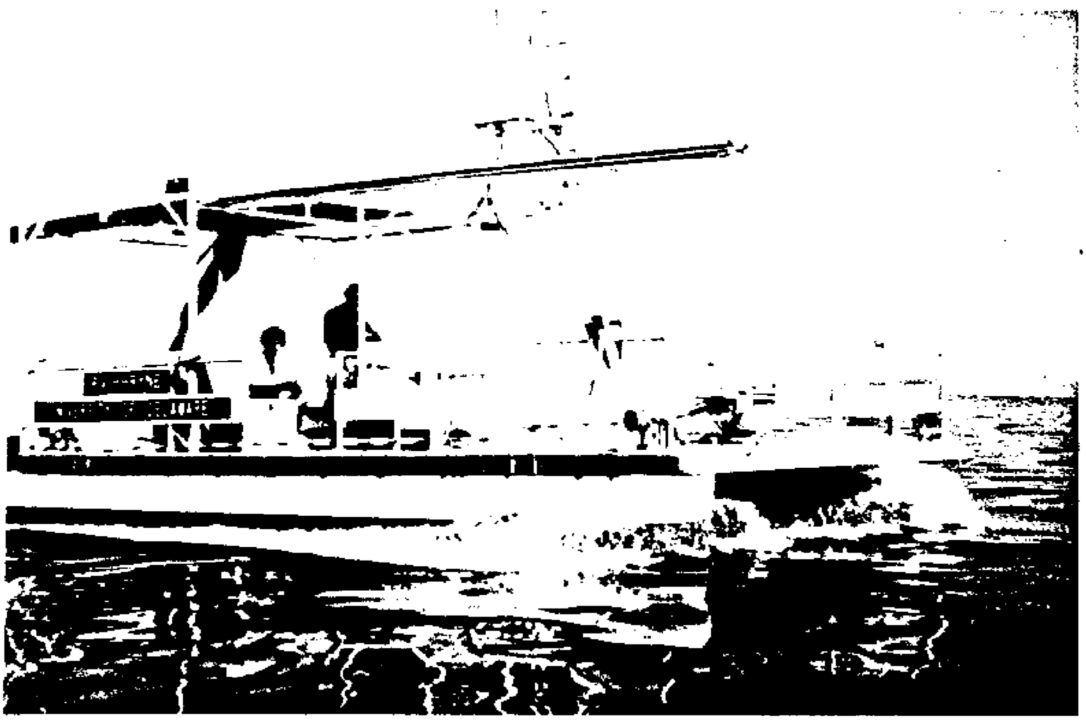


FIGURE VII-1. Photograph of R/V PHRYNE vibracoring barge underway.

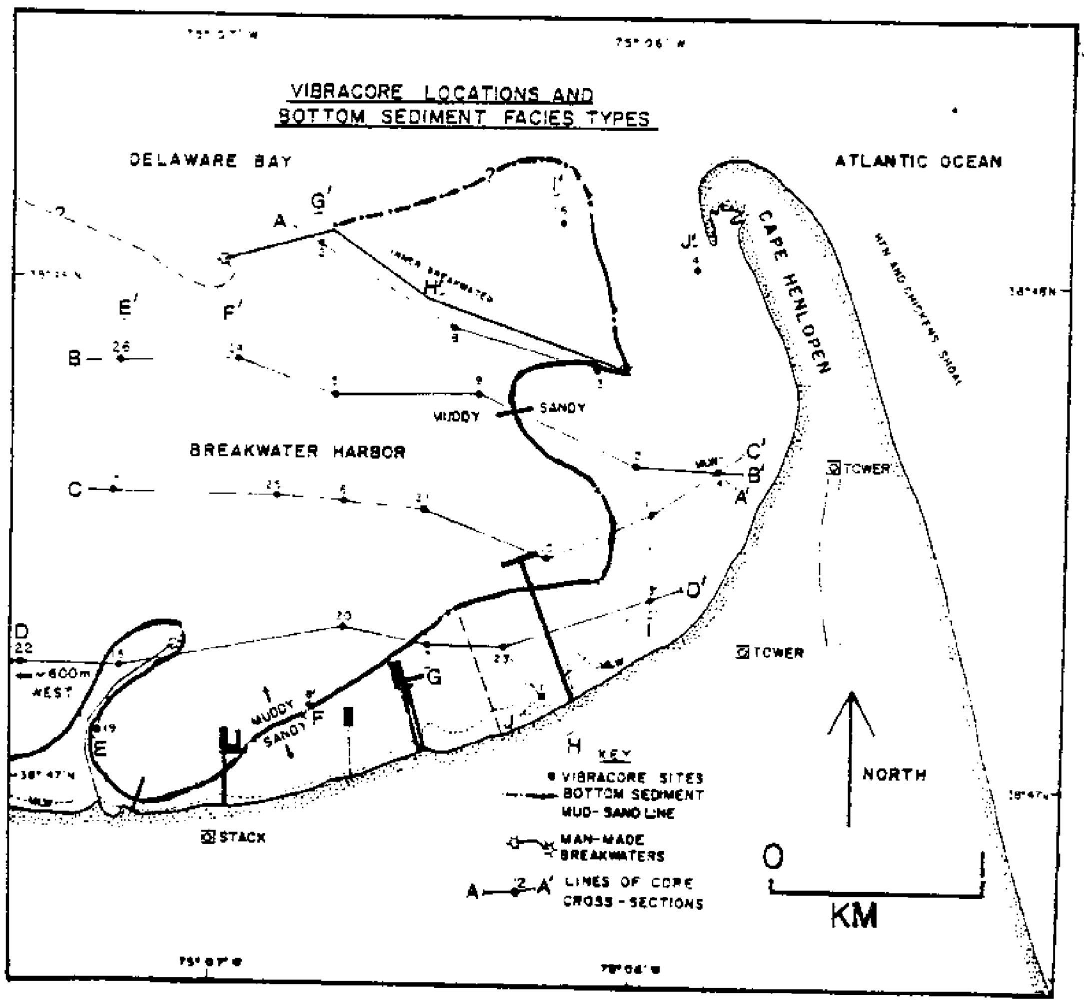


FIGURE VII-2. Vibracore locations and geologic cross-section lines. The line drawn with triangle annotations is the mud/sand interface.

TABLE VII-1. VIBRACORE DATA, BREAKWATER HARBOR (DATUM: MEAN LOW SEA LEVEL)

CORE #	LOCATION	LATITUDE (N)	LONGITUDE (W)	CORE LENGTH (m)	WATER DEPTH (m)	ELEVATION OF CORE BASE (m)	AGE OF BASE (YEARS B.P.)	RECOVERY (%)
WHH-BH-78-1	Southeast harbor shoreline, West of Army Pier	38°47'10"	75°06'11"	1.90	-0.2	- 2.10	~150	94
" " -2	Northwest harbor, near Westernmost Inner Breakwater dog leg	38°48'03"	75°06'45"	3.94	-1.2	- 5.14	~150	98
" " -3	Southeast harbor shoreline, East of Army Pier	38°27'25"	75°05'57"	2.00	0	- 2.00	~200	93
" " -4	Northwest tip of Cape Henlopen	38°48'02"	75°05'51"	1.15	-0.6	- 1.75	~30	58
" " -5	Central Harbor	38°47'45"	75°06'42"	5.10	-2.1	- 7.20	~150	80
" " -6	Central Harbor	38°47'33"	75°06'41"	8.50	-2.4	-10.90	~6,000	90
" " -7	South-central harbor	38°47'17"	75°06'28"	10.40	-2.7	-13.10	~10,000	98
" " -8	Northeast harbor, near easternmost dog leg	38°47'53"	75°06'27"	6.10	-2.1	- 8.20	~150	90
" " -9	Northeast harbor	38°47'43"	75°06'23"	6.40	-2.4	- 8.80	~150	94
" " -10	Southeast harbor, just east of Army Pier Tip	38°47'27"	75°06'12"	5.00	-2.1	- 7.10	~150	91
" " -11	Eastern harbor	38°47'32"	75°05'57"	3.70	-0.3	- 4.00	~150	88
" " -12	Eastern harbor	38°47'37"	75°05'59"	5.70	-3.3	- 9.00	~150	95
" " -13	Northeastern harbor, near eastern Inner Breakwater	38°47'49"	75°06'06"	5.10	-6.7	-11.80	~200	96
" " -14	Eastern harbor shoreline	38°47'38"	75°05'46"	1.30	+0.2	- 1.10	~100	60
" " -15	Northwest of Ferry Breakwater	36°47'12"	75°07'11"	3.00	-3.0	- 6.00	~50	50
" " -16	Northeast of Inner Breakwater	38°48'04"	75°06'08"	5.40	-3.3	- 8.70	~200	95
" " -17	West of Central harbor	38°47'34"	75°07'12"	6.00	-3.3	- 9.30	~10,000	90
" " -18	Southwest harbor	38°47'09"	75°06'45"	5.60	-2.7	- 8.30	~200	89
" " -19	Ferry harbor, adjacent to Ferry Breakwater	38°47'05"	75°07'14"	5.30	-3.3	- 8.60	~10,000	93
" " -20	Southwest harbor	38°47'12"	75°06'46"	6.70	-3.0	- 9.70	~200	89
" " -21	Central harbor	38°47'33"	75°06'31"	10.70	-2.4	-13.10	~10,000	91
" " -22	West of harbor, off Lewes Beach	38°47'05"	75°07'43"	5.10	-3.3	- 8.40	>12,000	85
" " -23	Southeast harbor, West of Army Pier	38°47'18"	75°06'16"	1.30	-0.9	- 2.20	~100	81
" " -24	Northwest harbor	38°47'49"	75°06'58"	7.50	-3.0	-10.50	~6,000	88
" " -25	Central harbor	38°47'33"	75°06'50"	6.70	-2.7	- 9.40	>12,000	92
" " -26	West of harbor	38°47'49"	75°07'10"	4.80	-3.6	- 8.40	>12,000	92

NOTE: The "Age of Base" is an approximation.

The average percent of recovery of all cores was about 87%, although this can be split into two distinct groups: sandy, nearshore cores recovered about 75% of the core length, whereas silty cores from the harbor showed about 95% recovery. Medium and coarse, well-sorted sands are hard to penetrate more than a couple of meters, and even then, they are very susceptible to plugging in the end (rodding) and/or sediment loss upon extraction.

Descriptive logs of each vibracore are presented in Appendix K. Interpretations of depositional environments for each core are also presented in Appendix K. Each core log is preceded by a page which shows the core's location and the key to the lithologic symbols used. The reader should familiarize himself/herself with the system used and the large amount of information presented in these descriptions. Special symbols indicate depths from which sediment samples were taken, and other symbols show areas which were x-radiographed. If the information contained in Appendix K is not detailed enough for your purposes, more detailed records can be obtained from the author or from the Department of Geology, core catalog, University of Delaware, Dr. J. C. Kraft, curator. An example of a core photograph (Vibracore 7) is contained in Hoyt and Kraft (1980b, Figure 13), but none is reproduced here. Munsell colors are listed on the vibracore descriptive logs, and the associated indexes are listed in Appendix L (Geological Society of America, 1975).

<u>Analyses Performed on Vibracore Sediment Samples</u>.

<u>Volatile Solids Determinations</u>. The percentages of volatile

solids lost in samples from vibracores was important in order to assess the organic composition of cores with time. This also allowed comparison with results from suspended sediment traps, bottom sediment traps, and bottom sediment samples collected with SCUBA. In general, the organic content, as reflected in volatile solids loss, decreases as one moves down through the water column and down the cores. These data are consistent with increased oxidation of organic materials with time. Table VII-2 summarizes these trends quantitatively.

TABLE VII-2.

VOLATILE SOLIDS OF SEVERAL TYPES OF SAMPLES FROM BREAKWATER HARBOR

SAMPLE/ENVIRONMENT TYPE	# OF SAMPLES	AGE (YEARS)	AVERAGE VOLATILE SOLIDS (%)
Suspended Sediment Traps	3	0	15
Near-Bottom Sediment Traps	7	0.7	11
Sediment-Water Interface	2	1	6
Recent Harbor Silts & Sands	3	100	10
Mid-Holocene Silts & Sands	6	5,000	2
Pre-Holocene Sands	5	12,000	1
Organic Mat/Detrital Marsh Grass	1	10	27
Coal Lamination in Core	1	128	24

Two highly volatile samples were found in: Vibracore 19 (organic mat), and Vibracore 7 (coal lamination). The organic mat (Figure VII-3) consists of detrital marsh grasses which were trapped behind the ferry jetty (breakwater) sometime after its construction in 1964. It is presumed that these detrital plant fragments became trapped behind the breakwater and then sank to the bottom. The coal lamination is located throughout the harbor area and probably represents the onset of coal-

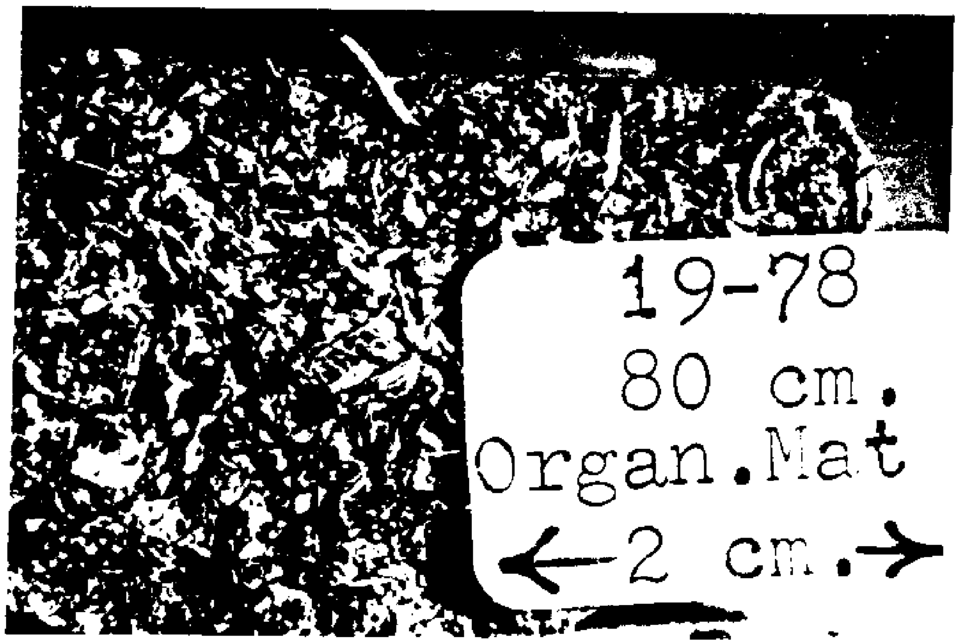


FIGURE VII-3. Salt marsh plant accumulation at Vibracore 19 east of the ferry breakwater.

fired steamships in the decade of the 1850's (See the following for a review of steamship history: Spears, 1915; Tyler, 1939; 1955; 1958).

X-Ray Diffraction of Clays and Silts. Mineralogies were determined for suspended clays and silts, for bottom sediment samples, and for vibracore samples in order to test whether mineralogy had changed with time and/or diagenesis (Appendix F). With one exception (Vibracore 22), no major mineralogical changes were observed; a minor increase in the relative abundance of quartz and feldspar down the cores was observed. It is likely that this down-core increase in quartz and feldspar clay and silt is simply due to the increase of sand-sized quartz and feldspar down the core. These sand grains are the source of the silt- and clay-sized particles. The sediments of Vibracore 22, which are very rich in kaolinite and quartz, lie below an emerged pre-Holocene soil horizon; the kaolinite probably is degraded feldspar because there is no longer any feldspar present. Quartz normally is associated with an appreciable quantity of feldspar in modern paralic and nearshore environments, as evidenced by the other samples in Appendix F.

The diffractometer used for each of the x-ray analyses is housed in the Department of Geology's Penny Hall in Newark. The following instrumental settings and components were used for the General Electric XRD-6: copper x-ray filament, scan speed of 2°/minute, 500 counts per second, 1.0 sec. time constant, 1.4 proportional counter setting, 128 gain setting, and on linear scale. The suspended sediment and harbor-bottom samples had the same settings as above, except that scan speed was 4°/minute.

X-Radiographs of Cores. Sixteen 30 cm sections of vibracores were cut and x-rayed in a Hewlett-Packard mobile unit to find internal sedimentary structures not visible to the naked eye. The exposure plate is extremely sensitive to variations in thickness and density of the sample, so it is difficult to reproduce a good positive image. Four photographs of particularly enlightening core sections are presented as Figures VII-4 to VII-7. Occasional sedimentary structures such as bed dips, bioturbations, and laminations were obvious in cores, but resolution of detail and clues as to origin were often not visible. Figure VII-4 from Vibracore 2 shows a typical 15-cm section of core from Breakwater Harbor. In this case, a massive, heavily bioturbated, upper segment (which contains shells) is about 10 cm thick. Underlying this are fine, convoluted but discrete, laminations; there are about 15 laminations to the centimeter (other cores display laminations up to 50 per centimeter). The upper zone of massive and bioturbated sediment in Figure VII-4 is sharply contrasted with the lower zone of finely laminated and non-bioturbated deposition. During repeated SCUBA dives to the harbor bottom in winter and summer, I noticed that there was abundant biologic activity on the bottom during the summer, but complete biological inactivity on the bottom during the winter. This suggested the possibility that I was looking at a seasonally controlled bioturbation of the sediments in sections such as that in Figure VII-4. Observations of abundant biologic activity during summer SCUBA dives

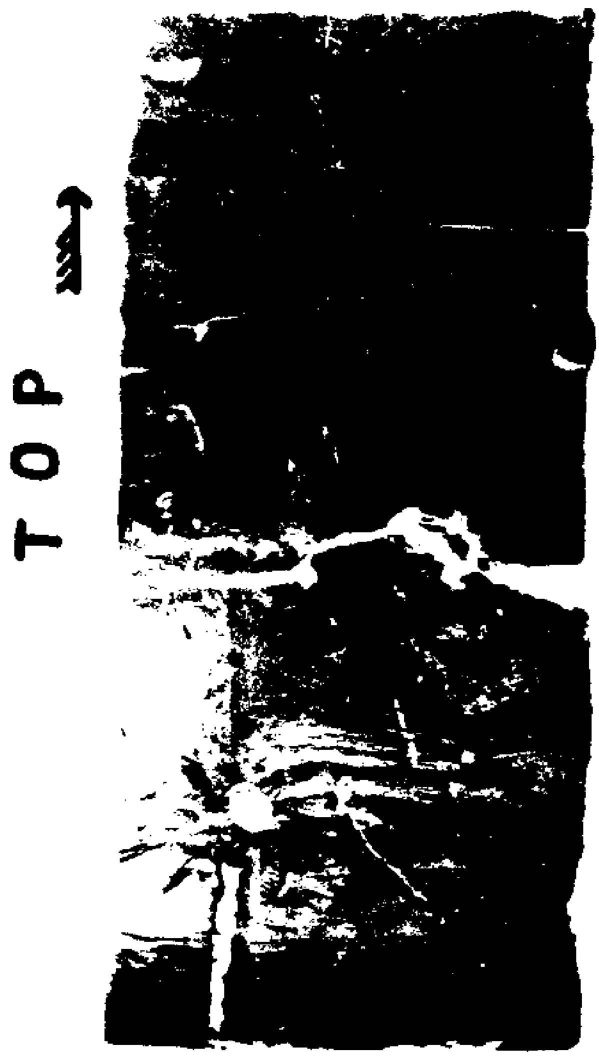


FIGURE VII-4. X-radiograph of Vibracore 2 (15-30 cm). Bioturbated zone above is contrasted with laminated zone below. X-radiographs are shown true scale.

FIGURE VII-5. X-radiograph of Vibracore 7 (370-385 cm on left and 385-400 cm on right). Contrast of bioturbated zones with laminated zones. X-radiographs are shown true scale.

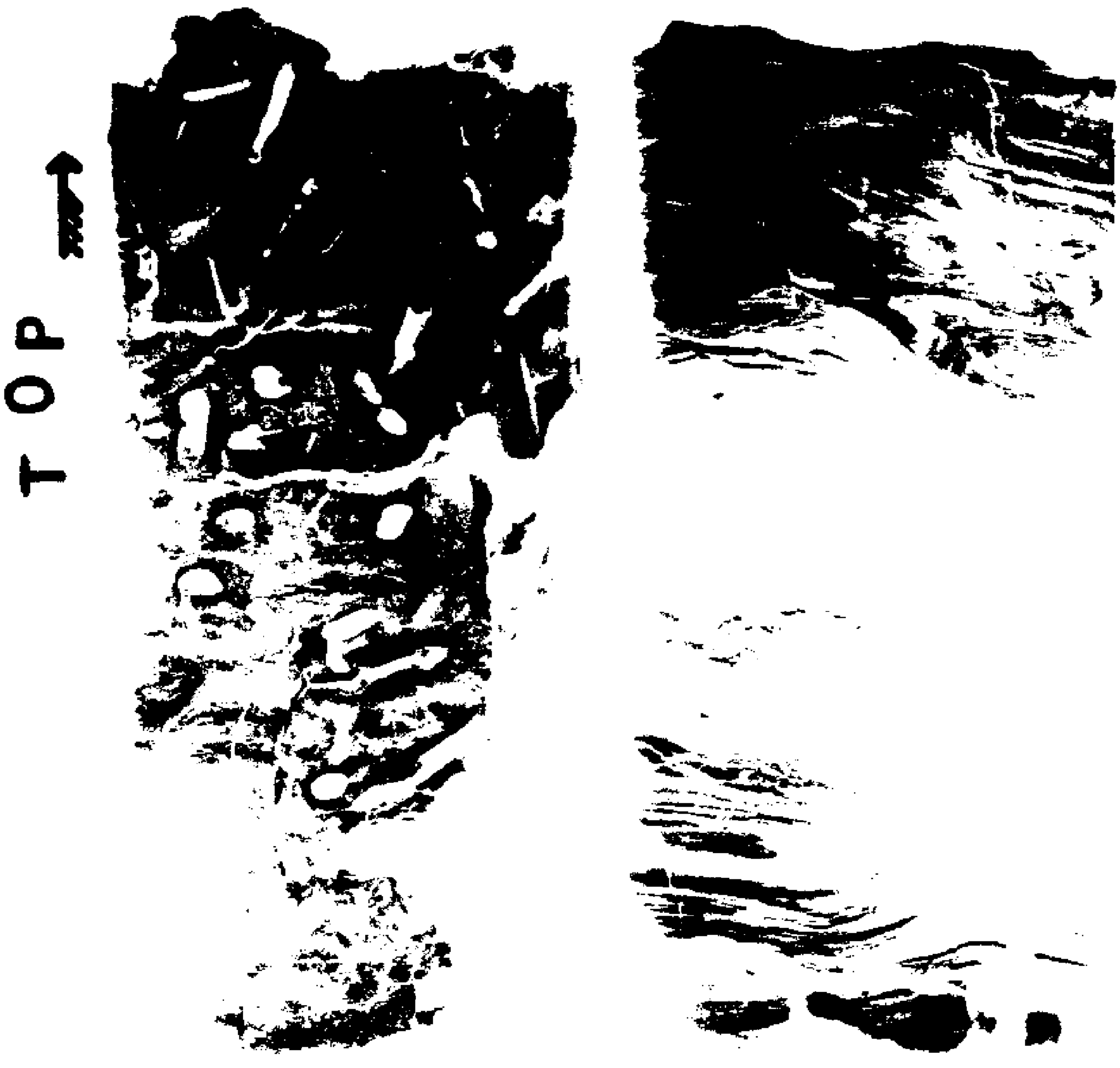


FIGURE VII-6. X-radiograph of Vibracore 8 (30-45 cm on left and 45-60 cm on right). Arcuate burrows visible on left, contorted laminations visible on right. X-radiographs are shown true scale.

FIGURE VII-7. X-radiograph of Vibracore 25 (490-505 cm on left and 505-520 cm on right). Both sections show massive structure typical of bioturbated muddy sands. X-radiographs are shown true scale.

contrasted sharply with the biological inactivity during cold, winter months.

Figures VII-5 (Vibracore 7) and VII-6 (Vibracore 8) both display variations on the winter-versus-summer depositional theme. The thicknesses of the summer and winter zones vary from about one centimeter to over 10 centimeters. Figure VII-6 shows the obvious contrast between the heavily burrowed sands and silts from 15-30 cm (left) and the finely laminated sands and silts from 30-45 cm (right). In a hand specimen, the holes looked like those created by gas bubbles. However, this x-radiograph demonstrates unmistakably that the holes were created by curving burrowers. Although several intermediate combinations of mixing between these two end-member types occur, it appears that most of the top contacts of the winter deposits are relatively abrupt. The bottom contacts of the winter deposits probably are created when winter storms bring in sand from the spit and these layers alternate with silt deposited in non-storm conditions (Hoyt and Kraft, 1980a). These contacts often appear to be erosional and irregular.

Figure VII-7 from Vibracore 25 shows a typical structureless deposit of muddy sand. Evidence of heavy burrowing exists in the abundant gastropod and bivalve fragments.

Models of proposed mechanisms of deposition in Breakwater Harbor are presented in Figure VII-8 and VII-9. The first of these two figures represents the relatively coarse-grained sedimentation (fine and medium sand) typical of vibracores from eastern Breakwater Harbor.

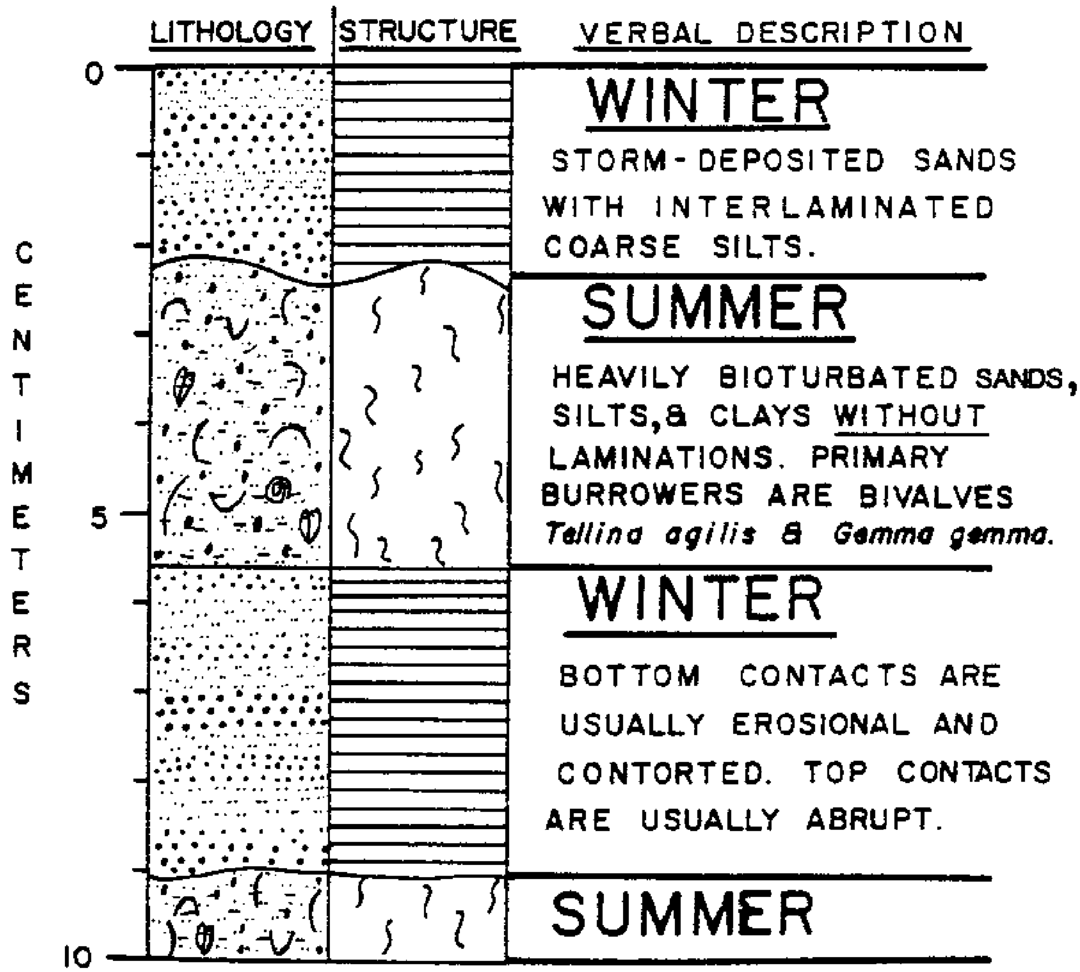


FIGURE VII-8. Model of Breakwater Harbor seasonal depositional mechanisms with associated lithologies and structures. This diagram is typical of areas in eastern Breakwater Harbor with the associated coarser grain sizes. Contrast with Figure VII-9.

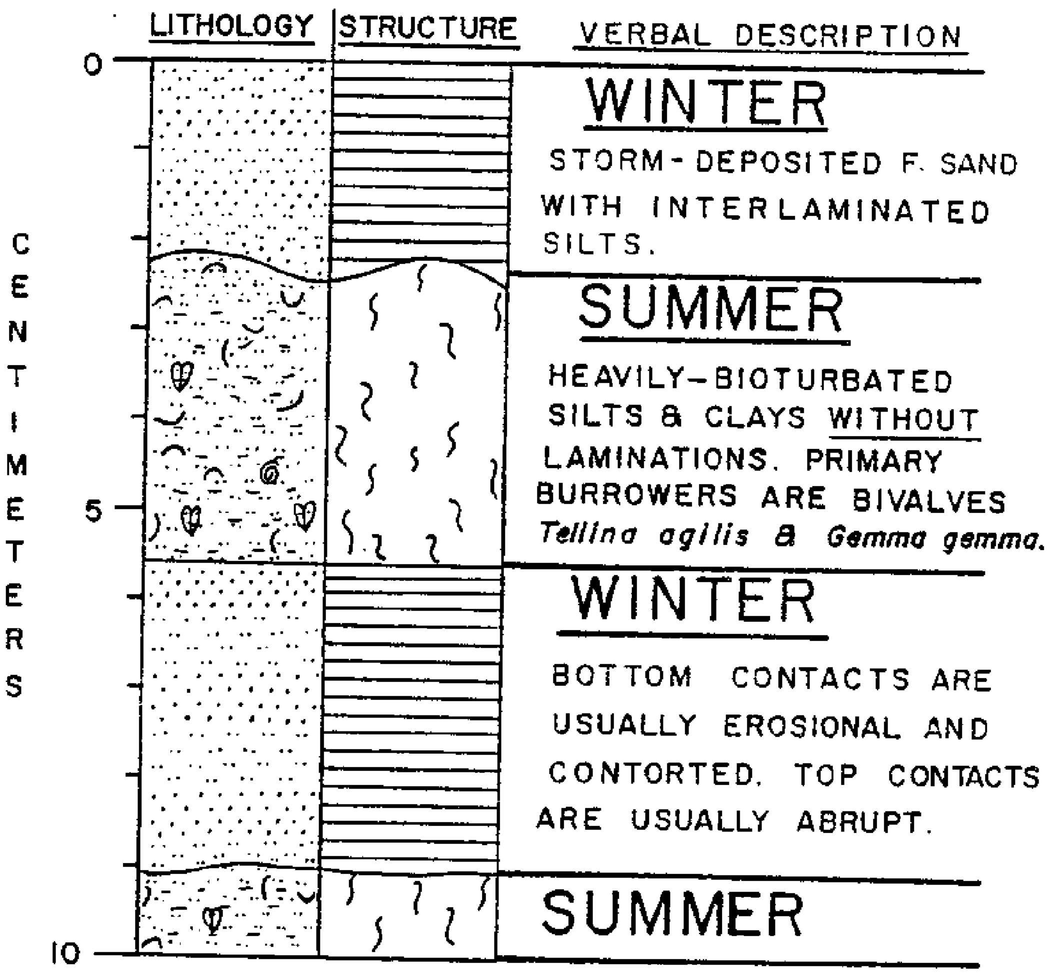


FIGURE VII-9. Model of Breakwater Harbor seasonal depositional mechanisms with associated lithologies and structures. This diagram is typical of areas in western Breakwater Harbor with the associated finer grain sizes. Contrast with Figure VII-8.

Also, this model represents patterns of sedimentation throughout Breakwater Harbor at a time prior to inner breakwater construction in 1831. Before the inner breakwater existed, strong flood and ebb currents transported sand into the study area. The second of these models (Figure VII-9) shows relatively fine-grained sedimentation (fine sand and silt) typical of vibracores from western Breakwater Harbor. The presence of the inner breakwater has prevented medium sand from Cape Henlopen from being transported into western Breakwater Harbor (Hoyt and Kraft, 1980a). The laminations drawn on these figures are not nearly as fine as in the cores. The frequency of laminations and the sedimentation rates presented later in this chapter suggest that the layers are added at the average rate of 2-4 per month, perhaps during neap-tide slack water and/or during the low current velocities of flood tide in the harbor. Of course, layers may be added more or less frequently than this depending on storm conditions or quiet periods. Also, not all winter and summer layers are preserved like the "ideal" one of Figure VII-4; some may have never been deposited, others may have been removed by erosion, and still others may have been bioturbated to great depths. Grain sizes during summer are coarser than those during winter, probably because borrowing organisms create faecal pellets (observed in "summer" units) which are larger than the silt and clay they ingest from the sediments (Haven and Morales-Alamo, 1968). Most of the faecal pellets observed in the cores of this study were medium sand sized.

Flora and Fauna From Vibracores. A list and brief description of all identified flora and fauna found in vibracores is included in Appendix M. These biological components are identified in Vibracore Descriptive Logs in Appendix K. Mollusks consisted of 11 different species of bivalves and four different species of gastropods. Rare Bryozoans and miscellaneous animal remains (fish teeth, crab claws, and faecal pellets) were present in a few cores. Cottonwood seeds, twigs, bark fragments, salt marsh plant mats, and pollen were the primary plant materials.

The most volumetrically abundant shells were those of *Gemma gemma* and *Tellina agilis*. Analyses of modern benthic bivalves also showed the dominance of these two species, in addition to *Nucula proxima* (Kinner and others, 1975). As many as 3,000 to 16,000 individuals of *T. agilis* have been reported in one square meter (R. Monihan, personal communication). The density of *G. gemma* is probably about twice that much, based on their density in the cores and their size.

Grain-Size Analysis Data From Vibracores. A total of 43 grain-size analyses was performed on samples from vibracores. Percent sand, silt, and clay, as well as sediment type according to the classification of Folk (1954), are listed in Appendix N. Sandy samples were analyzed with the Rapid Sediment Analyzer (R.S.A.), and the samples containing appreciable silt and clay were analyzed with the hydraulic-suction sieve system and pipetting (methods contained in Appendix J).

Although cores in the central areas of Breakwater Harbor are generally fining upwards, there are many exceptions to this. Usually only 2 cm of core were incorporated into each sample; even within these samples, vastly different grain sizes could be juxtaposed or mixed. Many of the cores displayed a wide range of grain sizes, such as the sandy muds, sandy silts, and muddy sands of Vibracore 7 from the central harbor. Other cores nearby (e.g. Vibracore 6) were more homogeneous, with each of the four samples being muddy sands.

The upper 1-2 m of most cores from the central area of the harbor visually appear to be finer than the zones immediately below: the core tops are often sandy silts (Vibracores 16, 19, 20, and 26) or muds (Vibracores 7 and 18). The central parts of the cores are most often muddy sands, and the basal sections of the cores are most often sands, although gravels are found frequently.

Discussion of Vibracores

In addition to the general trends noted above, several cores contain interesting features worthy of comment (locations in Figure VII-2). Toward the bottom of the cores, thick layers of *Gemma gemma* shell hash 60-70 cm thick are present in Vibracores 6, 7, 20, and 21 at approximately the same depth (9-9.7 m below mean low water). Many of these small clams were articulated and in their growth positions, suggesting that this layer of shells is not a lag deposit. Based on the age estimates of these cores (Table VII-1 and further information presented in Chapter VIII), it appears that a few thousand years ago, favorable conditions existed offshore of the ancestral Cape Henlopen in which this prolific community of small bivalves could thrive. Further up the cores, hiatuses to much younger sediments occur. In the vicinity of the eastern end of the inner breakwater, several vibracores (8, 9, and 13) contain blue mussels (Mytilus edulis) and bryozoans (Canopeum tenuis) which had attached to the rocky breakwater since its construction in 1831. Based on the first occurrence of coal from steamships, as well as presence of mussels and construction materials, these cores record very rapid shoaling in the period from 1850 to 1978; from 3.2 to 5.4 m of deposition has been added, which is considerably above the average sedimentation rate for the entire harbor (discussed in the next section).

In addition to the coal present in the 12 vibracores in the central harbor, frequent bark and wood fragments are located just below the coal. It is well known that log mats were used to provide berths for the inner breakwater construction (Snyder and Guss, 1974). Wood and bark fragments found in Breakwater Harbor sediments, therefore, reasonably can be ascribed an age of about 1830. It has been further proposed by Kraft and Caulk (1972) that the wood came from nearby shorelines and that this deforestation caused the initiation of the Great Dune at Lewes.

Vibracore 11 records the progradational nature of the Cape Henlopen spit. (In a stratigraphic sense, according to Walther's Law, this is a regressive marine feature.) Offshore estuarine sands and silts, in the bottom half of the core, are overlain by spit sands. The complex geometric relationships between the spit sands and the finer-grained harbor sediments will be discussed later in this chapter in the section entitled Geologic Cross-Sections.

The core site located just northwest of the ferry breakwater records conditions in the harbor prior to the 1964 ferry breakwater construction. Above this in the core, sandy foundation material for the breakwater and timber-mat base debris are found. Deposition of silt and fine sand began with relatively high sedimentation rates in the late 1960's and early 1970's. However, it appears that in the mid-to-late 1970's, a continuous flow of littoral drift (sand) moved around the north end of the ferry jetty (breakwater), aided in its movement by strong ebb-tidal currents. The core site on the east side of this breakwater (Vibracore 19), on the other hand, experienced much lower energy conditions. The ferry harbor area itself (exemplified by sediment record in Vibracore 19) has been a deposition center par excellence since 1964, when the ferry jetty was built. More than three meters of organic-rich, sandy silt have been deposited here in only 14 years (average rate of 22 cm/yr). These sediments include organic mats of salt marsh plant debris (Figure VII-3).

North of the inner breakwater and west of Cape Henlopen, a shoal is building up in the ebb and flood shadow of these two features (Figure VI-5). Vibracore 16 is taken on this shoal, and it reveals alternating layers of sand and silt. The sand is transported in from the east during storms, and the silt is deposited from suspension in quiescent periods. The muds in the upper meter of the core are probably the result of multiple harbor-dredging operations which deposited their spoil about 400 m south in the last three decades.

Scouring of bottom sediments in the area of Vibracore 17 is recorded in that core. This scouring was caused by the inner breakwater construction or by the ferry breakwater construction. There is no 1850 coal horizon here, so it is hard to say what the age of the scouring is.

Vibracore site 22 is located west of the harbor about 300 m offshore. At about 4 m depth in this core (about 7.3 m below mean low water), a soil horizon is found, indicating that this was an emerged surface prior to the Holocene transgression. The sugary-white sands with abundant kaolinite rock flour suggest a pre-Holocene deposit here. Blue mussels near the top of the core probably were attached to an old pier nearby.

Evaluation of Techniques for Dating Recent Estuarine/Marine Sediments

Although it was not difficult to establish the pre-Holocene surface based on compaction, color, erosional contacts and gravel-lag deposits at the Pleistocene-Holocene unconformity, establishing exact ages of the Holocene sediments was difficult. It is true that erosional contacts and gravel lag deposits also exist within Holocene sediments, but the contacts display no marked changes in compaction and color of the sediments across their boundaries. Since the last few thousand years have been so full of geologic changes in the study area (Kraft and others, 1978), it is critical to understand this time frame in order to learn of the past and predict the future. Three major groups of techniques are available, but only certain ones of those listed below were found useful in Breakwater Harbor vibracores. The methods considered were:

. radiometric methods using natural and man-made isotopes (C^{14}, Cs^{137}, Pb^{210}, etc.);

. man-made and man-deposited materials discovered in the cores; and

. detailed bathymetric surveys since 1842 to place ages on sediment horizons.

Radiometric Methods. The C^{14} technique of dating is perhaps the most reliable of the listed techniques for dates within the last few thousand years. Unfortunately, the few times there was sufficient organic material for a radiocarbon date, the age of the sediment was known by other means. Also, all of the plant and wood fragments found in Breakwater Harbor were detrital, representing some older date than that of sediment deposition. Fossil shell material existed in great abundance in several cores, but there was always an admixture of older shells transported in from elsewhere. Although some information on early Holocene sedimentation rates probably could have been obtained from a radiocarbon date on shells, the presence of the Pleistocene surface within a few meters provided a good date and therefore made radiocarbon dating unnecessary.

A sea level rise curve for the Delaware Bay and continental shelf vicinity has been constructed by Belknap and Kraft (1977). This curve, presented as Figure VII-10, shows the C^{14} age of basal peats growing on the Pleistocene surface versus their elevation. Thus, for the Pleistocene surface in Vibracore 22 found at 7.3 m below mean low water, one can use the curve to calculate that sea level rose past this point some 4,800 years B.P. In a similar manner, sea level rose above the Pleistocene surface in Vibracores 21 and 7 some 6,700 years B.P. Since these are the deepest cores in the harbor, the Holocene estuarine sediments cored in this study must all be 6,700 years or younger. However, gravel-lag deposits at the base of the Holocene may be somewhat older because they are immediately above the Pleistocene. Some mixing of sediments by current scour occurred near the Pleistocene unconformity; in addition, mixing of sediments by burrowing organisms occurred to various degrees farther up the cores.

Since the initiation of nuclear testing, the radio-isotope cesium-137 has been introduced artifically into the world's atmosphere during these fission reactions. This isotope first appeared in significant quantities in 1954, and the peak years of fallout were 1959, 1963, and 1968 (Brickman, 1978). It would be expected that accumulating sediments (barring any significant vertical mixing and/or diffusion) would reflect these years of peak fallout and that measured activity of cesium-137 in a vertical core would display these peaks at the years mentioned above. The measurement technique for dating purposes has been very successful in lakes and reservoirs where physical and chemical mixing are at a low level (Pennington and others, 1973; Ritchie and others, 1973; Robbins and Edginton, 1975; and Ashley and Moritz, 1979).

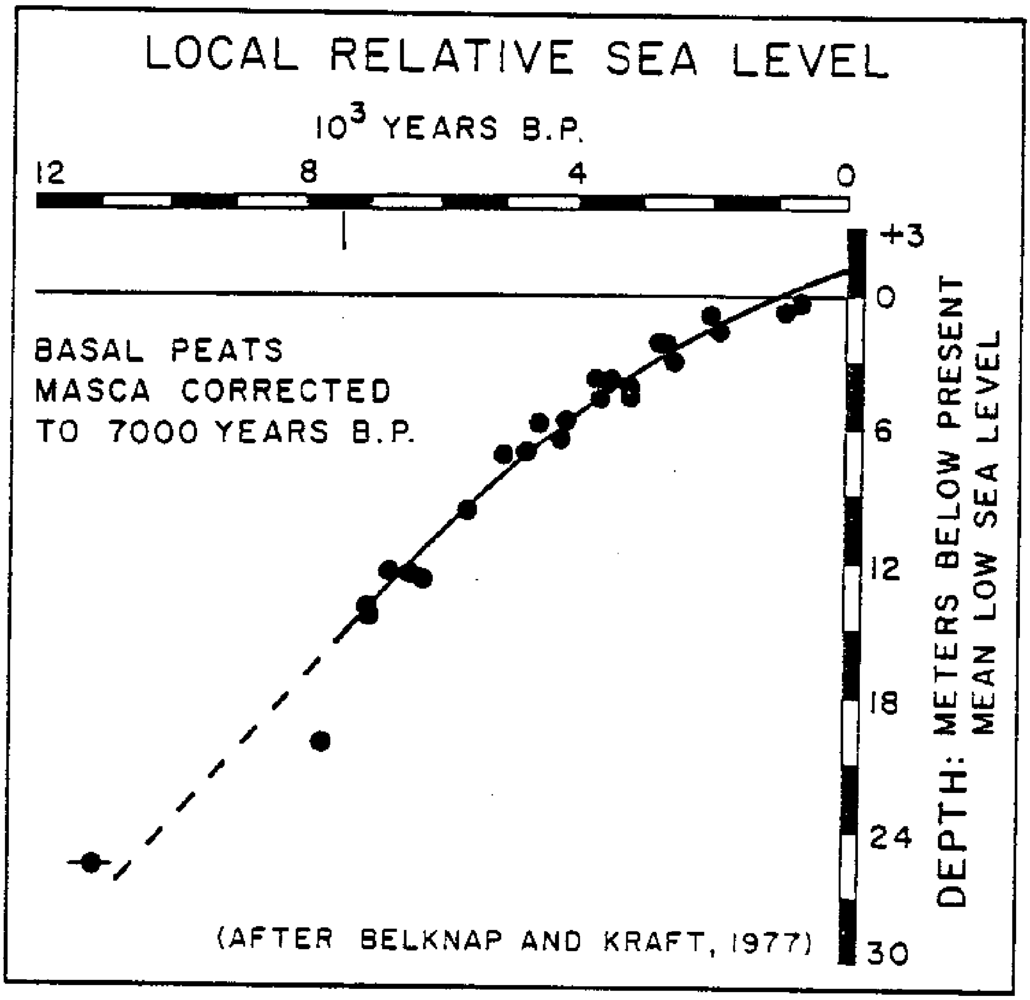


FIGURE VII-10. Local relative sea-level-rise curve for Delaware Bay.

Recently, Brickman (1978) has applied the technique successfully to Delaware tidal salt marsh sediments, so chemical diffusion of cesium-137 in a brackish environment can be dealt with. However, according to G. Ashley (personal communication), increasing salinity renders the method useless because the sodium, calcium, and potassium ions of sea water fill the sites where cesium would attach to the sediments. Moreover, with any salinities above brackish (about 15 $^{o}/oo$), the cesium-137 will not be accepted onto the sediments due to electro-chemical repulsion. Therefore, few if any successful applications of this technique have been possible in the lower reaches of estuaries where salinities approach normal, open-ocean values. Measured salinities year-round in Breakwater Harbor range from 22 $^{o}/oo$ during spring melting of fresh water to 31 $^{o}/oo$ in times of drought. As a result of these findings, it was decided that the cesium-137 method would not be possible in Breakwater Harbor, especially due to the intense physical mixing caused by animal bioturbation discussed earlier in this chapter. Also, the amount of sedimentation since 1959 is usually a relatively small portion of that accumulated in Breakwater Harbor in historical times.

<u>Sedimentation Rates Based on Man-Made or Man-Deposited Materials</u>. The only man-made material found in vibracores from Breakwater Harbor was boiler-slag material from coal-burning boilers. As established earlier, steamships first began using Breakwater Harbor in the decade of the 1850's.

Man-deposited materials were quite abundant in the vibracores; most often, coal granules from these same steamships were found. Other man-deposited materials included bark, wood, and foundation sand used in construction of the inner breakwater and the ferry breakwater.

Using 1850 as the year of onset of this man-deposited debris, sedimentation rates in the harbor and along its shorelines have been calculated for the last 128 years (Table VII-3). The average sedimentation rate for central Breakwater Harbor vibracores is 2.3 cm/yr, with ranges from 1.3 cm/yr to 4.1 cm/yr. These are only averages, and there is a high probability that rates several times the average value occurred in some years. The rates of shoaling in the sandy shoreline areas average 0.7 cm/yr, but many of these cores are so short that they do not record the first occurrence of coal which is somewhere deeper.

Incidentally, the volume of coal deposited in this harbor is substantial. Assuming there is on the order of a 10-cm thickness of pure coal in each of the cores in the central area of the harbor (area is 2.25 km^2), there are about 2.25×10^5 m^3 of coal in the sediments of the harbor bottom. Assuming a coal density of about 2.0 gm/cc, this amounts to 4.5×10^5 metric tons, which may, some day, be a mineable deposit.

Since the rate of sea-level rise for the tide gage in Breakwater Harbor is only 0.33 cm/yr (Hicks and Crosby, 1974; Demarest, 1978), the rate of shoaling in the harbor is about seven times that of local sea-level rise. The shoaling rates in Breakwater Harbor, however, are only

TABLE VII-3.

SEDIMENTATION RATES OF THE LAST 128 YEARS, BASED ON COAL'S FIRST OCCURRENCE IN VIBRACORES

GENERAL LOCATION	CORE #	DEPTH OF FIRST OCCURRENCE OF COAL (cm); 1850	YEARS SINCE 1850	AVERAGE SEDIMENTATION RATE (cm/yr.)	
	2	255	128	2.0	
	5	325	"	2.5	
	6	170	"	1.3	
	7	245	"	1.9	
Silty	8	320	"	2.5	
Central	9	530	"	4.1	Average: 2.3 cm/yr. since 1850
Harbor	10	370	"	2.9	
Cores	11	330	"	2.6	
	13	175	"	1.4	
	18	240	"	1.9	
	21	325	"	2.5	
	25	190	"	1.5	
Sandy	1	115	"	0.9	
Shoreline	3	105	"	0.8	
Cores ✪	4	65	"	0.5	Average: 0.7 cm/yr. since 1850
	14	115	"	0.9	

✪ NOTE: Cores are probably too short to sample first occurrence of coal. Coal may well be reworked up the core and redistributed along shorelines.

about one-tenth as fast as for rapidly shoaling areas in the Mississippi River Delta as studied by Cronin (1967). On the other hand, shoaling in Breakwater Harbor is about ten times faster than for other estuaries in humid climates which Cronin (1967) has studied.

Sedimentation Rates Based on Bathymetric Surveys. Another way of calculating shoaling rate is to use historic bathymetric maps of the area from 1842 to 1971. Demarest (1978) collected data for this purpose and his data were used to calculate the shoaling rates presented in Table VII-4. It should be made clear, however, that Demarest's data include the shoaling caused by the northwestward progradation of Cape Henlopen in addition to harbor shoaling. Consequently, his average sedimentation rate of 3.4 cm/yr would be higher than the 2.3 cm/yr found in vibracores because it includes the rapid buildup of Cape Henlopen since 1842. After breakwater construction, harbor deepening occurred until 1863. After that, shoaling has been the rule, but recent harbor shoaling rates have dropped remarkably since 1945 (see Table VII-4). Cape Henlopen has shoaled rapidly from 1945 to 1971. Since these rates from Demarest (1978) combine the shoaling from the harbor and Cape Henlopen as one figure, the shoaling of Breakwater Harbor must have been greatly reduced since 1945. This finding is in opposition to the widespread belief that shoaling rate is accelerating in Breakwater Harbor (J. C. Kraft, personal communication).

The implications of these data for the future shoaling of Breakwater Harbor will be considered in detail in Chapter XI.

TABLE VII-4.

BREAKWATER HARBOR AND CAPE HENLOPEN SEDIMENTATION RATES BASED ON SHOALING AS DETERMINED BY HISTORIC BATHYMETRIC MAPS (CALCULATED FROM DATA IN DEMAREST, 1978)

TIME SPAN	YEARS	NO. OF DEPTH SOUNDING AVERAGES USED IN CALCULATIONS	SHOALING RATES (cm/year)	
1842-1863	21	149	-0.6	(harbor deepened)
1863-1883	20	150	5.6	
1883-1929	46	139	4.9	Average: 3.4 cm/year
1929-1945	16	139	5.7	
1945-1971	26	128	1.3	

CHAPTER VIII

GEOLOGIC CROSS-SECTIONS BASED ON VIBRACORES

Introduction

Ten lines of cross-sections were constructed throughout the Breakwater Harbor and west Cape Henlopen area (refer to Figure VII-2, pg. 132, for locations). Four of these sections are east-west and six are north-south. Each cross-section is drawn at a vertical exaggeration of 125X, and each has lithologic vibracore descriptions placed in the proper horizontal and vertical locations. The sections show the generalized sediment types encountered in Breakwater Harbor, as well as the age relationships of the sediment bodies. In addition, the intertonguing relationship between muddy, harbor sediments and sandy, Cape Henlopen deposits is shown.

The lithologic symbols used in the cores are primarily those found in Appendix K. The "C"s on the sections refer to the first occurrence of coal coming up the cores. The "D"s on the sections refer to the depths in 1840 as found on bathymetric maps studied by Demarest (1978).

The exact geometric relationships between the sediments of Breakwater Harbor and those of Cape Henlopen were not known prior to this study. Moreover, the internal bedding structures of the harbor sediments were also unknown. However, several other studies onshore (Kraft, 1971a, b; John, 1977; and Kraft and others, 1978) and offshore (Strom, 1972; Sheridan and others, 1974; Maley, 1981; and Marx, 1981) discuss Holocene and Pleistocene environments in the surrounding areas.

East-West Cross-Sections

Four east-west sections run from A-A' in the north to D-D' in the south (Figures VIII-1 through VIII-4). The bottom contours show a shallowing of the harbor exit channel toward the south. Dredged channels in eastern and western Breakwater Harbor also are indicated. In the northern part of eastern Breakwater Harbor, an ebb-tide scour channel is visible (Sections A-A' and B-B'). The pre-Holocene surface slopes down to the northeast so that thicker sections of Holocene sediment are recorded as one moves east and north. A narrow zone from 20 to 80 cm thick contains a gravel lag on top of the Pleistocene surface. Prior to the construction of offshore structures (such as the inner breakwater in 1831), Cape Henlopen was not nearly as far north as it is now (Kraft and Caulk, 1972). During Colonial occupation of the area by Europeans (starting in 1631), the area presently occupied by Breakwater Harbor was the site of deposition of estuarine sands and silts, as evidenced by Colonial reports of bottom sediment (Kraft and Caulk, 1972). Sand layers, probably derived from the Cape Henlopen spit, are observed in vibracores from the central area of present-day Breakwater Harbor (e.g., Vibracores 7, 21, 5, etc.). These estuarine sands and silts

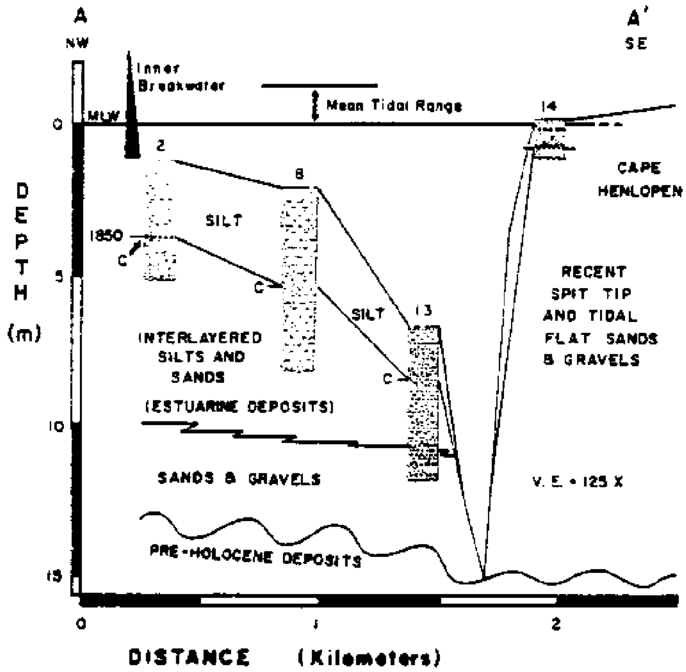


FIGURE VIII-1. Geologic cross-section A-A'. Location of section shown in Figure VII-2. Letter C refers to first coal found comming up the core.

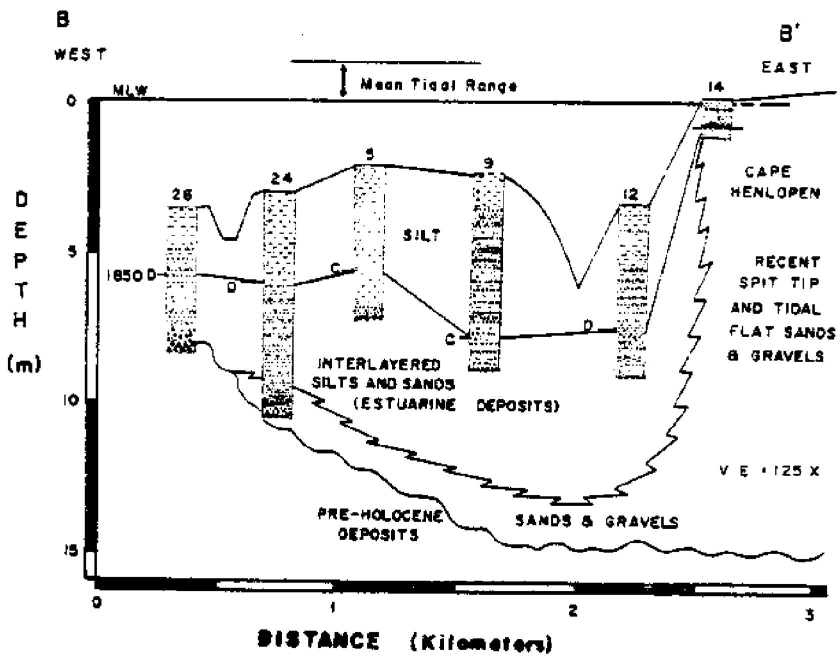


FIGURE VIII-2. Geologic cross-section B-B'. Location of section shown in Figure VII-2. Letter C refers to first coal found comming up the core. Letter D refers to the depth in about 1850.

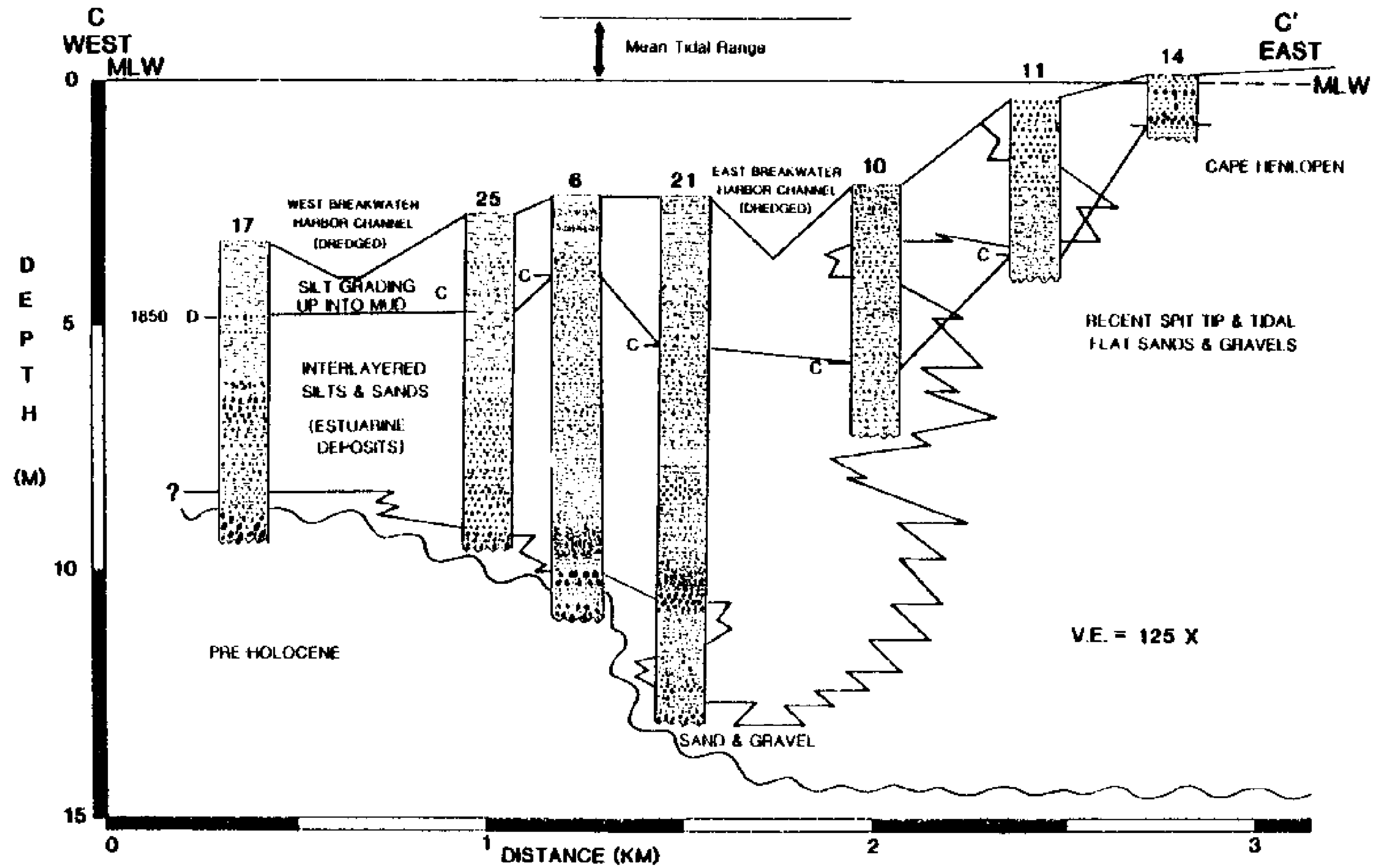


FIGURE VIII-3. Geologic cross-section C-C'. Location of section shown in Figure VII-2. Letter C refers to first coal found comming up the core. Letter D refers to the depth in about 1850.

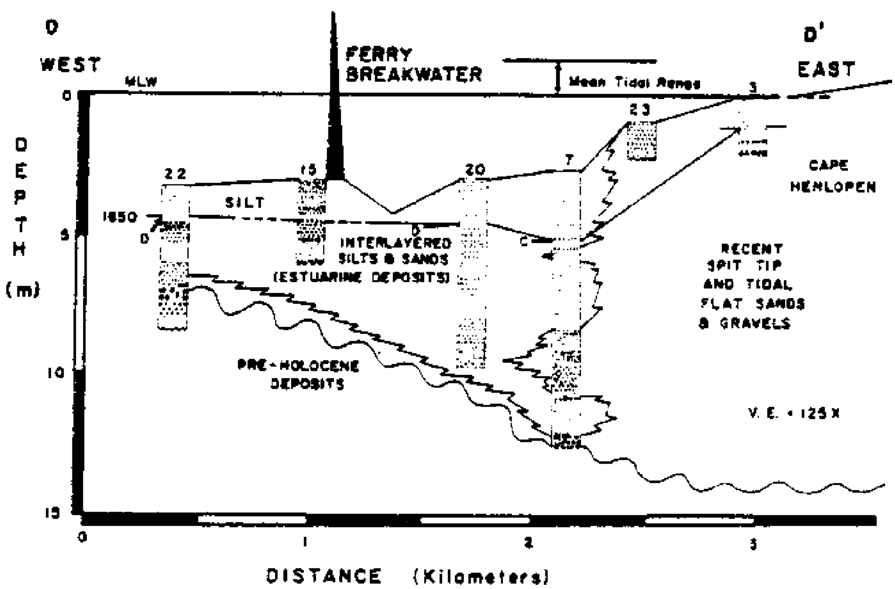


FIGURE VIII-4. Geologic cross-section D-D'. Location of section shown in Figure VII-2. "C" refers to coal in cores and "D" refers to water depth in 1850.

were deposited in late Holocene or Recent time offshore of a tidally scoured Cape Henlopen.

Shallower in the cores, silts and muds dominate the sediments since a date of about 1850. The 1850 date is based on the first occurrence of coal deposited by steamships (first discussed in Chapter VII). Occasional pulses of sandy material were transported into Breakwater Harbor after 1850, presumably derived from Cape Henlopen during northeast storms (Hoyt and Kraft, 1980a). Examples of vibracores which contain sandy pulses of the post-1850 sediments are 7, 10, and 11. The future shoaling patterns in Breakwater Harbor will be considered in Chapter X.

North-South Cross-Sections

Six north-south cross-sections in Breakwater Harbor run from E-E' in the western end of the harbor to J-J' in the eastern end of the harbor adjacent to Cape Henlopen (Figure VII-2, pg. 132). These north-south cross-sections are shown in Figures VIII-5 through VIII-10. The Pleistocene surface gradually descends from about 8-10 m depth in the south to about 10-15 m in the northeast. Breakwater Harbor shoreline sands and Cape Henlopen sands and gravels are present in the cores in the east and south parts of the harbor, respectively. The vibracores in the eastern part of the harbor (e.g. vibracores along cross-sections J-J', I-I', and H-H') have a higher precentage of sand than cores farther west in the harbor. The silty and muddy deposits normally laid down in the Harbor during quiet periods is punctuated by storm-transported,

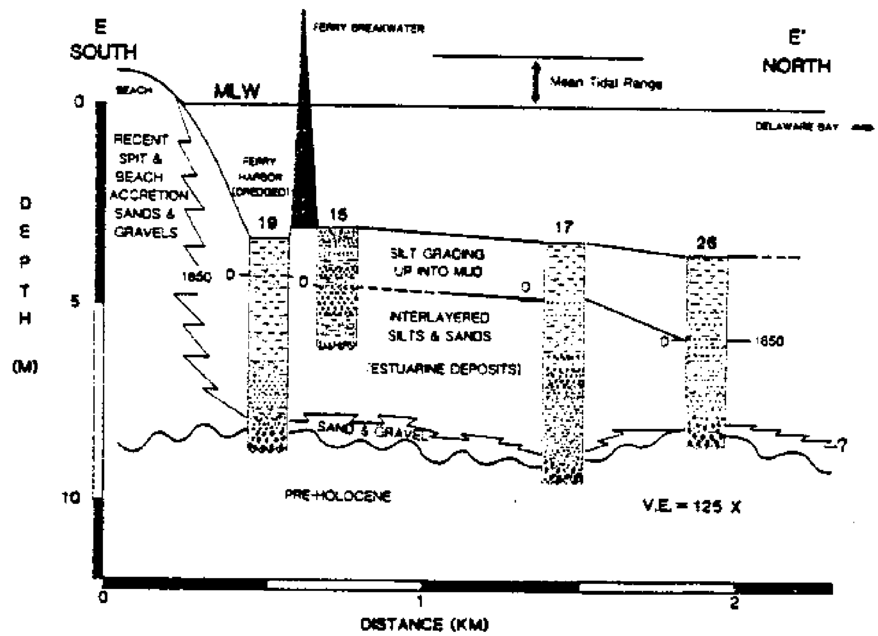


FIGURE VIII-5. Geologic cross-section E'-E. Location of section shown in Figure VII-2. Letter D refers to water depth in 1850.

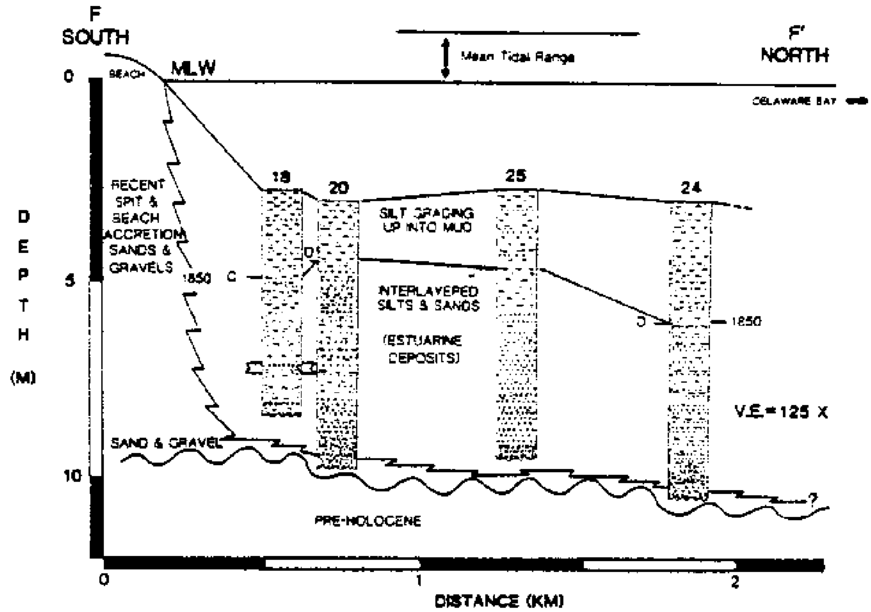


FIGURE VIII-6. Geologic cross-section F'-F. Location of section shown in Figure VII-2. C refers to coal, D refers to 1850.

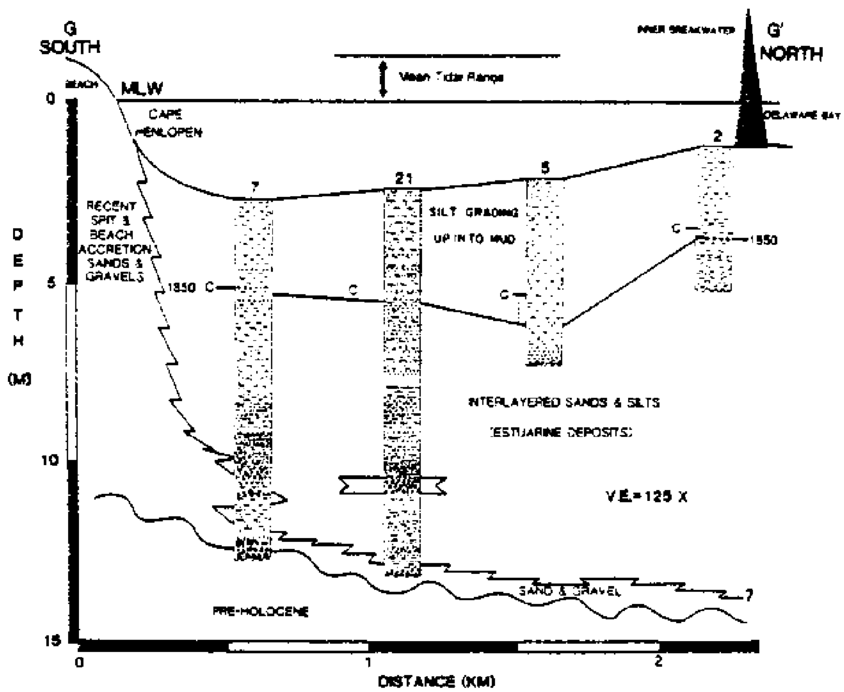


FIGURE VIII-7. Geologic cross-section G'-G. Location of section shown in Figure VII-2. Letter C refers to the first coal found in core comming up from the base.

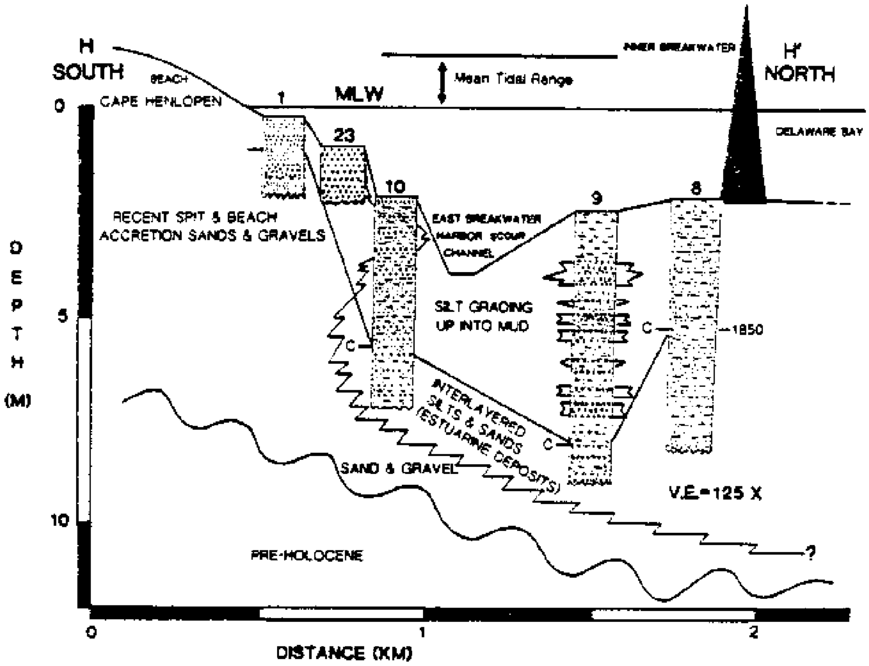


FIGURE VIII-8. Geologic cross-section H'-H. Location of section shown in Figure VII-2. C refers to coal in cores.

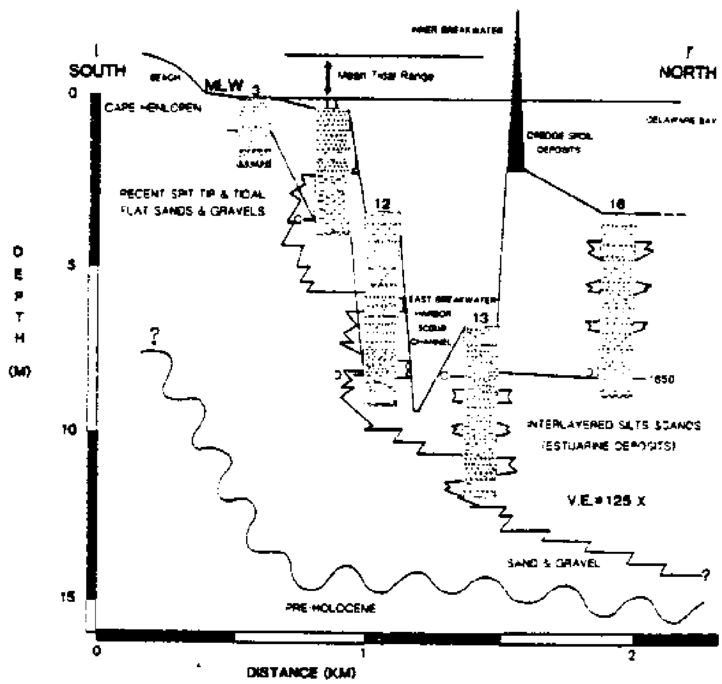


FIGURE VIII-9. Geologic cross-section I'-I. Location of section shown in Figure VII-2. C refers to first coal in cores comming up from the base. D refers to the water depth in 1850.

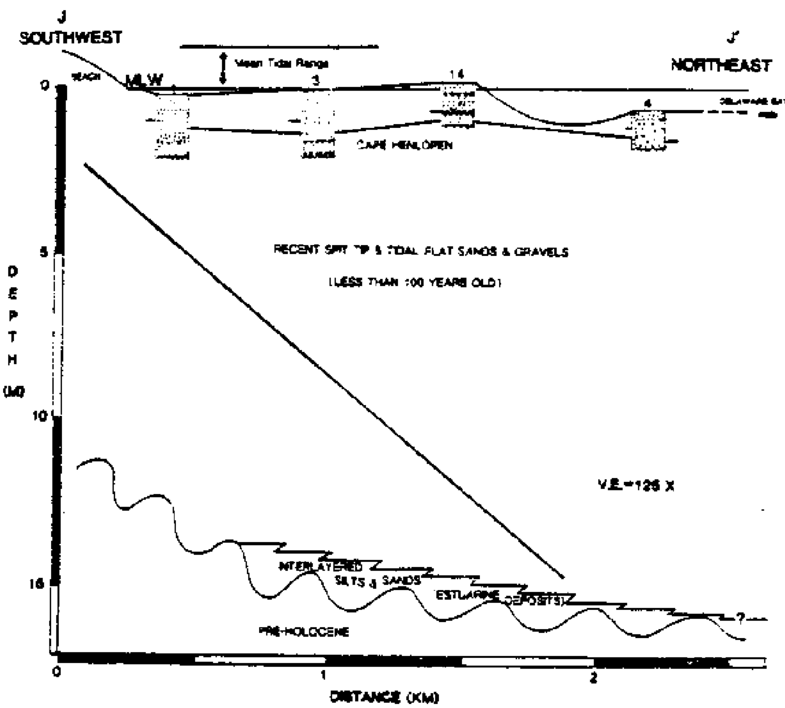


FIGURE VIII-10. Geologic cross-section J'-J. Location of section shown in Figure VII-2.

sandy layers originating from Cape Henlopen (Hoyt and Kraft, 1980a). Several regionally restricted beds of this sand are shown along cross-sections I-I' and H-H'. As one moves farther west in the harbor, these storm-deposited beds become finer and thinner. However, it has not been possible to trace individual sand beds representing one instantaneous event between core sites across the harbor; there is a multiplicity of beds with the exact same provenance and physical characteristics.

The general stratigraphy of the central harbor sediments is the same as that described for the east-west cross-sections. The Cape Henlopen spit recently has been encroaching from the southeast to the extent that all of the vibracores in cross-section J-J' contain sediment which was deposited less than 100 years ago. The young age of Cape Henlopen's north part is known from historical records compiled by Kraft (1971a). The coal horizons deposited in these vibracores (1, 3, 14, and 4) have resulted from reworked older deposits and probably do not represent the decade of the 1850's.

CHAPTER IX

GEOLOGIC CROSS-SECTIONS BASED ON SEISMIC PROFILING

Introduction and Purposes of Study

Although regional seismic stratigraphy of the Atlantic inner shelf off Delaware is fairly well known (Strom, 1972; Sheridan and others, 1974), previous efforts to recover good seismic records from Breakwater Harbor itself have failed (R. Sheridan and J. Demarest, personal communication). It was felt that seismic records would be useful in correlating between the 26 vibracores of this study (presented in Chapter VII). It was also hoped that seismic information off of Cape Henlopen would shed some light on future migration tendencies of that sand body (discussed in Chapter X). In addition, the relationship of the pre-Holocene surface to Holocene depositional patterns was important to discover.

Sheridan and others (1974) described subbottom stratigraphy of the offshore area from central Delaware south to Bethany Beach, Delaware. In addition to the high resolution, 3.5 kHz and 7 kHz seismic reflection profiles, 16 vibracores throughout the area were taken, two of them in the Harbor of Refuge. The regional slope of the Pleistocene surface displayed on a profile north of the inner breakwater is down to the northeast. At a point one kilometer west of the west end of the inner breakwater, the depth of the Pleistocene surface is about 9 m below mean low water; there are about 3 meters of Holocene sediments above that (Sheridan and others, 1974). As one moves north and east along the profile line toward the Harbor of Refuge, the depth to Pleistocene dropped off to deeper than 20 m in an old channel of the Delaware Bay. In a diagramatic cross-section from south to north across Breakwater Harbor and the Harbor of Refuge, Sheridan and others (1974) plotted one core at the base of Cape Henlopen (DH-2-71) and three offshore vibracores. Overlying the oxidized Pleistocene sands and gravels are Holocene open estuarine or shallow marine silts. Deposited on top of these units are regressive sands from the Cape Henlopen spit complex and the associated silts in Breakwater Harbor. Several channels cut into the Pleistocene surface are probably Delaware River tributary valleys of the ancestral Delaware River.

Methods of Study

In this study, profiles covering about 35 cm of track lines were collected from Breakwater Harbor and Cape Henlopen. A 7 kHz transducer attached to a Raytheon PTR subbottom profiler was used to obtain the records. A chart recorder on board the R/V PHRYNE II provided a permanent record of the profiles (Figure IX-1). (A description of the R/V PHRYNE II can be found in Hoyt and Demarest, 1981a, b.)

Photographs of the original records are displayed along with the interpretations of the seismic profiles. Depths plotted on these records are based on the assumption that sound propagation through

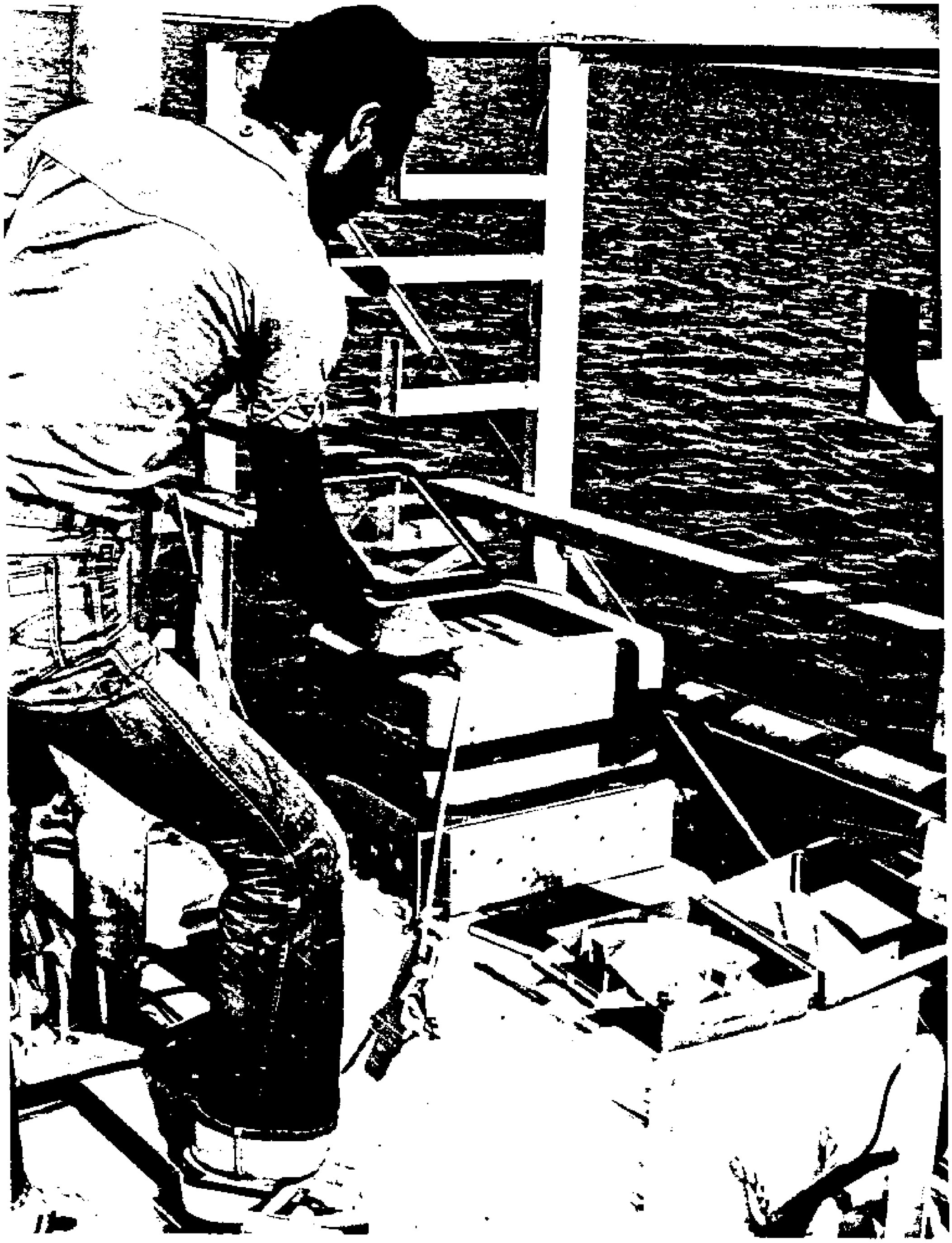


FIGURE IX-1. Photograph of 7 kHz seismic reflection profiling system set up on board the R/V PHRYNE II.

these predominantly silty sediments is only slightly faster than the velocity of sound in water (probably less than 5% faster).

Geologic Cross-Sections Based on Seismic Profiles

The seismic profile track lines are shown in Figure IX-2 and the locations of seismic sections reproduced here are shown in bold lines with Roman numerals I through VIII. In addition, detailed information on the track lines, including vibracores plotted on the records, is listed in Table IX-1.

Throughout the Cape Henlopen area, certain zones of hard, sandy bottom yield an excellent bottom reflector but no subbottom reflectors. This often occurs when acoustically reflective sands exist on the bottom. Another problem which was encountered concerned sound attenuation in the sands, silts, and muds of Breakwater Harbor. The causes of this attenuation are probably gasses in the sediment and/or lack of acoustic contrast in these deposits. A third difficulty arose when concentrations of suspended sediment in the water column attenuated the sound even before it reached the bottom. This occurred twice in the study: once at Point N in an area of vigorous tidal currents northeast of Cape Henlopen and once at Point K after passage of the ferry in the ferry harbor (Figure IX-2). Based on concentrations of suspended sediment measured throughout the area (reported in Chapter IV), it appears that the particle density where sound attenuation prohibits seismic data recovery is at about 200 mg/liter. Despite these difficulties, many good seismic records displaying subbottom sediments were obtained.

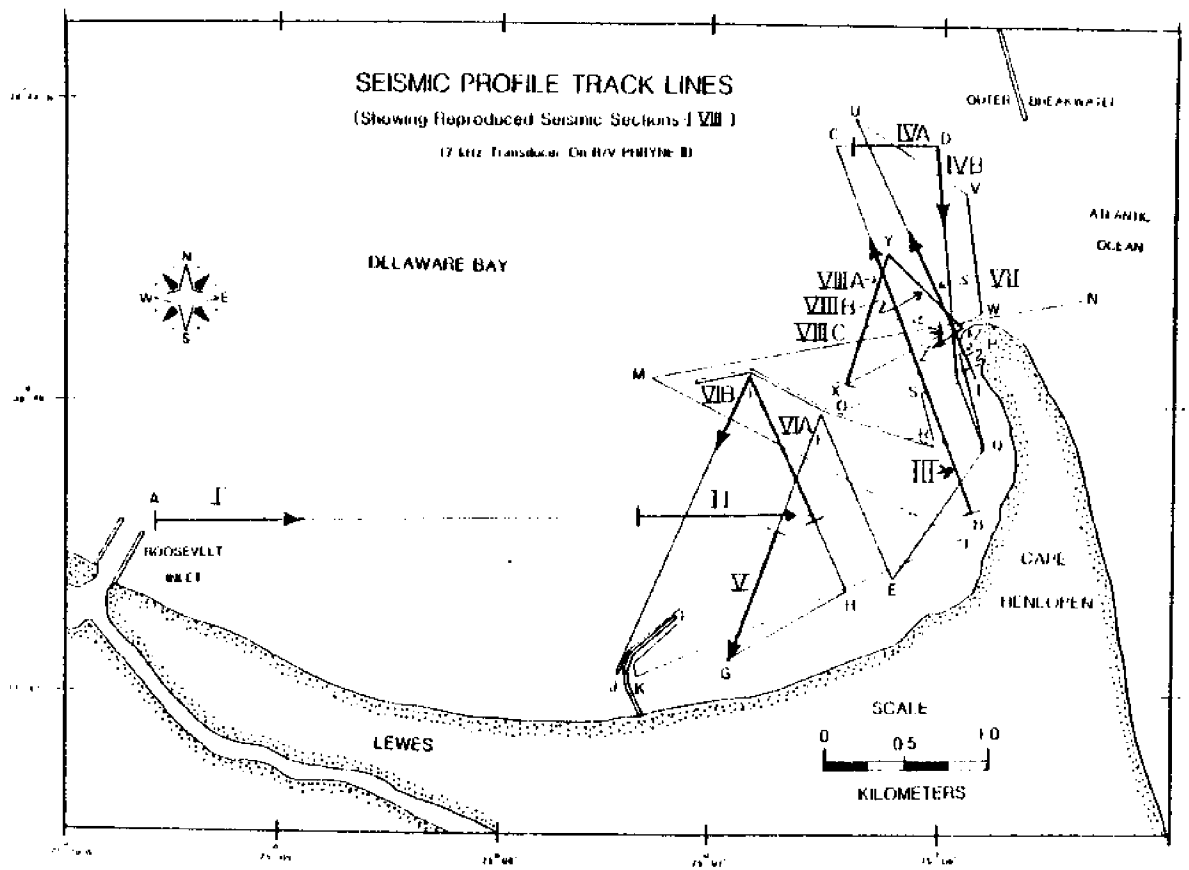


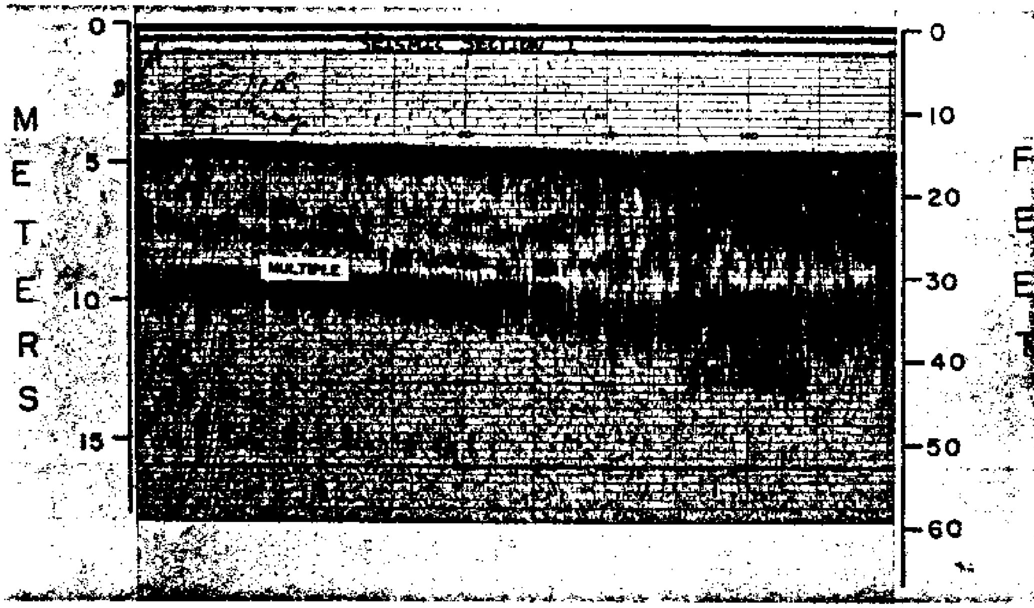
FIGURE IX-2. Locations of seismic profiles and the sections reproduced in this chapter (Roman numerals). Letters refer to course change (C/C) points on the seismic profiles (shown in Figures IX-3 through IX-10 following).

TABLE IX-1. SEISMIC PROFILING TRACK LINES

LINE	SEISMIC SECTIONS	VIBRACORES PLOTTED	TRACK LENGTH (km)	TRACK HEADING (degrees)
A - B	I, II	17, 25, 6, 21	5.2	90
B - C	III	14, 16	2.4	340
C - D	IV A		0.64	90
D - E	IV B		2.8	178, 165, 220
E - F			1.08	335
F - G	V	6, 20	1.64	200
G - H			0.84	60
H - I	VI A	5, 2	1.48	340
I - J	VI B	2, 24	2.04	205
J - K			1.2	Adjacent to Ferry Breakwater
K - L			2.2	62, 75
L - M			2.2	295
M - N			2.6	78
O - P			0.8	65
P - Q			0.6	165
Q - R			0.28	258
R - S			0.32	345
S - T			0.28	75
T - U	VII		1.72	343
U - V			0.8	132
V - W			0.76	169
W - X			0.88	245
X - Y	VIII A		0.84	28
Y - Z	VIII B		0.64	146
Z - Z'	VIII C		0.2	255
		TOTAL:	34.4	

The slope of the Pleistocene surface is toward the east-northeast at about 1:500 or 0.2°. The Pleistocene surface was identified by its strong reflectivity; this harder, more dense surface also occurred at the proper depth to correlate with the known Pleistocene sediments seen in vibracores. At Roosevelt Inlet, the depth of the Pleistocene surface is 7 m; at western Breakwater Harbor, the depth of this unconformity is 9.5 m; and at Cape Henlopen it is at 17 m depth. The Pleistocene surface drops off even more steeply out into the Delaware Bay entrance (Sheridan and others, 1974).

In Seismic Section I (Figure IX-3), very distinct subbottom reflectors are visible north of Roosevelt Inlet and western Lewes Beach. The acoustic contrast of sediments here is great, with the sands of an older, shore-parallel spit called Cape Lewes (Maurmeyer, 1978) underlying well-developed beds of silt. Also, the Pleistocene reflector is near the sediment-water interface and can be penetrated acoustically before sound attenuation and the overstepping of the multiple trace obliterate subbottom data. Some dense debris is seen displayed in the records off of Roosevelt Inlet; it may be shipwreck debris. In addition, what may be a tributary valley of the ancestral Delaware Bay/River was seen on the seismic records at a position about 700 m east of Roosevelt Inlet. The valley is about 225 m across and about 4 m deeper than the regional Pleistocene surfaces to the east and west. The existence of such valleys was theorized by Kraft and others (1974) and Strom (1972). They all think the age of active channel cutting was Late Wisconsinin until about 5,000 to 7,000 years B.P.



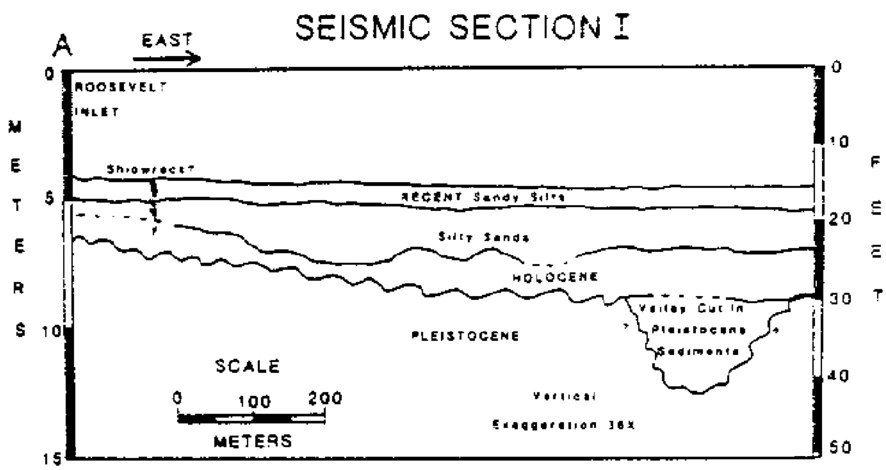


FIGURE IX-3. Photograph and associated line drawing interpretation (below) of Seismic Section I.

Seismic Section II covers the area of west-central Breakwater Harbor (Figure IX-4). The ferry channel itself consists of sandy sediments which are acoustically opaque; on either side of the channel, however, sediments are acoustically transparent silts. I propose that the passing ferry suspends silts (Chapter IV) and leaves a coarse lag of sand, pebbles and shells. Strong acoustic reflectors elsewhere throughout Breakwater Harbor correspond to dense horizons of coal, shells, and/or sand underlying silt. These interpretations are confirmed repeatedly in vibracores obtained in profiled areas (the cores are plotted on the seismic sections and can be checked in Appendix K). Other shipwreck(?) debris protruding from the bottom is found between core sites 25 and 6. The dredge pipe for the hydraulic dredge in the harbor is visible as a thin spike on the extreme right side of the photograph.

The ebb-scour channel west of Cape Henlopen and the shoal north of the inner breakwater are shown in Seismic Section III (Figure IX-5). Slopes on the wall of the channel are quite steep, from 1:5 to 1:10 (18° to 9°). However, crossing this channel at right angles would increase this apparent slope by about twice as much to 40°. West of Point Q below the recent spit deposits, the Late Holocene bay bottom can be seen at a depth of 13-14 m below mean low water. Below this is a layer of estuarine sandy silts at 15 m below datum.

The north-south ebb channel west of Cape Henlopen appears to have been migrating westward as the cape grew in a westerly direction.

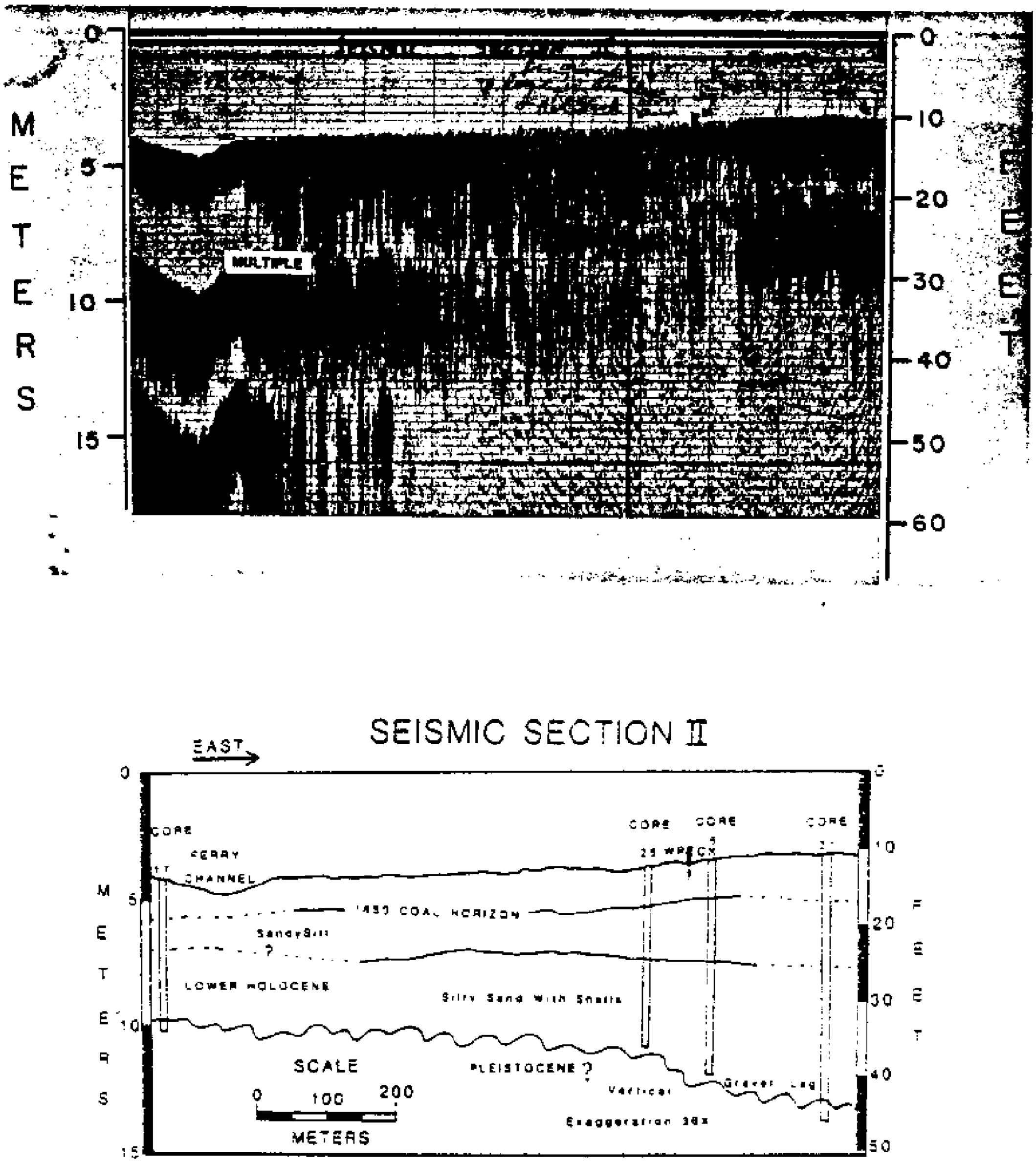


FIGURE IX-4. Photograph and associated line drawing interpretation (below) of Seismic Section II.

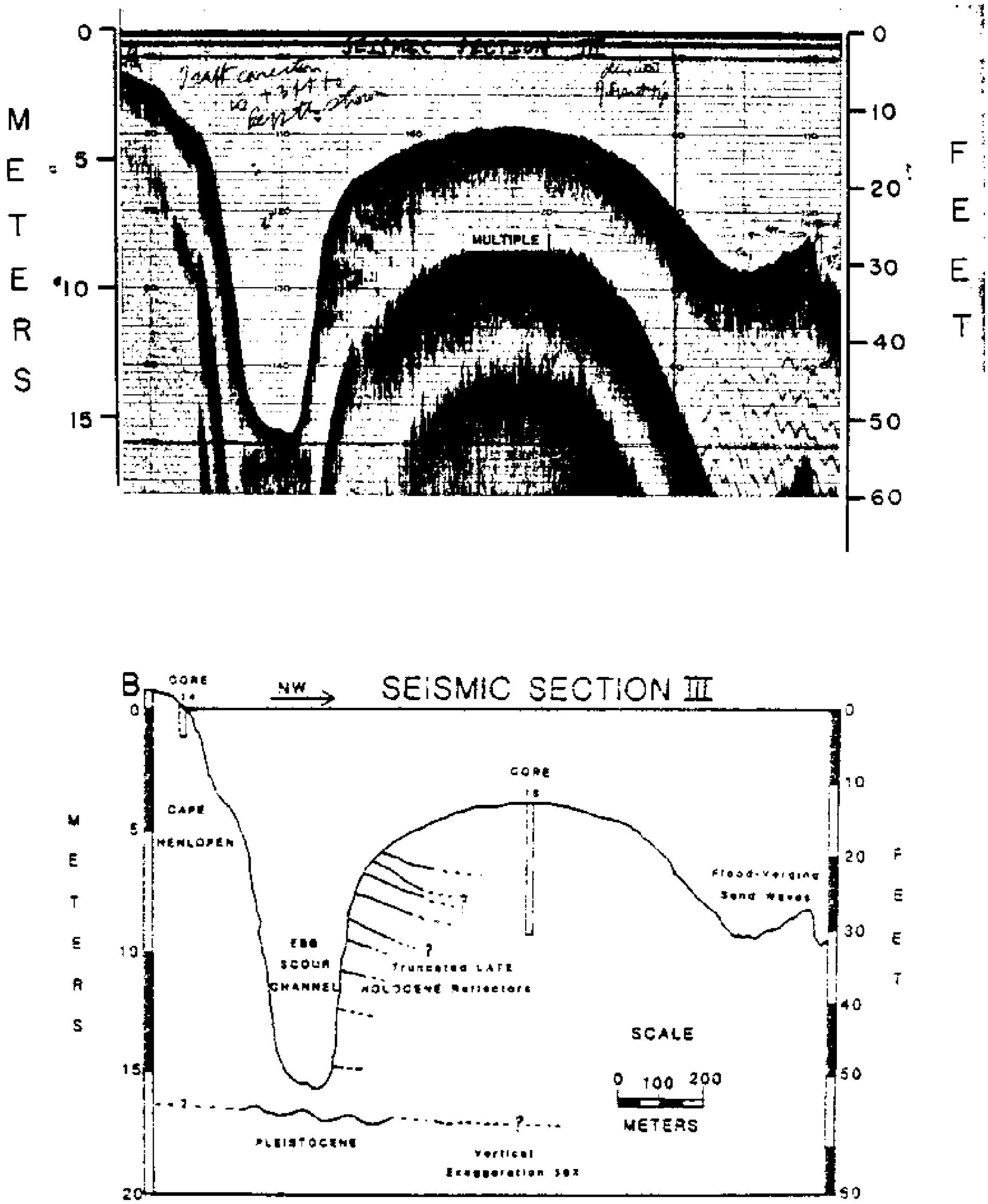


FIGURE IX-5. Photograph and associated line drawing interpretation (below) of Seismic Section III.

Evidence for this is present in the truncated Late Holocene and recent reflectors shown in Figure IX-5. Core 16 suggests deposits in this shoal consist of flat-lying silts and sands deposited north of the inner breakwater. This shoal is presently in a "shadow zone" during both ebb and flood tide: on ebb tide the inner breakwater protects the area from rapid tidal currents; likewise, during flood tide, Cape Henlopen protects the area from strong flood currents. This is precisely why the site has been chosen repeatedly for the deposition of dredge spoil (Chapter XI). However, Klemas and others (1974) have found that material dredged to a site just west of here can be transported on flood tide back into Breakwater Harbor, from which it was just taken. Consequently, future dredging projects in Breakwater Harbor can be expected to deposit spoil at the area just south of Core 16 on the north side of the inner breakwater. In October of 1980, during seismic data collection for this study, such a dredging project was actively under way.

Flood-oriented sand waves are found north and west of Cape Henlopen on Seismic Sections III and IV (Figure IX-6). These submerged, large-scale, migratory sand bodies exist in abundance in the vicinity of Cape Henlopen. The amplitude of these sand waves ranges up to 3 m and the wavelength ranges up to 200 m. A full range of smaller features exists down to ripples a few centimeters high and tens of centimeters in wavelength. Layers of estuarine silt deposited in mid-late Holocene time occur beneath a thin veneer (2 m) of migratory sand bodies north and west of Cape Henlopen (Figure IX-6). The Pleistocene

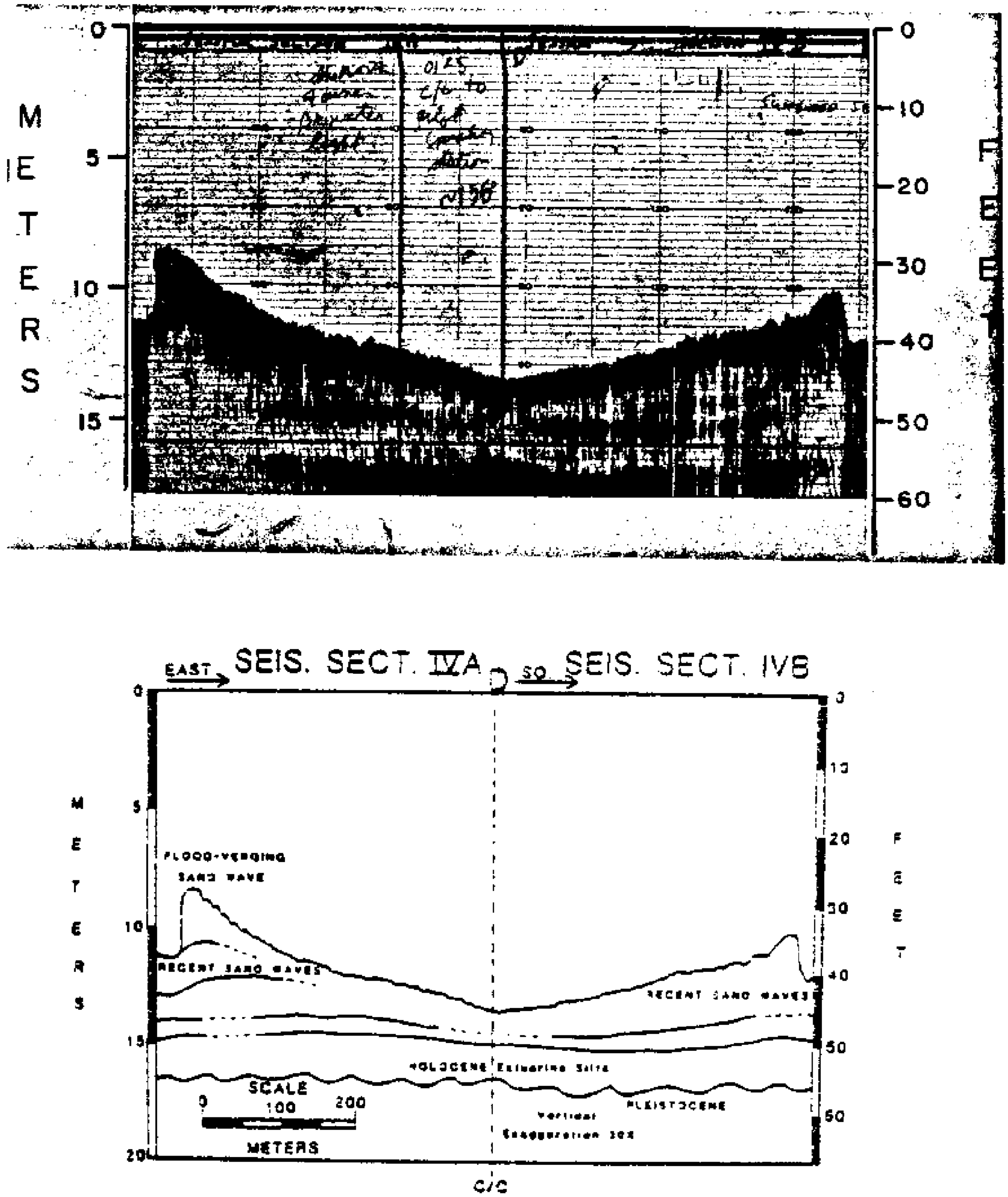


FIGURE IX-6. Photograph and associated line drawing interpretation (below) of Seismic Section IV. The notation "C/C" refers to a course change of the boat.

surface is from 3-6 m below the harbor bottom north of the spit tip, but is being eroded into by deeply scouring ebb currents in two localities:

. east of the inner breakwater to a depth of 17 m below mean low water (Figure IX-5); and

. immediately northwest of Cape Henlopen to a depth of 18 m below mean low water (Figure IX-10).

Both of these scour holes were created during successive ebb-tidal cycles which brought swiftly moving water out of Delaware Bay and Breakwater Harbor. The holes were created and are maintained by a vortex of water exiting from eastern Breakwater Harbor.

Seismic Sections V (Figure IX-7) and VI (Figure IX-8) traverse areas of Breakwater Harbor which contain sandy silts on top of silty sands. Shell horizons and coal horizons (1850), which are found in cores, are visible on the seismic records, especially in Section V. These coal horizons are discussed in detail in Chapter VII. Seismic Section VI shows mostly opaque silts in the northwestern area of the harbor where shoaling rates have been some of the most rapid and where depths are the shallowest.

In the active sand wave regime in the vicinity of Cape Henlopen, Seismic Section VII (Figure IX-9) shows these surficial features on the spit margin. Faint reflectors under the spit margin are probably gravel-lag deposits created when the toe of the spit stabilized for a period of time, probably in the decade of the 1960's. Just northwest

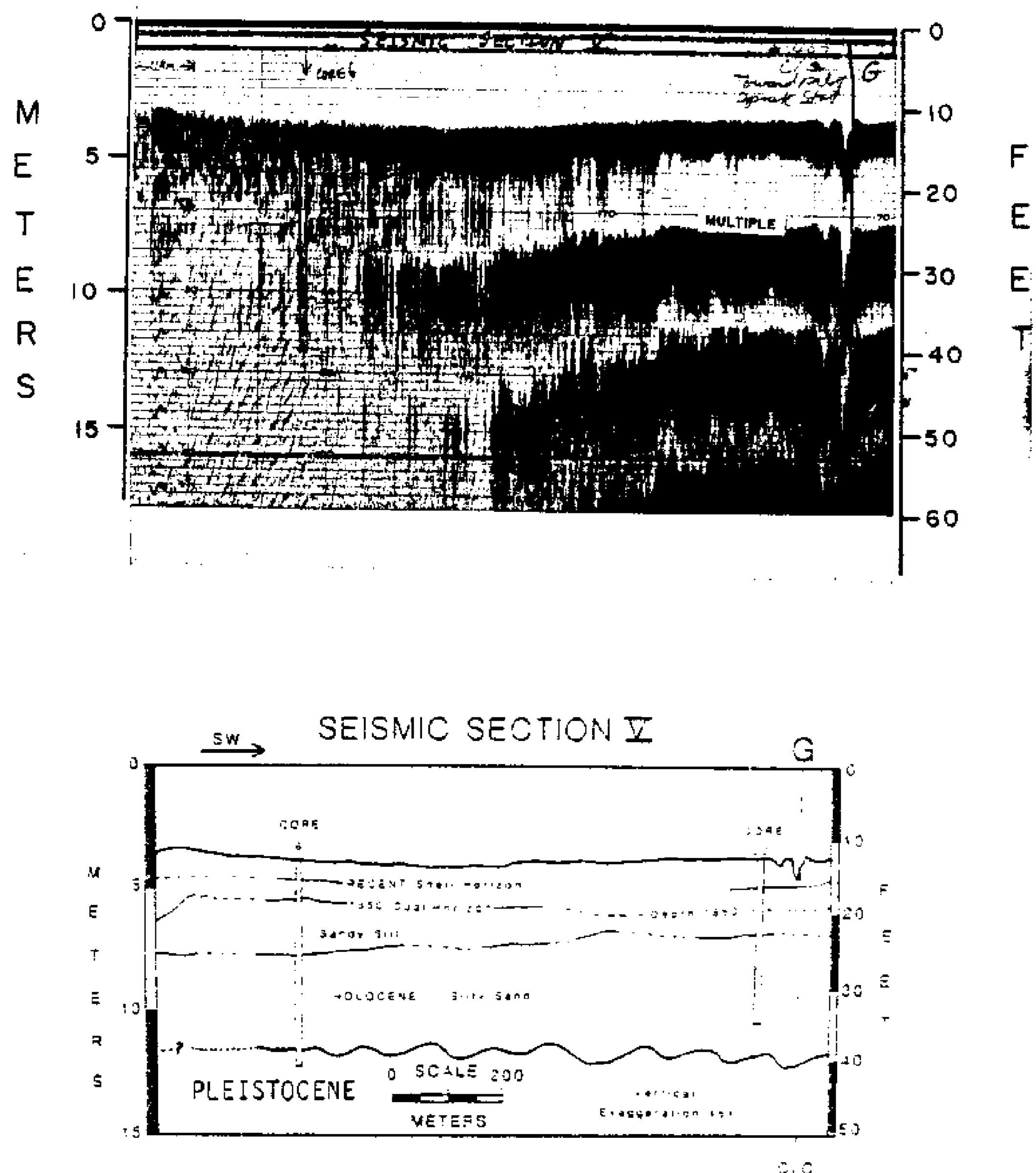


FIGURE IX-7. Photograph and associated line drawing interpretation (below) of Seismic Section V. The notation "C/C" refers to a course change of the boat.

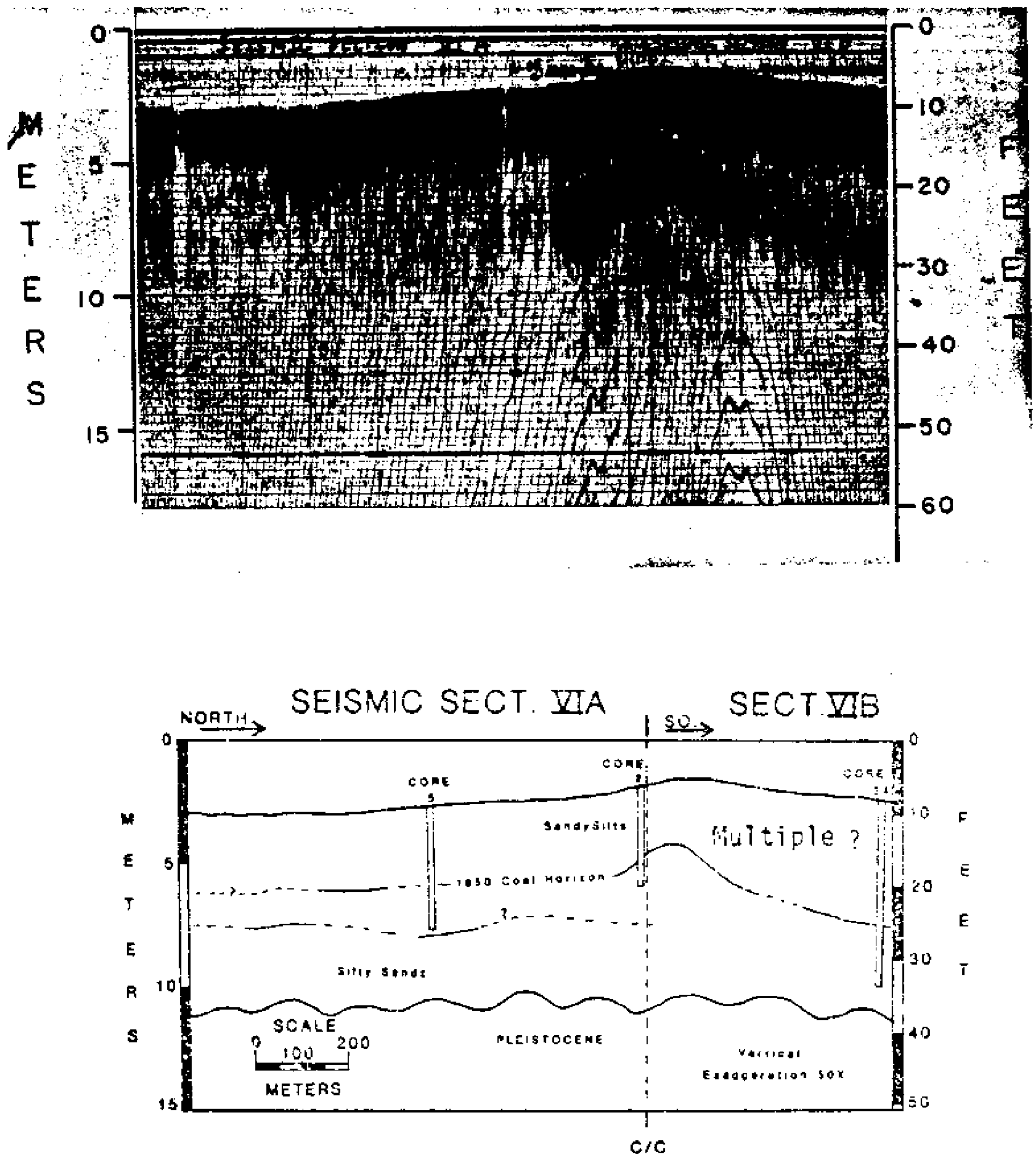


FIGURE IX-8. Photograph and associated line drawing interpretation (below) of Seismic Section VI. The notation "C/C" refers to a course change of the boat.

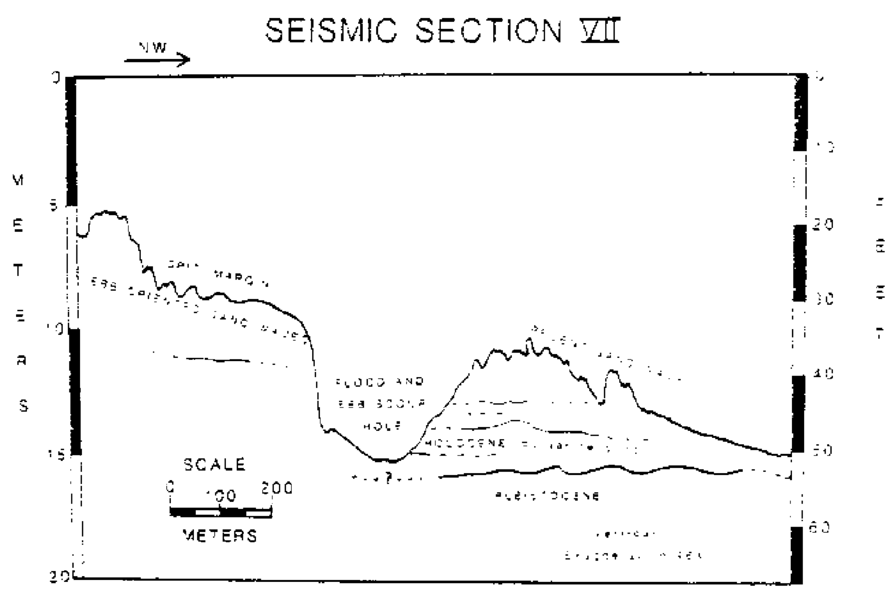


FIGURE IX-9. Photograph and associated line drawing interpretation (below) of Seismic Section VII.

of here is the deep-flood and ebb-scour hole created by the current vortex off the spit. The truncated Holocene reflectors north of the hole show that this excavation has migrated northwest with time.

Three traverses northwest of the spit tip are displayed in Seismic Section VIII (Figure IX-10). Northwest of the spit tip, the bottom slopes down very sharply (1:10 or about 9°) to a depth of about 18 m (60 ft). The bottom then rises to the northwest in a series of surficial sand waves 1-5 m thick. Underlying these migratory sand bodies are two or three shallow reflectors which probably consist of estuarine silty sands like those collected for this study from the bottom (Chapter V). The age of the upper three reflectors is probably Holocene. Below these layers, there is a well-defined reflector of considerable aereal extent. I suspect that this strong reflector represents the Pleistocene surface. All of these surfaces dip to the southeast and are truncated by the northwesterly migrating channel in front of the spit tip. All of the beds are flat-lying to the northwest, but concordantly dip into the walls of the channel toward the southeast.

A simple interpretation of these records suggests that the deepest part of the Pleistocene surface (presumably a channel) lies somewhere under the present spit tip. The similarly shaped Holocene reflectors suggest that the deepest part of the channel repeatedly has been located under the present spit tip. The logical conclusion is that the tendency has been for the channel to be south of its present position, and we might expect forces to continue toward this trend. Only in about the last 20 years has the channel moved slightly northwest

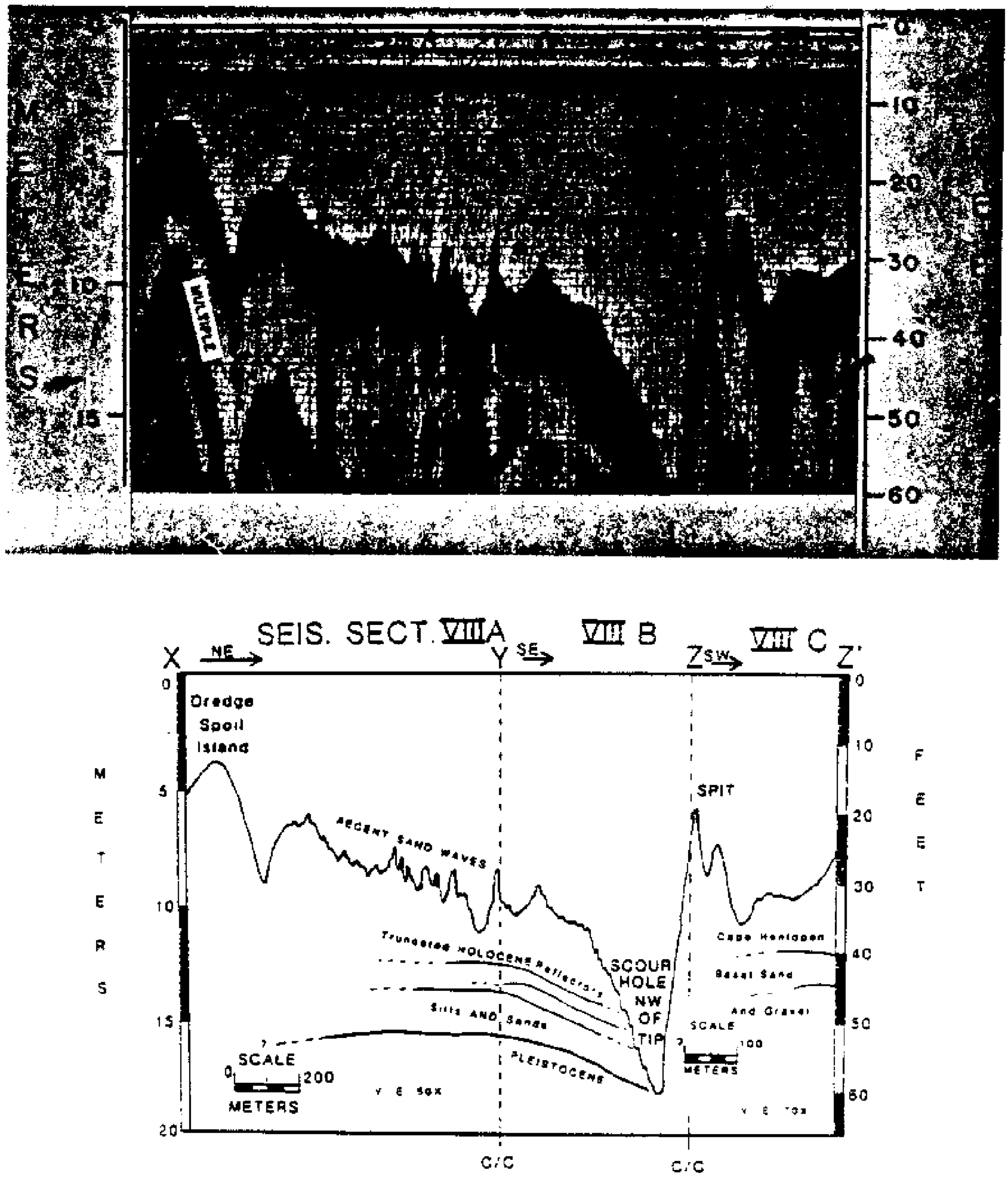


FIGURE IX-10. Photograph and associated line drawing interpretation (below) of Seismic Section VIII. The notation "C/C" refers to a course change of the boat.

of its normal location and cut into the reflectors farther north. This will be discussed further in the next chapter on future growth trends of Cape Henlopen.

Other features of interest are not shown on the seismic sections. A series of ebb-oriented sand waves are found adjacent to the northwest side of the ferry breakwater. As the easterly littoral drift brings sand up against the west side of the shore-attached ferry jetty (breakwater), strong ebb currents continue to move sand around the tip of the breakwater into the ferry channel. The sand waves are about 60 cm high and 125 m in wavelength. Flood tide has very low current velocities here. Demarest (1978) noticed this sand starting to come into the harbor in his sampling program in 1976.

During the active hydraulic dredging operation of October 1980, sediment deposited as a light, fluffy layer was displayed on the profile records at several locations adjacent to the spoil site. Samples of the layer confirmed that it was made up of sandy silt about 60 cm thick. Samples closer to the dredge outfall were thicker than this and also were coarser. It is probable that some silt was carried out of the spoil area, but it could not be traced acoustically or through bottom sediment samples.

A map of geomorphic features of the sea floor off Cape Henlopen and in the Harbor of Refuge was constructed based on grain-size characteristics and the above observations. This map was presented and discussed in Chapter VI (Figure VI-5).

PART THREE

THE GEOLOGIC FUTURE OF CAPE HENLOPEN AND BREAKWATER HARBOR

CHAPTER X

GROWTH TRENDS OF CAPE HENLOPEN

Introduction

Although an excellent review of Holocene growth trends of Cape Henlopen is contained in Maurmeyer (1978), these data will be discussed here in order to set the stage for the data collected in the present study and to give background for implications of the future growth of Cape Henlopen. In addition, historic accretion rates of littoral drift sand coming into Cape Henlopen will be evaluated in order to assess how long it might take to fill in channels and build shoals northwest of the Cape.

Past Cape Henlopen Growth

Growth From 0 A.D. to 1765. Archaeological dates of shell middens on the recurved spit tips of ancestral Cape Henlopen establish that spit recurves were building actively about 2,000 years ago. Between that date and approximately 1500 A.D., the Cape evolved gradually from a recurved spit to a broad, cuspate foreland (Kraft and Caulk, 1972). When the Dutch arrived in the 1600's, a lagoon deep enough to anchor in existed behind the recurves.

<u>Growth From 1765 to 1969</u>. Historical maps and records establish that Cape Lewes, a 500-meter-wide, shore-parallel spit, grew from Cape Henlopen northwestward to Broadkill Beach between 1700 and 1917 (Maurmeyer, 1978). The distance Cape Lewes traversed in this period was about 15 km, at an average rate of about 70 m/yr. However, after 1842, the rate of growth was less than one-half that or even less (Maurmeyer, 1978), probably because the inner breakwater (built in 1831) drastically reduced littoral drift to Cape Lewes. The waves coming from the northeast quadrant were blocked effectively by the inner breakwater, and when the outer breakwater was constructed in 1901, littoral transport driving the growth of Cape Lewes was reduced even further. Consequently, the northwestward growth of Cape Lewes stopped in 1917, and the direction of littoral transport along Lewes Beach (a new name for Cape Lewes) was reversed.

Sometime around 1820-30, Cape Henlopen began to form a simple spit, and the Atlantic littoral drift began to be trapped at the spit tip. Records of the northwesterly growth of the spit and of the shoreline erosion on the Atlantic coast have been compiled by Maurmeyer (1978, her Figure 38). Between 1765 and 1933, rates of growth at the spit tip averaged 5-12 m/yr. Erosion on the Atlantic (east) side of Cape Henlopen was about 1-5 m/yr. In the period 1933 to 1968, accretion rates at the spit tip rose to 15-18 m/yr, and erosion rates on the east side of the Cape were about 3 m/yr.

Using vertical aerial photographs from the United States Department of Agriculture, I superimposed Cape Henlopen shorelines from

1939 and 1969 (Bausch and Lomb Stereo Zoom Transfer Scope). A control on the scope could correct photographs which were originally taken within less than 25° of the vertical. A review of this method and others using air photography to evaluate coastal problems is contained in El-Ashry (1977). During the 30-year period from 1939 to 1969, Cape Henlopen grew northwestward 650 m, which resulted in an annual growth rate of 21.6 m/yr. This rate is slightly higher than the rates cited in Maurmeyer (1978), but the agreement between the two rates is fairly good.

Growth From 1969 to 1977. In a series of very recent studies, Kraft (1971), Maurmeyer (1974), and Brickman and others (1977) measured the short-term growth and erosion of Cape Henlopen in the field by means of surveying. Based on short-term studies (primarily during summer months), these authors proposed that accretion of Cape Henlopen's northwest tip ranged from 20-30 m/yr from 1969 to 1976. These authors also reported erosion rates of the east side of Cape Henlopen at about 3 m/yr.

In order to check the validity of these short-term studies over the entire time period from 1969 to 1977, I used vertical aerial photographs from the United States Department of Agriculture. These photographs were brought to the same scale and superimposed exactly on a Bausch and Lomb Stereo Zoom Transfer Scope, so that shoreline accretion and erosion trends could be measured. Photographs from 1969 and 1977 were compared in this manner, and the results were checked repeatedly to insure accuracy. Different operators also arrived at the same result. Figure X-1 shows these two photographs superimposed and the unexpected result. In the northwest area of the spit, the shorelines are nearly superimposed, although the spit has grown about 21 m in the eight years. Thus, the spit, over a total of eight years, has grown only a average of 2.6 m/yr. This fact is contrasted with the results of the short-term studies listed above which reported rates of 20-30 m/yr, about ten times the net rate which actually occurred over that eight-year period.

The vast disparity of these results may be largely due to two factors, although it also is possible, though unlikely, that earlier researchers made miscalculations or errors in surveying:

. short-term studies measure accretion over only a short period of time and then extrapolate those results to a yearly rate; if the studies were undertaken primarily in accretional periods of the summers (which most were), then the yearly rate will reflect only summer accretion and not account for erosion during winter storms; and

. the short-term studies stopped in 1976, whereas the photograph in Figure X-1 is dated 1977, one year later.

Hurricane Belle passed through this area between 1976 and 1977, but measurements incorporated in this study (Chapter III) show that this storm accounted for only about 10 m of shoreline erosion. If the Cape had been growing 25 m/yr toward the northwest during each of the years from 1969 to 1976, then about 175 m of growth should have been measured. Figure X-1 demonstrates the extreme unlikelihood that the

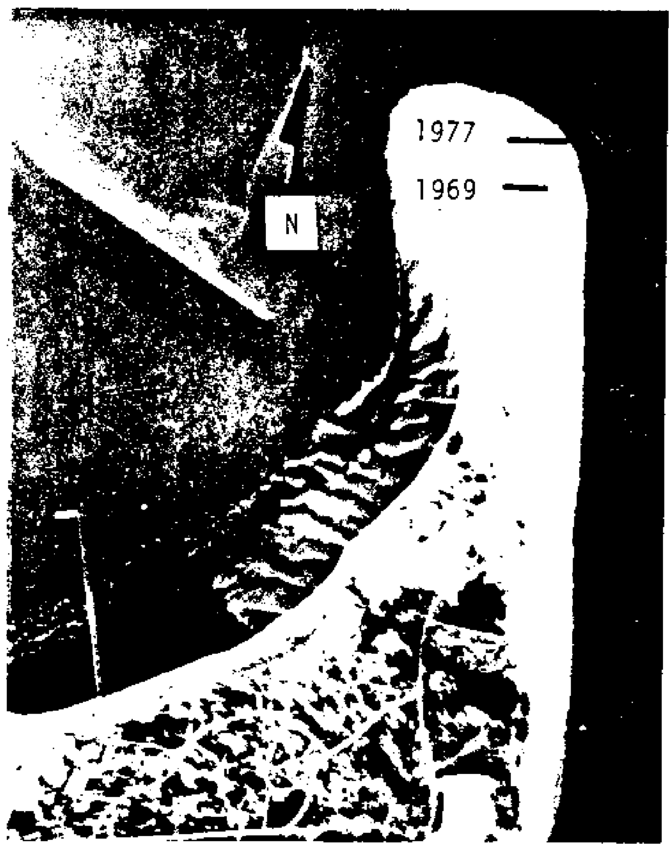


FIGURE X-1. Superimposed vertical aerial photographs of Cape Henlopen from 1969 and 1977. Notice that growth on the northwest has nearly stopped, but that accretion to the northeast has occurred.

short-term accretion rates reported above are valid for the entire eight-year period from 1969 to 1977.

Information since 1977 can be obtained from beach profiles taken on Cape Henlopen from 1976 to 1979. Profiles were taken from August of 1976 to September of 1979 at east Cape Henlopen and north Cape Henlopen. The 11 profiles, collected over 37 months on the east side of the Cape (Figure III-2), show a net accretion averaging 13 m/yr. Farther south, at the base of the Cape, erosion is still going on. The 13 profiles taken for this study on north Cape Henlopen were taken within the same time period, 37 months. Accretion and erosion fluctuated wildly, but net accretion averaged 12 m/yr, which is more than the rates from the photos, but less than those cited by short-term studies.

One obvious conclusion which can be drawn from Figure X-1 is that the sand which had been building the northwest part of the spit prior to 1969 has gone into building the northeast side of the spit since 1969. This implies that the zone of least energy (where deposition occurs) has shifted from northwest Cape Henlopen to northeast Cape Henlopen. The spit has grown about 70 m seaward at its widest point, which translates into about 9 m/yr of growth to the east over the eight-year period. This compares favorably with the accretion rate here of 13 m/yr reported from 1976-1979 in Chapter III of this study.

Implications for Future Growth of Cape Henlopen

It appears that Cape Henlopen is no longer relentlessly increasing its rate of advance to the northwest. It is also clear that the Atlantic shoreline of the spit near the northern tip is accreting, not eroding. These conclusions, supported by data that seem impeccable, make it necessary to reconsider predictions of future growth of the Cape. First, however, Table X-1 reviews the accretion history of north Cape Henlopen as assembled from vertical aerial photographs.

TABLE X-1.

AVERAGE ANNUAL ACCRETION RATES AT NORTHWEST CAPE HENLOPEN TIP
(Data from U.S.D.A. vertical aerial photographs)

INTERVAL	YEARS IN INTERVAL	DISTANCE (m)	RATE OF GROWTH (m/yrs)
1939-1954	15	414	27.6
1954-1960	6	120	20.0
1960-1969	9	115	12.8
1969-1977*	8	21	2.6

* Most spit accretion during this period accumulated on the northeast side of the spit, about 70 m of growth in eight years.

These photographs demonstrate a gradual slowing in rate of advance, not an acceleration in rate as claimed by Kraft (1971), Maurmeyer (1974), and Demarest and Kraft (1979). Kraft (1971, p. 164) felt that the spit was growing so rapidly that it would join the inner breakwater by 1976. Of course, this did not come to pass. In another updated prediction, Demarest and Kraft (1979, p. 22-23) state that the Cape will attach to the north end of the inner breakwater about 1995-2005 (Figure X-2). This future geographic map from Demarest and Kraft (1979) shows Cape Henlopen growing westward in the next 15-25 years a total of about 2 km

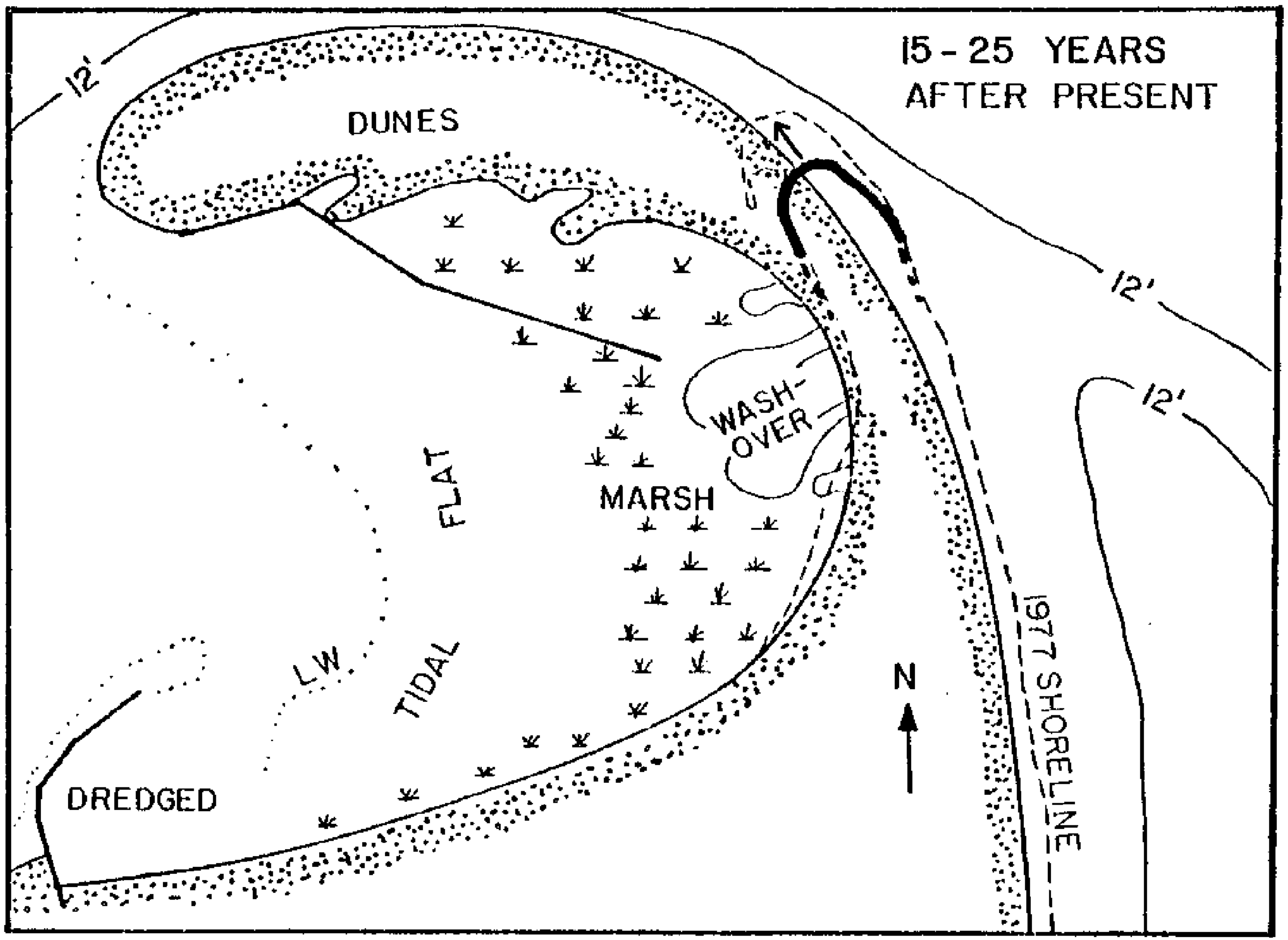


FIGURE X-2. Projection of Cape Henlopen growth in next 15-25 years as predicted by Demarest and Kraft (1979). For reference, the growth of the spit in the last 25 years is shown with a bold line and an arrow.

and taking up an area and volume vastly larger than the present spit. In order to have this prediction come true, growth of the spit would have to be at the fantastic average rate of 80 to 133 m/yr, rates which have no historical precedent or modern analog for a spit some 750 m wide and 10 m deep in its area of growth. Moreover, the area which historically has accreted to the Cape since 1900 is about 230,000 m^2; this averages to be about 3,000 m^2 added in area each year. If the Demarest and Kraft (1979) prediction were to come true, then an area of 40,140 m^2 to 66,900 m^2 would need to be added annually. Again, this value seems absurdly large because it is more than an order of magnitude larger than the historical average.

If the Cape were to connect to the inner breakwater, it would probably accelerate somewhat in accretion rate, but there simply is not enough littoral drift coming into the area to create a spit with such a large volume in as short a time as Demarest and Kraft (1979) predict. The average volume added to the Cape Henlopen spit complex each year since historical records have been kept is between 106,000 and 167,000 m^3 (U.S. Army Corps of Engineers, 1968; and the present study, later in this chapter). In order for the spit which Demarest and Kraft have drawn to grow from that average yearly volume, it would take about 60 to 100 years. I cannot see where the additional sand will come from to build the spit in only 15-25 years. Some sand may be pirated from the present spit, but that would only reduce the time by about 20%.

In order to estimate how many years shoaling west of the spit and the Cape's eventual connection to the inner breakwater might take, I followed these steps:

. I determined the annual rate of accretion to the Cape Henlopen spit complex since 1600 and compared that value to measurements covering only a few years;

. I measured the volume of sand required to shoal the area between the spit and the inner breakwater to an elevation of mean high water; this volume would be filled by littoral drift coming into the area; and finally,

. I tempered those rigid geometric calculations with knowledge of the growth trends of Cape Henlopen form 1969 to 1979 and with an assessment of the hydrologic factors which bring about scouring at the spit tip.

In order to measure the amount of sediment added to the spit complex since 1600, the aerial dimensions and depth of this sediment had to be estimated. Assuming a sediment thickness of 13 m, the volume added to the spit since 1600 is about 2.6×10^7 m^3. In addition, sand added to Hen and Chickens Shoal and to the "T"-shaped shoal west of Cape Henlopen (which was found to exist by Demarest, 1978) amounts to 5.1×10^6 m^3. Furthermore, sand blown into the Great Dune at Lewes should be included in the total because the primary source of that windblown sand is the beach area (Great Dune's volume is about 1.5×10^6 m^3). Thus, the total amount of material brought into the Cape Henlopen spit complex by littoral transport from 1600 to 1968 is 5.9×10^7 m^3. Over 368 years, this average littoral drift is 160,000 m^3/yr. Some material is lost to the estuary and to the Atlantic Ocean, so this is a maximum figure.

Measuring the annual littoral drift from 1920 to 1968 by the same methods employed above yielded an annual littoral drift of 167,000 m^3/year.

My own calculations of the littoral drift for the spit (about 160,000 m^3/yr) are larger than the 1968 estimates of the U.S. Army Corps of Engineers (106,000 m^3/yr). Their figure probably does not include all shoals and high dunes.

The next step in the process was to estimate the volume of sand required to attach the spit to the north end of the inner breakwater. Although several projected routes and forms of the spit are possible, it is felt that increased shoaling of Breakwater Harbor (Chapter XI) will reduce tidal currents very gradually over the next century and will allow the spit to recurve to the west. The projected course of the recurved spit is shown in Figure X-3. The bulge on the northeast part of the spit probably will be maintained in some form, while the Atlantic shoreline will continue to erode farther south. The future spit is drawn to about the same width as the present spit; there seems to be no rationale I can think of which would create a much wider spit in the future [as Demarest and Kraft (1979) have drawn]. If the spit does take my proposed course in some shape similar to what is shown in Figure X-3, then the volume of sand required to build it can be calculated. This volume for the spit alone is 3.8×10^6 m^3. Based on an estimate of 106,000 m^3/yr for material added to the spit alone (excluding shoals, etc.), it would take about 36 years to fill that volume. Since the spit sketched in Figure X-3 does not include shoals, the

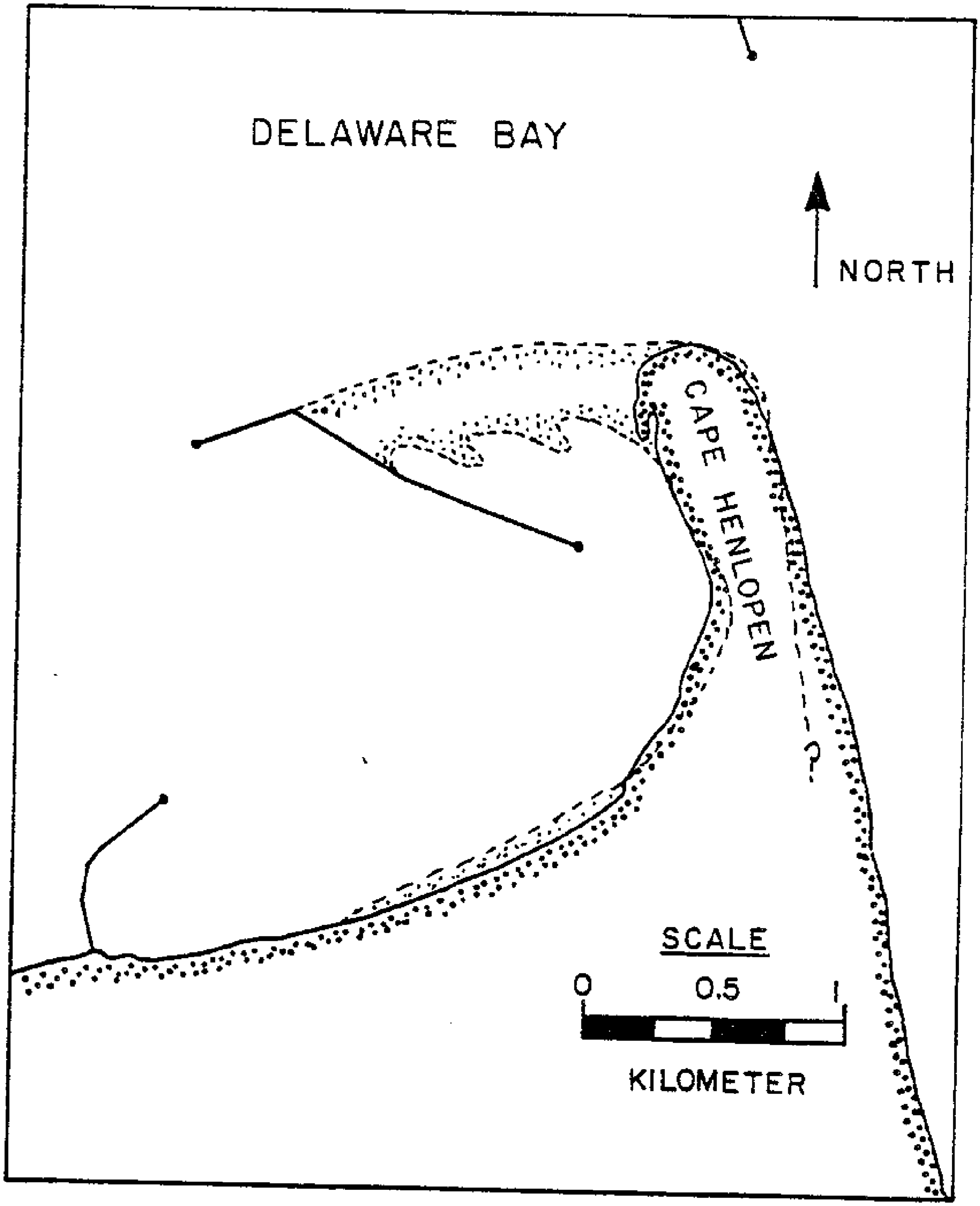


FIGURE X-3. If and when Cape Henlopen grows across to the inner breakwater, this is the probable shape and direction it would take.

annual littoral drift excluding shoals (106,000 m^3) is the correct one to use. That would amount to a migration rate of approximately 33 m/yr.

However, this rate of spit accretion is not likely to occur with this rapidity. Although sand continued to come into the spit from 1969 to 1977, this period saw the sand being piled up on the northeast side and the migration toward the northwest slowed to 2.6 m/yr. This is due to the scouring effects of the ebb tide coming out of Breakwater Harbor and out of Delaware Bay. Since the inner and outer breakwaters are fixed barriers, a given volume of water coming out of Breakwater Harbor and Delaware Bay will try to maintain its total flux by eroding sand. If the cross-sectional area of the eastern Breakwater Harbor exit channel is decreased by westerly spit migration (which has occurred), then the depth of the channel would increase (which has also occurred, Demarest, 1978). The chance of the spit building across this deepening channel seems remote, unless a huge storm moves about half of Cape Henlopen into the channel and dams off the ebb-tidal channel. The likelihood of such a storm is extremely remote, as the largest storm in the last 50 years (1962) did not produce such an effect. Moreover, the sand would need to be deposited in the channel during one flood tide because the next ebb-tidal currents would be competent enough to remove even gravel (based on tidal currents measured for this study and reported on in Chapter I).

In a similar manner, the northerly growth of the Cape is being prohibited by ebb-tidal currents leaving Delaware Bay between Cape Henlopen and the southern end of the outer breakwater (Figure X-3). It may be that an equilibrium condition between sand buildup at the spit and flux out of Delaware Bay exists now. How else could one explain the buildup of sand on the northeast side of the Cape from 1969-1977? Apparently, a littoral dam exists on the northeast side of Cape Henlopen. One would expect sand to accumulate on the east side of the Cape and on Hen and Chickens Shoal. Evidence from seismic profiles (Chapter IX) shows that the channel bayward of ancient spits near this part of the bay has been farther south since sometime in the Pleistocene. The "hydrologic tendency" of Delaware Bay ebb tide probably would be to maintain this channel into the future, which would tend to prevent Cape Henlopen from growing farther north.

When Will Cape Henlopen Attach to the Inner Breakwater? The likelihood of Cape Henlopen's attaching to the north end of the inner breakwater in the next three to five decades seems very remote. However, as Breakwater Harbor continues to shoal, the volume of water exiting the east Breakwater Harbor channel would be reduced. If this occurs, then current velocities would be reduced, and the Cape might be able to grow across toward the inner breakwater at a gradual rate.

Based on the average harbor shoaling rate of 2.3 cm/yr (presented in Table VII-3) and the present average depth of the central harbor area (about 2.3 m), it would take about 100 years to shoal to mean low water. As shoaling of the harbor progresses, westerly migration of the Cape should resume and accelerate. However, since the northwesterly migration of the Cape has stopped in the last decade, it is reasonable to assume that harbor shoaling may well be at a low rate, or it could have stopped completely. On the other hand, the last decade may be representative of only a hesitation in cape growth trend; the spit may be accumulating a larger volume on its northeast side which will make crossing the channel toward the inner breakwater more likely: a single, large storm would then have more sand supply with which to fill the channel and attach to the inner breakwater.

The existence of a subtidal shoal to the west of Cape Henlopen was proposed originally by Demarest (1978a, p. 113-117). He compared computer-generated depth maps for the years 1945 and 1971. In the zone about 100 m west of the Cape Henlopen spit tip, the 1971 depths are reported as 2.9 m (9.4 ft.), 1.5 m (4.9 ft.), 5.4 m (17.8 ft.), and 5.2 m (16.9 ft.) along a north-south line. Since these depths are considerably shallower than those shown on the National Ocean Survey Bathymetric Chart #12216 of the area (presented as Figure 3 of this dissertation), I decided it was necessary to take bathymetric soundings myself. I ran eight sounding lines on the west side of Cape Henlopen to determine the depths of water in the area between the Cape and the inner breakwater. The locations of these lines are shown in Figure IX-2 of this dissertation. All of the eight lines confirmed that maximum depths of the bottom ranged from 9 m (29 ft.) to 16 m (52 ft.) between Cape Henlopen and the inner breakwater. These depths agree with those found on the National Ocean Survey map, but disagree by a large margin with the 1971 depths reported on p. 117 of Demarest (1978a).

The reason for this discrepancy is the manner in which the computer selected depth readings for Demarest's study. In areas of steep bottom slopes, such as the area on the west of Cape Henlopen, the computer will go through its normal interpolation procedure of collecting depth soundings from the surrounding areas; if the surrounding areas are all shallow, the computer will assign a shallow number to the depth, despite the fact that there could be a narrow trough or channel running through that area. Apparently, something of this nature occurred and resulted in errant 1971 depths used by Demarest.

If the 1971 depths used by Demarest (1978a) were incorrect because the depths reported were too shallow, then the shoaling map from 1945 to 1971 is also incorrect. This means that the shoal reported west of Cape Henlopen by Demarest is probably nothing more than an artifact of errant computer-generated data. In conclusion, there appears to be no major shoaling trend in the channel running parallel to the west side of Cape Henlopen. Thus, submarine shoaling west of Cape Henlopen is not nearly as significant as Demarest and Kraft (1971) purport. The Cape Henlopen spit is not moving west across that channel with the rapidity reported by Demarest and Kraft (1979). However, despite the above problem, I think that there is a shoal building up northwest of the spit, as shown in my Figure VI-5 and suggested by Demarest's (1978) data. Once removed from the unusually steep slopes of Cape Henlopen's west side, there is no question that Demarest's (1978) shoaling diagrams are correct.

The history of coastal change at Cape Henlopen over the last 170 years suggests that Cape Henlopen will connect to the inner breakwater--it is a geological necessity, assuming littoral drift continues into the area from the south. The debate as to when the Cape will join the inner breakwater will continue up until the day it does connect. Based on the best information I have available to me, I suggest the following scenario. The gradual deceleration in rate of spit advance shown by aerial photographs from 1939 to 1977 (Table X-1) may last for several more decades, or it may end very soon. I believe it will last for several more decades because the trends of the last 40 years are expected to continue: I expect the spit will continue building out to the northeast and will build only very little to the northwest. Based on all the factors considered, I would expect Cape Henlopen to grow across the channel no sooner than 50 years from now. More likely, I believe, the Cape will not attach to the inner breakwater for more than 100 years. Of course, additional engineering structures and dredging could alter drastically these predictions, but most conceivable alterations would tend to increase the time for Cape-breakwater hook-up.

CHAPTER XI

SHOALING FUTURE OF BREAKWATER HARBOR

Introduction and Previous Work

Earlier studies evaluating the shoaling future of Breakwater Harbor include Rothman (1972) and Demarest (1978). Rothman found that no deposition was occurring in the eastern Breakwater Harbor hole and said that deposition would not occur there until ebb-current velocities dropped considerably. In Demarest's comprehensive study of Breakwater Harbor shoaling based on old bathymetric maps, he found that the shoaling history of the harbor from 1842 until 1971 was irregular (Figure XI-1, his Figure 27). Based on surveys in the years indicated, Demarest found that slight deepening of the harbor occurred until about 1860. He felt this was due to the constricting effect and resultant higher current velocities created by the presence of the inner breakwater. Then, in the period from 1860 to 1971, shoaling advanced at rates between 1 and 5.5 cm/yr (average about 3 cm/yr). Demarest (1978) concluded that periods of erosion or deepening of the harbor occurred after construction of the inner breakwater, filling the center section of the inner breakwater, construction of the outer breakwater, and the ferry jetty construction. It appears that these erosional periods lasted about two decades. Consequently, the harbor probably still is experiencing the scouring effects of the 1964 ferry breakwater

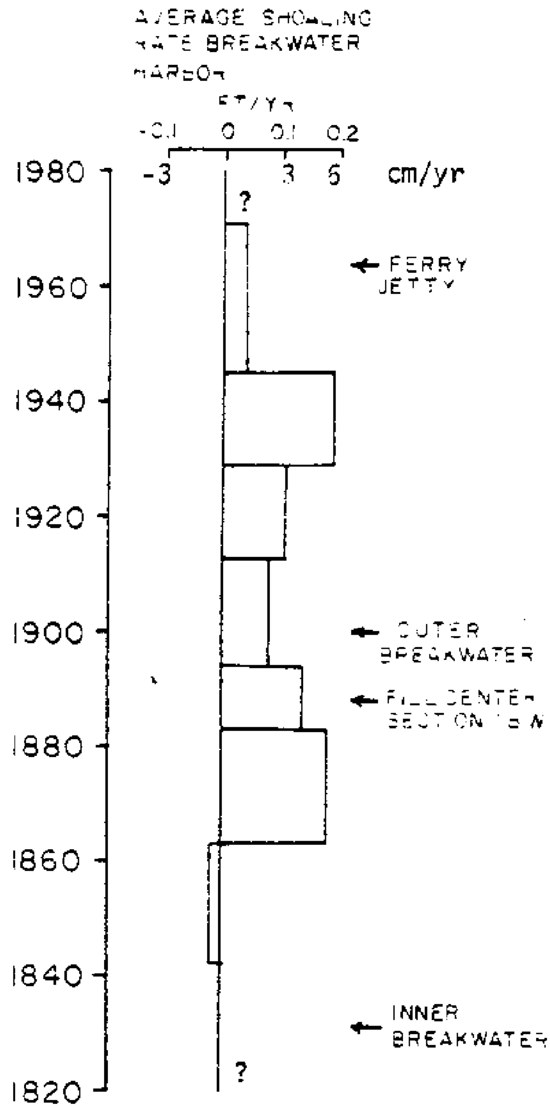


FIGURE XI-1. Historical shoaling rates in Breakwater Harbor, based on bathymetric surveys from 1842 to 1971 (modified after Demarest, 1978).

construction. However, if past trends are followed, this periodic scouring shown in Figure XI-1 may soon yield to major deposition.

The shoaling rates of the last 128 years have also been measured by information gained from vibracores of the present study (Table VII-3). Those shoaling rates, based on the first occurrence of coal, average 2.3 cm/yr. These rates have been used in the subsequent sections of this chapter.

Sedimentary Stability of Harbor Entrances and Exits

In an effort to predict quantitatively the effect of continued Breakwater Harbor shoaling on the future geologic evolution of the area, analyses of future current velocities and total water fluxes were made for various assumed shoaling conditions. For convenience in modeling, Figure XI-2 shows the dimensions of segments in Flow System A (in Breakwater Harbor) and in Flow System B (in the Harbor of Refuge).

In the first case, consider the addition of a volume of sediment on the west side of Cape Henlopen as shown in Figure XI-3. Although this type of shoaling has not been the observed trend from 1969 to 1977, all earlier migrations of Cape Henlopen in historical time have resulted in a westerly migration (Chapter X). If sand is deposited on the west side of the Cape by littoral processes and overwash, the shape of that sand deposition would be something similar to that shown in Figure XI-3. Since current velocities are known at the present time for 13 locations throughout the area (Chapter I), one can identify present current velocities in the two flow systems. One can then use

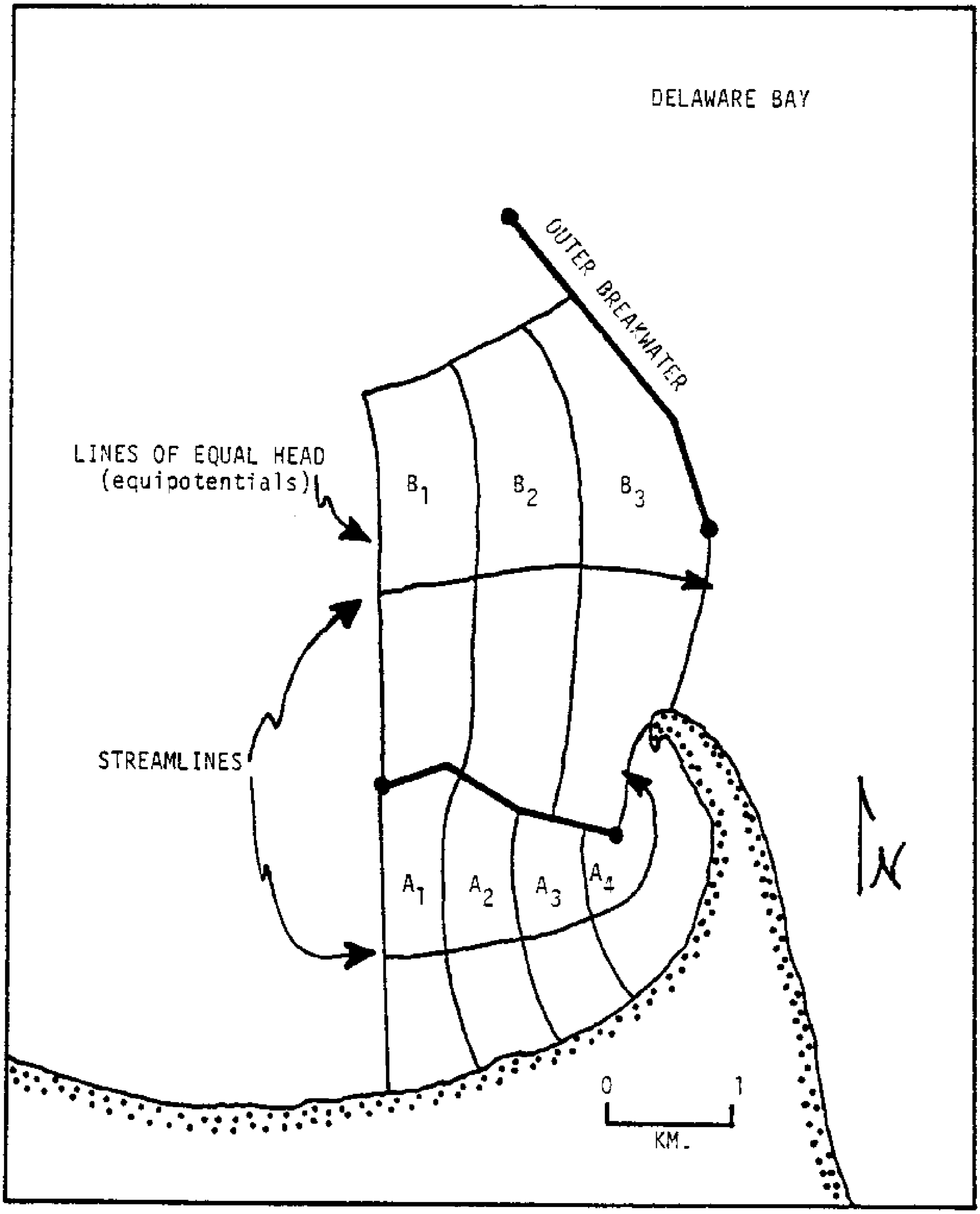


FIGURE XI-2. Definition sketch for flow systems in Breakwater Harbor (A) and the Harbor of Refuge (B).

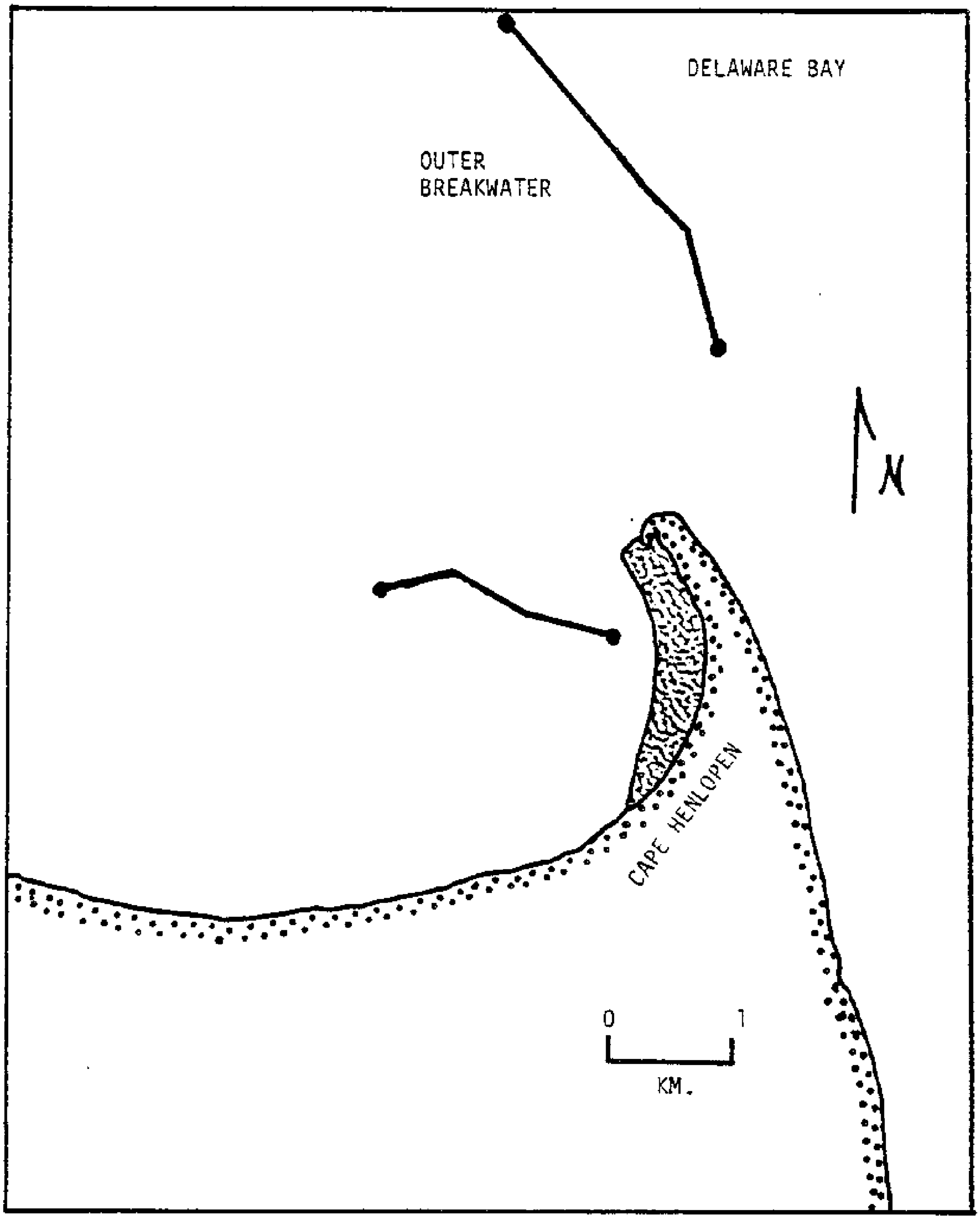


FIGURE XI-3. Assumed shoaling on the west side of Cape Henlopen and in Breakwater Harbor.

these known velocities to estimate the current velocities under various assumed future configurations. In a similar manner, we know the present flux of water through the harbor entrances and exits, and by using the models, one can predict future changes in flow as a result of shoaling.

Before developing this first case, the mathematical basis of the flow systems (principles from O'Brien, 1969; O'Brien and Dean, 1972) must be established. If it is assumed that head loss from the west to the east sides of both flow systems is the same and that this head loss will not be affected substantially by deposition, then we can use the following expression to equate head losses and arrive at a flux ratio between System A and System B (Table XI-1 shows the dimensions of each flow system segment).

$$h_L = \left(K_{ent.} \frac{1}{w^2 h^2} + K_{exit} \frac{1}{w^2 h^2} + \frac{f}{4} \sum \frac{\Delta x}{w^2 h^3}\right) \frac{Q^2}{2g} \quad \text{(eqn. 1)}$$

where,

h_L = head loss

$K_{ent.}$ = minor loss coefficient at entrance

K_{exit} = minor loss coefficient at exit

w = length of flow system segments

h = average depth of segment

Δx = width of segment

f = Darcy-Weisbach friction coefficient

Q = flux of water through flow systems

g = acceleration due to gravity

TABLE XI-1. DIMENSIONS OF PRESENT FLOW SYSTEMS USED IN CALCULATIONS.

FLOW SYSTEM A

SEGMENT	x (m)	w (m)	h (m, below mean sea level)
A_1	640	1,920	2.4
A_2	549	1,554	2.1
A_3	732	823	3.0
A_4	823	366	7.6

FLOW SYSTEM B

SEGMENT	x (m)	w (m)	h (m, below mean sea level)
B_1	549	2,515	7.6
B_2	686	2,926	10.4
B_3	640	3,200	18.9

Then, setting the head loss of flow systems A and B equal, we have:

$$(0 + 1.3 \times 10^{-7} + \frac{0.1}{4} 8.7 \times 10^{-5})\frac{Q_A^2}{2g} = h_L = (0 + 0 + \frac{0.1}{4} 3.01 \times 10^{-7})\frac{Q_B^2}{2g}$$

This equation simplifies to:

$$2.3 \times 10^{-6} \frac{Q_A^2}{2g} = 7.5 \times 10^{-9} \frac{Q_B^2}{2g}$$

or,

$$Q_A = \frac{7.5 \times 10^{-9}}{2.3 \times 10^{-6}} Q_B$$

$$Q_A = 0.057\ Q_B \quad \text{(eqn. 2)}$$

and equivalently,

$$V_A h_A w_A = 0.057\ V_B h_B w_B$$

Using the above ratio, the ratios of velocities at the entrances and exits of the two flow systems can be calculated.

Entrances:

$$\frac{V_A}{V_B} = 0.057 \frac{h_B w_B}{h_A w_A} = 0.057(\frac{25}{8})(\frac{3,300}{2,100})$$

$$\frac{V_A}{V_B} = 0.28$$

Exits:

$$\frac{V_A}{V_B} = 0.057\ \frac{h_B w_B}{h_A w_A} = 0.057\left(\frac{40}{25}\right)\left(\frac{2,700}{400}\right)$$

$$\frac{V_A}{V_B} = 0.62 \quad \text{(eqn. 3)}$$

The accuracy of the calculated exit velocities, $V_A/V_B = 0.62$, can be tested by taking measured current velocities at the exit of System A (Current Meter Station #2, see Chapter I) and the exit of System B (Current Meter Station #3, see Chapter I). During mid- and late-ebb tides, the average ratio $V_A/V_B = 0.67$, which is very close to the calculated 0.62 (measured velocities are 78cm/sec/117cm/sec = 0.67). Therefore, the representations of the flow systems closely approximate the actual conditions and we can move on justifiably to the effects of shoaling.

In the two cases considered here, the velocities of flow at the west Breakwater Harbor entrance are very similar and are therefore not discussed further. Shoaling is much more likely to occur at the eastern harbor exit than in the western harbor.

Continuing with the first case of shoaling on the west side of Cape Henlopen (as displayed in Figure XI-3), a 200-meter-wide sand body can be added, thereby decreasing the area of segment A_4 by about 65%. One might expect that this constriction of the Breakwater Harbor exit would result in a lower flow through the Harbor, but a higher exit velocity. The calculations corroborate this expectation and show that the volume of water (Q_A) flowing through Breakwater Harbor on an average ebb tide would be about 7% less, but that the velocity of flow at the exit would go up by about 84%. That would make the present current velocity at the exit go up from 78cm/sec to 143cm/sec. The clear implication of these results is that the more the eastern exit channel of Breakwater Harbor is constricted, the more rapid and erosive the ebb currents will become. Hjülstrom's curve (Figure I-10) shows that current velocities of 142cm/sec can even erode cohesive gravels. Of course, if the shoaling of Breakwater Harbor continues at the rates similar to the last 128 years, then the volume of water passing through the harbor will decrease in the future. The limiting case is shoaling to sea level, at which time the spit would recurve rapidly and close off the eastern end of Breakwater Harbor as is shown in Figure X-3. Even if Breakwater Harbor shoaled to sea level, a channel or series of channels would remain inside the harbor, with the provision that the eastern end of the harbor remained open to the sea. Of course, it is possible that a very large storm will deposit enough sand west of the Cape to block off eastern Breakwater Harbor from the sea. In that case, the rate of harbor shoaling would increase from about 2.3 cm/year to perhaps ten times that. We can turn now to the likely effects of shoaling in the next 25-50 years.

Based on shoaling rates in the past 128 years (Table VII-3), one might expect similar shoaling in the next 25-50 years, although rates conceivably could become faster or slower (as discussed earlier in this chapter). By about the year 2005, the central and western parts of the Harbor will shoal by about 0.6 m (2 ft.); the eastern part of the Harbor will shoal by about 1.2 m (4 ft.). Given these conditions, the volume of water flowing through the harbor will decrease by about 30% (according to eqn. 2); the velocity at the exit would decrease from 78cm/sec to 62cm/sec (according to eqn. 3). This latter velocity still is competent to erode cohesive gravels.

If one takes the shoaling process further into the future (2030), Harbor shoaling will be at least 1.2 m (4 ft.) in the central and western areas of the Harbor and at least 2.4 m (8 ft.) in the eastern area of the Harbor. Given these conditions, the volume of water flowing through the harbor will decrease by about 61% (according to eqn. 2); the velocity at the exit would decrease from 78cm/sec to 42cm/sec (according to eqn. 3). At the latter current velocity, gravels can still be eroded, although the velocity is becoming marginal in that sense.

In conclusion, it will take almost complete shoaling before gravel will remain in the east Breakwater Harbor exit channel. Likewise, it may take almost complete closure of that channel between Cape Henlopen and the east end of the inner breakwater in order to be close enough for a catastrophic, flooding, storm tide to fill the gap with a small plug of sediment which will not be removed by the next ebb tide. Ebb current velocities will continue to go up as the channel narrows. However, as the channel fills in, the total flux of water out of the harbor will decrease: the water can go past the north side of the harbor without ever passing through it.

Overall Predictions of Future Shoaling

In order to arrive at a reasonable estimate of future shoaling, the following factors must be considered:

. recent shoaling rates of the harbor based on old bathymetric maps and on vibracores;

. future suspended sediment input to the harbor;

. current velocities and other physical factors (flocculation, resuspension of bottom sediments by boats, bed friction, etc.);

. migrations of Cape Henlopen and associated channels in the harbor; and finally,

. the effects of man's alterations, such as additional coastal engineering structures and dredging of harbor channels.

With such a complex and interrelated list of variables, predicting exact shoaling must be considered somewhat speculative. Assuming that suspended sediment input from Delaware Bay remains about the same, one would expect the flocculation and settling of materials to continue at rates similar to those of the past. Kranck (1979) believes that zones of high turbidity in estuaries experience high flocculation and sedimentation only because of increased particle contact, not because of zones of higher salinity. Results of suspended sediment trappings for the present study (Chapter IV) under various salinity conditions between 26 and 32 $^{o}/oo$ (Chapter I) indicate that different salinities in this range have no measurable effect on suspension and deposition of sediment. This information supports Kranck's (1979) belief that flocculation occurs primarily as a result of high turbidity. With the continued high turbidity of waters in Breakwater Harbor, I would expect sedimentation to continue at rates of 2 to 3 cm/yr.

As the harbor shallows, the distance that particles must fall in order to reach the bottom will decrease, and the rate of sedimentation would be expected to go up. On the other hand, as shallowing occurs, bed friction as a result of currents would also be expected to increase as a result of higher Froude number in shallower water. The Froude number is a dimensionless coefficient expressed as $Fr = V/\sqrt{gD}$ (Blatt and others, 1972). The terms are defined as follows: V = water velocity, g = acceleration due to gravity, and D = water depth. Higher Froude numbers indicate more erosive conditions at the sediment-water interface. It also may be true, however, that current velocities will be reduced markedly as shallowing occurs, a factor that would lower the Froude number and increase sedimentation. It appears that several of these natural factors offset each other. The best estimate of shoaling rates in the future would be probably about the same as now, 2 to 3 cm/yr.

The effects of man's continued alteration of the area probably will control the geologic future of shoaling in Breakwater Harbor. The present boat traffic in the harbor suspends tremendous quantities of sediment for redistribution throughout the harbor (Chapter IV). Any shoaling of the harbor area can be dredged; presently, two major channels are maintained in the harbor to depths of 4 to 5 m. Plans call for the continued maintenance of these channels, as well as perhaps some others called for in existing development schemes (Chapter XII). Dredge spoil has been placed north of the eastern part of the inner breakwater (Figure XI-4), and in some cases, it has been built up above mean low water. Placement of material at this point will increase the likelihood that Cape Henlopen will grow across to this shoal. Although land-dredge disposal sites are much more costly in a variety of ways, more serious consideration of this option ought to be given in the future planning of the harbor.

Considering all of the above factors, I would predict shallowing of the harbor to continue, probably at lower rates than in the last 128 years. Since the erosive tendency of the bed (Froude number) will go up with an inverse, square-root relationship of the water depth ($Fr = V/\sqrt{gD}$), shallower water depths will result in vastly increased bed scour. However, if the current velocities decrease due to channel constriction, then the tendency to scour the bed would be reduced. On the one hand, shoaling would increase bed scour, but on the other hand, lower current velocities would decrease scour on the bed. I cannot predict which of these two factors will dominate. Channelizing of the harbor bottom also may occur as shoaling progresses. Therefore, it would take well over 100 years, in my estimation, for the harbor to shoal to mean low water. But, even then, there would be at least two or three channels maintaining themselves throughout the harbor.

FIGURE XI-4. Hydraulic dredge-spoil mound north of the inner breakwater in October, 1981.

CHAPTER XII

CONCEPTUAL PLANS FOR REVITALIZATION OF BREAKWATER HARBOR

Introduction

Several proposals for increased utility of Breakwater Harbor have been discussed publicly and privately in the last five years. Because of its proximity to deep water (20 m) within only about one kilometer, Breakwater Harbor has been an attractive site for various potential activities requiring marine ports. These include offshore oil- and gas-drilling support bases, commercial and recreational fishing, coal bulk loading/transferring terminal, fertilizer terminal (presently operating), ferry service from Cape May, New Jersey, to Lewes, Delaware (presently operating), and other facilities. Since much of the harbor shoreline already is zoned for commercial development and has been used for such in the past, development of the area is limited only by permit acquisition, economic incentives, and fear of future shoaling problems concerning both Cape Henlopen and Breakwater Harbor. I will address myself here to only problems of future shoaling; the other two aspects are, perhaps, even more speculative than my geological predictions.

Using examples from offshore breakwaters, harbors, and spits from all over the world, various design schemes are reviewed ranging from *laisse faire* to the construction of many other engineering structures in the area. Certainly, the complex geometry of structures and the sedimentary processes of the Cape Henlopen and Breakwater Harbor area are unique in the world; therefore, no other area can be used as an example of the present study area. If coastal geologists and engineers can understand fully the complexities of Cape Henlopen and Breakwater Harbor, the lessons learned can be applied effectively to similarly complex situations which may be proposed in other areas of the world.

Examples of Coastal Engineering Structures in Similar Areas Throughout the World

Offshore breakwaters have been found to interrupt littoral transport and accumulate sand behind them (Sato and Irie, 1970). Examples of these include the Channel Islands Harbor, California, breakwater (Bruno and others, 1979), the Netanya, Israel, breakwater (Spar, 1978), and the Port Latta, Tasmania, breakwater (Chappell, 1975). These cases differ from Cape Henlopen in that littoral drift in the case of Breakwater Harbor almost has been stopped from both longshore directions: from the west by the ferry breakwater (shore-attached) and from the east by Cape Henlopen.

In a manner similar to that of the ferry breakwater, other shore-attached breakwaters trap sand on their updrift sides. Some examples of such structures occur in Rockland, Maine, and St. John, New Brunswick (personal observations). Although all shore-attached breakwaters accumulate sediment from littoral transport on their updrift ends and cause erosion downdrift, they accumulate fine-grained sediment in the area protected by the breakwater at vastly different rates. The Rockland and St. John shore-attached breakwaters represent two end members in sedimentation rates behind the breakwaters: the Rockland breakwater was built on a section of the Maine coast having very low turbidity and minimal shoaling; and the St. John breakwater was built in a highly turbid area of the Bay of Fundy with high shoaling rates (personal observations). Breakwater Harbor's shoaling rates place it at the high end of historical shoaling rates, probably among the fastest rates in the world (Chapters VII and XI).

The complicating effects of man-made structures in the coastal zone have been reviewed by many authors including: Kidby and Oliver (1966 for Clatsop Spit, Oregon), Sireyjol (1977 for the Port of Cotonou, North Africa), and Demarest (1979) and Hoyt (1979), both for Cape Henlopen and Breakwater Harbor. All of these studies concluded that man-made, coastal-engineering structures, including offshore breakwaters, shore-attached breakwaters, inlet jetties, groins, and other structures, have a major, if not dominating, influence on the morphologic evolution of the area. Perhaps nowhere else in the world except Holland is there an ocean/estuary coastline more affected by man-made structures than in southeastern Delaware Bay. However, even in Holland, there are no offshore breakwaters in a configuration similar to that of the Cape Henlopen/Breakwater Harbor area.

Although other studies have examined siltation behind offshore breakwaters (Chappell, 1975, for Port Latta, Tasmania, van Nieuwenhuise and others, 1978, for Charleston Harbor, U.S.A.; and Demarest, 1978b, for Breakwater Harbor, Delaware), none have investigated causes of shoaling and prospects for the future to the extent that the present study addresses those questions.

The Addition of Engineering Structures to the Study Area

Although an infinite variety of engineering structures is possible in the study area, only three which display particular merit are discussed here. The concept of trapping littoral-drift sand at the Cape Henlopen spit tip to forestall spit recurving is sketched in Figure XII-1 (Structures 1 and 2). It should be pointed out that the spit is doing this at the present time (1969-1977) by itself, although this is probably just a temporary phase of unknown duration. Accretion on the northeast side of Cape Henlopen has been happening from at least 1969 to 1977. However, should the spit start to migrate west into the channel again, a groin (Structure 1) and/or offshore breakwater (Structure 2) would trap sand and diminish the westerly growth. However, Hen and Chickens Shoal is already acting as an offshore breakwater because it is so shallow (about 2 to 4 m). Waves often have been observed to break on the shoal.

In the event that the inner breakwater and Cape do attach, Breakwater Harbor would shoal rapidly and become useless for boats (although it may become a shellfish paradise). Then, one might consider taking the rocks from the inner breakwater and beginning to connect the south end of the outer breakwater to the tip of Cape Henlopen (Structure 3). Of course, supplemental rock would be required. This would

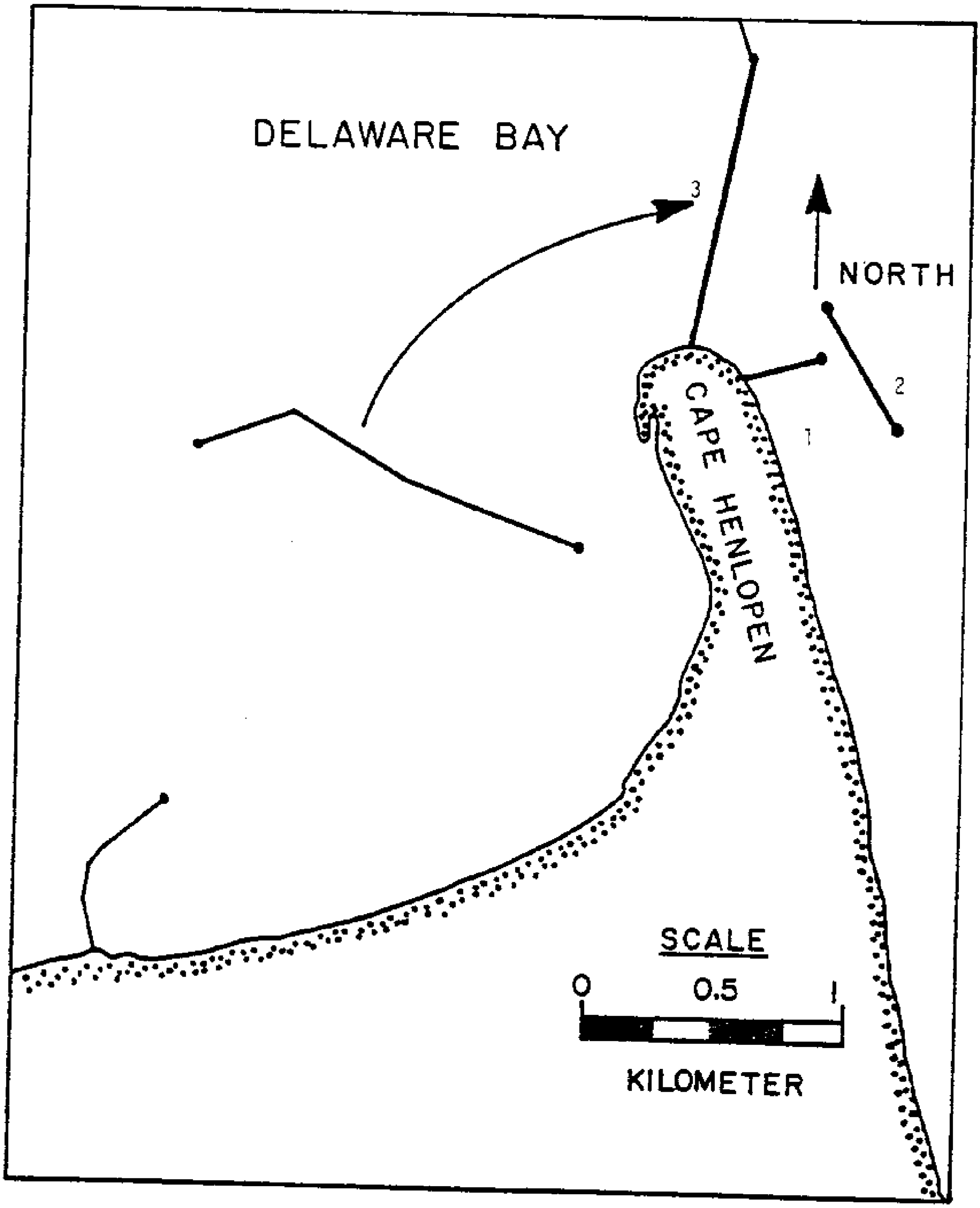


FIGURE XII-1. Concepts of useful engineering structures in the study area in the next century.

produce a very large Harbor of Refuge in southeastern Delaware Bay. Cape Henlopen would then grow north and around the east side of the outer breakwater. This plan would provide a harbor for many decades, although the entire area might be expected to shoal at rates of 5 to 10 cm/yr. Nevertheless, a large, deep-water area would be provided.

If the reader has any doubts as to the technological feasibility of such a project, he is referred to the Dutch case of the Zuider Zee program (Seeger, 1980). In the area of Zeeland, The Netherlands, a ten-kilometer-wide dam across part of the Scheldt estuary is nearly completed. Parts of the estuary channel are more than 50 m deep, and vigorous flood and ebb tides scour it. Since the section of Delaware Bay discussed here is only one-half as deep and one-tenth as long, there is only one-twentieth the area to fill as in the Dutch case. Again, I am not considering the economic, political, and ecological factors.

There also have been suggestions to remove part(s) of the inner breakwater in the near future in order to make a groin as shown in Structure 1. However, I would advise against this, because then the funneling effect of the ebb tide would be reduced, and the Cape would be more likely to migrate rapidly. Stone probably could be obtained at competitive costs from a source other than the inner breakwater.

A Best Case Scenario: No New Engineering Structures

Under the conditions which presently exist in the Breakwater Harbor and Cape Henlopen areas, I would expect the harbor to be functional for its present purposes another 50 to 100 years. The present locus of economic activity in the harbor centers in its western end. In the longer term of 50 to 100 years, this is a better locality to operate from, because the chances of rapid shoaling due to sand littoral drift are less in the western harbor locality (this was previously pointed out by Demarest and Kraft, 1979). However, the area northeast of the ferry breakwater may also shoal slightly because of littoral transport from the west (Chapter II).

It should be reiterated that planning to use the easterly harbor entrance between Cape Henlopen and Breakwater Harbor (even in the next 25 to 50 years) could be a very dangerous and economically costly mistake. One very large storm could fill the present channel and massive dredging efforts would be required to keep that shipping channel open. There is no reason to take a chance on this potentially mobile eastern end when such an excellent channel already exists out the western end. The distance to deep water in either case is about the same. Moreover, if dredging of Cape Henlopen is proposed, a special permit would be required to remove land which legally belongs to the Delaware Seashore State Park.

When the Cape attaches to the inner breakwater and the harbor shoals rapidly, one might consider moving port facilities to deeper water, perhaps replacing Breakwater Harbor with the Harbor of Refuge. If I live to see that day, my predictions will be proven false.

SUMMARY AND CONCLUSIONS

The objectives of this study were to:

1) define and quantify modern sedimentary processes in the Cape Henlopen/Breakwater Harbor area;

2) evaluate the detailed Holocene geological history of the area by means of subsurface information; and

3) use these two sets of data to model and predict the geological future of the vicinity.

Modern Sedimentary Processes

In order to fully understand sedimentary processes presently active in the area, several aspects of littoral sediment movement and deeper harbor sediment movement were studied. Among these were current meter and drogue studies, measurements of surf zone sediment movements and associated shoreline changes (beach profiles), measurements of sediments suspended in the water column of Breakwater Harbor and vicinity, and measurements and observations of emergent sand transport on the rapidly migrating Cape Henlopen spit.

Based on fourteen bottom current meter stations throughout the study area, the average tide of a lunar cycle results in a net easterly flow through Breakwater Harbor. Ebb-tide duration is about three-quarters of all time and flood tide occurs during only about one-quarter of all time. Likewise, velocities during ebb tide in central areas of the harbor exceed those of flood tide by about a factor of two (60 cm/sec on ebb tide and 30 cm/sec on flood tide). During ebb tide, bottom current velocities as high as 90 cm/sec are found at the constricted eastern end of Breakwater Harbor. These high current velocities have maintained a deep hole some 18 m (55 ft.) deep. Likewise, maximum ebb current velocities in the central harbor (60 cm/sec) are competent enough to transport and erode silts and sands. Current velocities during flood tide and slack water are slow enough to allow the deposition of silts and sands. This deposition has been observed throughout historic time (Kraft and Caulk, 1972; Demarest, 1978a).

In order to understand sediment movements in the surf zones of the study area, both bedload sediment and suspended sediment were measured. Sixteen surf zone sampling stations were established between east Cape Henlopen and Roosevelt Inlet. Between February, 1977 and July, 1978, bedload and suspended sediments were collected during thirteen separate days. Results of these studies demonstrated that wave height and longshore current were the two most important variables controlling sediment concentrations. The zone of highest surf zone energy was the tip of Cape Henlopen. The zone of lowest energy was the harbor shoreline south of the inner breakwater. The Lewes Beach shoreline west of the ferry breakwater (jetty) and east of Roosevelt Inlet had energy levels intermediate between those of Cape Henlopen and Breakwater Harbor. During storm conditions, the maximum concentrations of bedload materials found in the trap were about an order of magnitude higher than during non-storm conditions (125 gm/liter versus 12 gm/liter). Likewise, the maximum concentrations of suspended sediment during storms were about an order of magnitude higher than during non-storm conditions (300 mg/liter versus 30 mg/liter). Overall, the results of surf zone sediment movements suggested that only a small amount of littoral drift is moving into Breakwater Harbor, both from its eastern entrance (Cape Henlopen) and from its western entrance (Lewes Beach). However, the exact quantity or rate of sediment transport into Breakwater Harbor could not be determined because offshore transport was only measured at one water depth (1 m). In order to determine an accurate sediment budget of the shorelines of the area, a future study would need to measure sediment transport across the entire surf zone.

Shoreline accretion and erosion were measured by means of beach profiles at eight locations throughout the study area during the time period 1976 to 1979. Between five and thirteen profiles were taken at each site to assess shoreline changes. The beach on eastern Cape Henlopen built seaward about 40 m in three years. This is a very recent reversal of the historical shoreline erosion which was observed prior to this study. On the northwest tip of Cape Henlopen, cycles of rapid shoreline erosion were followed by shoreline accretion. Although net accretion occurred during the three-year period from 1976 to 1979, the rate of accretion on the northwest part of the spit was slower than on the east part of the spit. The shorelines of Breakwater

Harbor experience only minor changes compared to Cape Henlopen. The amount of wave and current energy available to move sand along the shorelines of Breakwater Harbor is very small. The shore-attached ferry breakwater (jetty) blocks sand from flowing east along the shoreline into Breakwater Harbor. In a similar manner, Cape Henlopen traps sand on the east side of the harbor and prevents substantial amounts of sand from flowing west along the shoreline into Breakwater Harbor. As a result, the shorelines of Breakwater Harbor were found to experience a net erosion of about 2 m/year. Because of massive beachfill projects east of Roosevelt Inlet, the net shoreline changes along Lewes Beach were all accretionary.

Very high concentrations of suspended sediment were observed in Breakwater Harbor during SCUBA dives. In order to quantify sediment in the water column during various tidal stages and seasons of the year, sediment traps were used. One type of trap was a set of jars suspended from the bottom of a drogue floating with the current. These traps demonstrated that the concentrations of suspended sediment increased logarithmically toward the bottom. During one flood tide in Breakwater Harbor, about 100 grams of sediment were found to settle on each square meter of bottom each hour. Thus, throughout the harbor during flood tide about 325 metric tons of sediment per hour were found to settle on the bottom. However, it should be pointed out that these sediment trap jars measure only flux through the water column, not actual permanent accumulation on the bottom. A large, flat pan was placed on the bottom in an attempt to find out how much of this sediment deposited during flood tide would be removed during the higher current velocities of ebb tide. However, current scour in the vicinity of the pan prevented acquisition of interpretable results. A second type of sediment trap captured volumes of water at 50 cm above the bed, 190 cm above the bed, and at the water surface. Concentrations of suspended sediment were measured in this manner during eight different days between March, 1979 and August, 1980. These data demonstrated that concentrations of suspended sediments in the harbor during ebb tide were between 10 and 100 mg/liter; however, during the lower current velocities of flood tide, concentrations were only between 5 and 30 mg/liter. It appears that sediment settles onto the bottom during flood tide and slack water, resulting in lower concentrations in the water column. During the higher current velocities of ebb tide, much more sediment is in suspension, most of it being transported through the harbor.

Visual observations of sediment suspended by the passage of large, shallow-draft boats (Cape May-Lewes Ferries) suggested that substantial volumes of sediment might be moved by this artificial means. Measurements of suspended sediment stirred up by the ferry propeller demonstrated that concentrations were consistently between 300 and 400 mg/liter. Every passage of the ferry suspends 56,000 metric tons of sediment, some of which is distributed throughout the area by tidal currents. Since about 4,000 passages of ferries have been made every year since the line's opening in 1964, the volume of sediment suspended by this mechanism since 1964 may well be a dominant factor controlling sedimentation in the vicinity. Unfortunately, the ferry runs year-round, and therefore, I was prevented from testing to see what effect the ferry might have on absolute suspended sediment concentrations.

Surficial sedimentary environments on the Cape Henlopen spit were studied in order to understand the sedimentary structures associated with a variety of environments. A new mechanism for transportation of sand to the northwest part of the spit was discovered. The back-berm runnel slopes down to the north and west. When storm waves overtop the berm, a channel begins flowing toward the northwest part of the spit. Some branches of these channels were found to cut through low areas in the dune line and form channels which transported sand to the western side of the spit also. The sedimentary structures associated with these storm wash-through channels include festoon cross-bedding and deltaic forms. Both of these are typical of fluvial systems. The fact that these "fluvial" sedimentary structures can occur on a regressive spit adds another variant to the structures geolgists might expect to see associated with spits in the ancient rock record.

Holocene Geologic History

The Holocene geologic evolution of Breakwater Harbor and Cape Henlopen was assembled by studying bottom sediment character, subsurface sediments (obtained from vibracores), seismic profiles, and vertical aerial photographs. Background information was obtained from several previous studies of the region. Geologic cross-sections based on vibracores provided a view of the geometric relationship between different sedimentary facies in the area.

Present bottom sediments in Breakwater Harbor were studied by Demarest (1978a). He found that sediments coarsened from muds in the western part of the harbor, to sandy muds and sandy silts in the central area of the harbor, to muddy sands and sands in the eastern part of the harbor adjacent to Cape Henlopen. Depths in the harbor generally deepen from about 3 m (10 ft.) in the west to about 17 m (55 ft.) in the east, where a deep hole created by the funneled waters of ebb tide exists. Evidence from subsurface cores and seismic records shows that the Pleistocene surface also slopes down to the east with a dip of about 0.2°. There is a fairly sharp dividing line on the surface sediments of the harbor which separates the sandy sediments of Cape Henlopen from the silty sediments of Breakwater Harbor. Offshore of Cape Henlopen, bottom sediment samples and seismic profiling records of bedforms and layers provided information on present bottom sediments as well as on relict bottom sediments. Around the north and west margins of the spit, deep scour channels exist at depths of 9 to 17 meters (30 ft. to 55 ft.). Strong tidal flow has caused the exposure of relict sediments in some areas of these channels. Flood- and ebb-oriented sand waves are found north of the cape. West and east of the cape, flood shoals and ebb shoals are found; both probably are formed from sediment which has been removed from the spit during flood and ebb tide.

Twenty-six vibracores from Breakwater Harbor and vicinity were obtained in order to determine the mechanisms and rates of shoaling in the Holocene sediments. Using information from visual inspection and x-radiographs of vibracores, I assembled a model of Holocene deposition in the Breakwater Harbor area. Prior to the inner breakwater construction in 1831, laminations of muds and medium sands were deposited throughout the harbor. The muds were deposited during quiescent times of slack water and the sands were deposited during storms. Two end members of internal sedimentary structures were preserved: 1) during the summer months, active benthic organisms bioturbated the sediments near the surface, effectively homogenizing any laminations which may have been present; and 2) during the winter months when burrowers were relatively inactive, distinct laminations of storm-deposited medium sands were alternated with fine sands or silts.

The above model of sedimentation applies to the eastern area of the harbor, even after the introduction of the inner breakwater in 1831. However, because of the breakwater's blockage of sandy sediments coming from Cape Henlopen during storms, the western area of the harbor did not receive medium sands after 1831. Therefore, the model of sedimentation after 1831 in western Breakwater Harbor is similar to the previous model except that the grain size is smaller.

Sedimentation rates of harbor deposits since 1850 were calculated by using the first occurrence of coal in the harbor cores. That coal was first deposited in the 1850's by coal-fired steamships which began using Breakwater Harbor. The average sedimentation rate throughout the harbor since 1850 was about 2.3 cm/year. Prior to 1850, sedimentation rates to the base of the Holocene section were about an order of magnitude less.

The geometric relationship between the sandy sediments of the prograding Cape Henlopen and the silty sediments of Breakwater Harbor is one of intertonguing facies. During storm events, the sandy sediments derived from Cape Henlopen were deposited in the harbor. These sandy lenses thin and fine toward the west where they blend into the normal silty sediments of the harbor. During subsequent quiescent periods, harbor silts would again build up until another storm initiates the next sequence. However, as the cape has continued to grow north, the source of sand for the harbor has been removed farther away from the harbor; the top meter of sediment in Breakwater Harbor consists entirely of silts. In summary, the sequence in the harbor is a clear, fining-upward one with gravel lag at the base, silty sands in the middle, and silts on the top. However, it should be pointed out that this fining-upward sequence does not indicate a deepening of water. Instead, this fining-upward sequence represents a shoaling phenomenon in the leeward of a regressive spit.

The Geological Future

The geological future of the study area involves two interdependent factors: 1) the future growth of Cape Henlopen, and 2) the future shoaling of Breakwater Harbor. However, since this area has been heavily impacted by man's coastal engineering structures in the past, one might be wise to include man's activities as an important factor. Although the exact timing of Cape Henlopen's westerly growth and eventual attachment to the inner breakwater is unclear, it appears indisputable that this event will occur. When this happens, the harbor would fill with sediments very quickly. It would be wise then to plan for this eventuality now by presenting concepts for harbor revitalization.

From 1830 to the present, we have reliable historical records of the growth of Cape Henlopen as a simple spit. From 1830 to 1930, the spit grew to the north-northwest at a rate of about 10 m/yr. From 1930 to 1969, the rate of advance accelerated to 15-18 m/yr. Throughout these historic records, the eastern side of the cape was eroding at about 3 m/yr. By superimposing vertical aerial photographs of the cape from 1939 to 1977, I was able to confirm the rapid rates reported, but I also noticed a reversal of the accelerated growth rates (Table X-1). In intervals of about 10 years from 1939 to 1977, the rates of northwesterly advance decreased from 28 m/yr. to 20 m/yr. to 13 m/yr., and finally, from 1969 to 1977, to 3 m/yr. During this latest interval, sand began building out on the northeast side of the spit at rates of about 10 m/yr.

I think the cause of this phenomenon is fairly simple: water leaving Delaware Bay during ebb tide flows south of the outer breakwater and north of Cape Henlopen. As Cape Henlopen grew north, the cross-sectional area of the channel was decreased, which then increased current velocities. It also may be true that Cape Henlopen simply grew out into a position where strong tidal currents have maintained a channel. Seismic records show reflectors of probable relict channels now located under the present Cape Henlopen spit tip. In either case, the current velocities coming out of Delaware Bay and out of Breakwater Harbor can now remove material from the spit tip and deposit it primarily on the eastern side of the spit. Demarest (1978a) also found that subtidal shoals exist to the west, north, and east of the spit.

Presently, the spit has stopped its rapid northwest migration and started to build out to the east. But, how long will this trend continue? Is this just a hesitation phase in which large quantities of sand will be stored on the east side of the spit in preparation for the final push across to the inner breakwater? It is very difficult to predict exactly when the spit will take off again, but it is most likely that a large storm will bring this about by filling in the narrow channel between the western side of the cape and the eastern side of the inner breakwater. However, present current velocities during ebb tide in this channel are fast enough to remove sand and pebbles. The storm event must fill the channel to such an extent that flow out of Breakwater Harbor will be substantially reduced. The last major storm, the 1962 Ash Wednesday storm, did not fill in this channel appreciably; depths are still about 9 m (30 ft.).

However, the channel is getting narrower, which makes it more vulnerable to sudden closure. My estimate of the timing of attachment of Cape Henlopen and the inner breakwater is about the year 2015, but it could be considerably longer. However, given a massive northeast storm or hurricane, this event could happen much sooner. Clearly, a high priority should be given to monitoring the growth of Cape Henlopen.

The uncertainty of the date of harbor closure on its eastern end should discourage plans to continue using the eastern entrance of Breakwater Harbor. As soon as sand fills that channel to the west of the cape, it would become extremely expensive to maintain the channel by dredging. The annual volume of littoral drift sand along the Atlantic coast is about 106,000 m^3. A much more predictable option would be to use the presently active shipping channel which leaves the west end of Breakwater Harbor. This channel is used by the Cape May-Lewes Ferry and by Delaware Bay Pilots. It has not been necessary to dredge that channel since it was opened in 1964. This is because the fine-grained materials which settle here are easily removed by propeller-induced scouring. A small amount of sand is coming around the ferry breakwater (jetty) from Lewes Beach, but compared to the amount of sand coming into Cape Henlopen, this is a trivial amount.

If the shoaling of Breakwater Harbor continues at its present rate (2.3 cm/yr.), it would take about 100 years for it to shoal to present mean low water. If Cape Henlopen attaches to the inner breakwater before this, it will take only about ten years to shoal to mean low water because ebb-tidal currents will then not be present to remove silt deposits. As the shoaling process continues, I expect a narrow channel to form through the harbor. Indeed, that process has started in the eastern end of the harbor area already (Figure 3 of the Introduction).

One future study which should be undertaken as soon as possible is to determine the sedimentation rate in the harbor in the last twenty-five years or so. One method which may help to do this is to use fallout from man-made isotopes which resulted from nuclear testing (Cs^{137}). There is hope that the technique would work (J. Wehmiller, personal communication).

Although the present situation in the study area is not suitable for major new engineering structures, the day may soon arrive when serious consideration is given to revitalizing the Breakwater Harbor area so that it may continue to serve as a marine port. One way to do this is to build a structure connecting the northern end of Cape Henlopen to the southern end of the outer breakwater. This would provide dock space adjacent to deep channels of Delaware Bay. This action would make Lewes the only deep-water port on the eastern seaboard. If you doubt the feasibility of such a project, keep in mind that the Dutch have already greatly surpassed this in their technological capabilities. I believe potential such as this will continue to make the area of Cape Henlopen and Breakwater Harbor one of the most exciting places in the world for process-oriented coastal geologists and engineers.

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APPENDICES

APPENDIX A

DATA FORMS USED

CURRENT METER DATA FORM

STATION # ____________ SHEET NO. _____ OF _____

DATE	TIME	DECLINATION°	INCLINATION°	RATE(cm/sec)	REMARKS

SUSPENDED SEDIMENT DATA FORM

STATION LOCATION: ____________ SAMPLE NUMBERS: ____________
DATE: ____________ TIDAL STAGE: ____________ TIME: ____________
TIME OF HIGH OR LOW WATER: ____________ WIND VELOCITY (km/hr.): ____________ FROM: ____________
WAVE HEIGHT (cm): ____________ DIRECTION: ____________ NOTES: ____________

SAMPLE #	HT. ABOVE BED (m)	BOTTLE #	VOLUME (ml)	FILTER #	FILTER WT. (gm)	FILTER + SED. (gm)	SED. WT. (gm)	SUSP. SED. CONC. (mg/l)	NOTES

SURF ZONE BEDLOAD SEDIMENT DATA FORM

STATION & SAMPLE	DATE	TIME	TEMP. (C) W	A	WIND (km/hr)	WATER DEPTH (cm)	L.S. CURRENT VELOCITY	FILTER #	FILTER WT. (gm)	SED. WT. (gm)	SUSP. SED. CONC. (mg/l)	NOTES

APPENDIX B

GRAIN SIZE ANALYSIS DATA -- CAPE HENLOPEN SHORELINES

LOCATION	%GRAVEL	%SAND	%SILT	%CLAY	$M_Z(\phi)$	SIZE	$\sigma_I(\phi)$	SORT.	$SK_I(\phi)$	SKEW.	$K_G(\phi)$	KURT.
CAPE HENLOPEN BEACH SAMPLES												
C.H. STA. 1, BEACH	0	100	0	0	1.6	M SAND	.58	M WELL	.01	NR SYM	1.26	LEPT
" BEDLOAD	0	100	0	0	1.7	M SAND	.62	M WELL	.10	NR SYM	.90	PLAT
C.H. STA. 2, BEACH	0	100	0	0	1.2	M SAND	.41	WELL	.12	F SKW	1.37	LEPT
" BEDLOAD	0	100	0	0	1.6	M SAND	.22	V WELL	.31	S F SKW	1.17	LEPT
C.H. STA. 3, BEACH	25.5	74.5	0	0	-.1	VC SAND	1.08	POORLY	-.16	C SKW	1.04	MESO
" BEDLOAD	4.1	95.9	0	0	1.3	M SAND	.95	M WELL	-.12	C SKW	1.19	LEPT
C.H. STA. 4, BEACH	0	100	0	0	1.3	M SAND	.59	M WELL	.35	S F SKW	.95	MESO
" BEDLOAD	0	100	0	0	1.6	M SAND	.56	M WELL	.22	F SKW	1.02	MESO
C.H. STA. 5, BEACH	0	100	0	0	1.4	M SAND	.46	WELL	-.29	C SKW	1.28	LEPT
" BEDLOAD	0	100	0	0	1.6	M SAND	.57	M WELL	.06	NR SYM	1.02	MESO
ROS. INLET, BEDLOAD	0	100	0	0	2.3	F SAND	.39	WELL	-.34	S C SKW	1.53	V PLAT
SO. BOWERS, BEDLOAD	0	100	0	0	2.0	F SAND	.54	M WELL	.12	F SKW	.89	PLAT
CAPE HENLOPEN POST-STORM SAMPLES												
C.H. STA. I	2.7	97.3	0	0	.9	C SAND	.61	M WELL	.44	F SKW	.49	V PLAT
C.H. STA. II	5	95	0	0	1.1	M SAND	.63	M WELL	.31	S F SKW	.49	V PLAT
C.H. STA. III	.4	99.6	0	0	1.1	M SAND	.69	M WELL	-.08	NR SYM	.80	PLAT
C.H. STA. IV	0	100	0	0	1.8	M SAND	.56	M WELL	-.19	C SKW	1.25	LEPT
C.H. STA. V	.3	99.7	0	0	1.2	M SAND	.69	M WELL	.01	NR SYM	.93	MESO
C.H. STA. VI	0	100	0	0	1.9	M SAND	.53	M WELL	-.03	NR SYM	1.13	LEPT
C.H. STA. VII	0	100	0	0	2.1	F SAND	.45	WELL	-.07	NR SYM	1.07	MESO
C.H. STA. VIII	.2	99.8	0	0	1.9	M SAND	.48	WELL	.07	NR SYM	1.09	MESO
C.H. STA. IX	0	100	0	0	2.2	F SAND	.54	M WELL	-.16	C SKW	.75	PLAT

APPENDIX C

SAMPLING STATION LINES (4 BOTTOM SEDIMENT SAMPLES ALONG EACH LINE)

STATION & SAMPLE LOCATION	% GRAVEL	% SAND	% SILT	% CLAY	$M_Z(\phi)$	SIZE
1 HIGH TIDE LINE	6.1	93.9	0	0	0.6	C SAND
1 HIGH TIDE 100cm DEPTH	25.6	74.4	0	0	-0.3	VC SAND
1 LOW TIDE LINE	12.3	87.7	0	0	0.6	C SAND
1 LOW TIDE 100cm DEPTH	1.4	98.6	0	0	2.1	F SAND
2 HIGH TIDE LINE	1.5	98.5	0	0	1.0	M-C SAND
2 HIGH TIDE 100cm DEPTH	1.9	98.1	0	0	1.4	M SAND
2 LOW TIDE LINE	11.1	88.9	0	0	0.4	C SAND
2 LOW TIDE 100cm DEPTH	2.7	97.3	0	0	2.0	F-M SAND
3 HIGH TIDE LINE	6.7	92.3	0	0	1.2	M SAND
3 HIGH TIDE 100cm DEPTH	1.4	98.6	0	0	1.8	M SAND
3 LOW TIDE LINE	0.6	99.4	0	0	0.8	C SAND
3 LOW TIDE 100cm DEPTH	0.4	99.6	0	0	2.0	F-M SAND
4 HIGH TIDE LINE	1.0	99.0	0	0	0.7	C SAND
4 HIGH TIDE 100cm DEPTH	0.8	99.2	0	0	1.1	M SAND
4 LOW TIDE LINE	2.9	97.1	0	0	1.0	M-C SAND
4 LOW TIDE 100cm DEPTH	3.4	96.6	0	0	1.3	M SAND
5 HIGH TIDE LINE	5.1	94.9	0	0	1.1	M SAND
5 HIGH TIDE 100cm DEPTH	12.0	88.0	0	0	1.5	M SAND
5 LOW TIDE LINE	0.0	100.0	0	0	1.7	M SAND
5 LOW TIDE 100cm DEPTH	0.0	100.0	0	0	1.7	M SAND
6 HIGH TIDE LINE	31.0	69.0	0	0	0.1	C SAND
6 HIGH TIDE 100cm DEPTH	9.5	90.5	0	0	1.3	M SAND
6 LOW TIDE LINE	0.0	100.0	0	0	1.6	M SAND
6 LOW TIDE 100cm DEPTH	0.0	100.0	0	0	1.8	M SAND
7 HIGH TIDE LINE	17.9	82.1	0	0	0.0	C-VC SAND
7 HIGH TIDE 100cm DEPTH	0.0	100.0	0	0	1.6	M SAND
7 LOW TIDE LINE	0.0	100.0	0	0	1.7	M SAND
7 LOW TIDE 100cm DEPTH	0.0	100.0	0	0	1.9	M SAND
8 HIGH TIDE LINE	23.6	76.4	0	0	0.1	C SAND
8 HIGH TIDE 100cm DEPTH	7.1	92.9	0	0	1.9	M SAND

STATION & SAMPLE LOCATION	% GRAVEL	% SAND	% SILT	% CLAY	$M_Z(\emptyset)$	SIZE
8 LOW TIDE LINE	24.9	75.1	0	0	0.1	C SAND
8 LOW TIDE 100cm DEPTH	0.0	100.0	0	0	1.9	M SAND
9 HIGH TIDE LINE	24.4	75.6	0	0	0.0	C-VC SAND
9 HIGH TIDE 100cm DEPTH	27.0	73.0	0	0	0.0	C-VC SAND
9 LOW TIDE LINE	50.7	49.3	0	0	-1.0	VCS - GRAV.
9 LOW TIDE 100cm DEPTH	0.0	100.0	0	0	2.1	F SAND
10 HIGH TIDE LINE	21.0	79.0	0	0	0.5	C SAND
10 HIGH TIDE 100cm DEPTH	18.8	81.2	0	0	1.0	M-C SAND
10 LOW TIDE LINE	32.5	67.5	0	0	0.0	C-VC SAND
10 LOW TIDE 100cm DEPTH	0.0	100.0	0	0	2.4	F SAND
11 HIGH TIDE LINE	6.7	93.3	0	0	0.8	C SAND
11 HIGH TIDE 100cm DEPTH	17.2	82.8	0	0	0.5	C SAND
11 LOW TIDE LINE	14.2	85.8	0	0	0.2	C SAND
11 LOW TIDE 100cm DEPTH	3.0	97.0	0	0	1.4	M SAND
12 HIGH TIDE LINE	32.4	67.6	0	0	-0.2	VC SAND
12 HIGH TIDE 100cm DEPTH	39.1	60.9	0	0	-0.7	VC SAND
12 LOW TIDE LINE	55.8	44.2	0	0	-1.3	GRAVEL
12 LOW TIDE 100cm DEPTH	0.0	100.0	0	0	2.8	F SAND
13 HIGH TIDE LINE	12.9	87.1	0	0	0.5	C SAND
13 HIGH TIDE 100cm DEPTH	31.9	68.1	0	0	-0.3	VC SAND
13 LOW TIDE LINE	30.7	69.3	0	0	-0.4	VC SAND
13 LOW TIDE 100cm DEPTH	0.0	100.0	0	0	2.2	F SAND
14 HIGH TIDE LINE	18.0	82.0	0	0	0.0	C-VC SAND
14 HIGH TIDE 100cm DEPTH	17.9	82.1	0	0	0.2	C SAND
14 LOW TIDE LINE	33.0	67.0	0	0	-0.5	VC SAND
14 LOW TIDE 100cm DEPTH	0.0	100.0	0	0	2.2	F SAND
15 HIGH TIDE LINE	32.1	67.9	0	0	-0.2	VC SAND
15 HIGH TIDE 100cm DEPTH	16.5	83.5	0	0	0.4	C SAND
15 LOW TIDE LINE	41.2	58.8	0	0	-0.7	VC SAND
15 LOW TIDE 100cm DEPTH	0.0	100.0	0	0	1.9	M SAND
16 HIGH TIDE LINE	25.6	74.4	0	0	0.0	C-VC SAND
16 HIGH TIDE 100cm DEPTH	7.6	92.4	0	0	0.4	C SAND
16 LOW TIDE LINE	11.8	88.2	0	0	0.2	C SAND
16 LOW TIDE 100cm DEPTH	0.0	59.0	41		3.1	VF SAND

APPENDIX D

PILOT STUDY BOTTOM SEDIMENT TRAP GRAIN SIZE ANALYSIS DATA

HEIGHT ABOVE BED (cm)	% SAND	% SILT	% CLAY
20, SPLIT A	44.8	31	24.2
20, SPLIT B	25.8	45.3	28.9
30, SPLIT A	33.5	36.8	29.7
30, SPLIT B	42.8	31.8	25.4
50	43.5	33	23.5
60	45	31.4	23.6
70, SPLIT A	35.7	36	28.3
70, SPLIT B	44.4	30.6	25
80	44.9	33	22.1
90	44.6	32.6	22.8

NOTE: SAND IS ALMOST ENTIRELY FINE AND VERY FINE SAND. ALL SAMPLES ARE SANDY MUDS.

APPENDIX E

VOLATILE SOLIDS DETERMINATIONS FOR SAMPLES FROM VIBRACORES, BOTTOM SEDIMENT TRAPS, SUSPENDED SEDIMENT TRAPS, AND SCUBA SAMPLES

NOTE: 6-78-2 refers to vibracore # 6, taken in 1978, sample # 2.

SAMPLE #	SEDIMENT TYPE	VOLATILE SOLIDS (% LOSS)
VIBRACORES		
6-Biot. (205-207cm)	Silty	10.73
6-78-2 (298-300cm)	Sandy	1.61
6-78-3 (520-522cm)	Sandy	0.97
6-78-4 (750-752cm)	Pebbly	0.70
7-78-1 (28-30cm)	Silty	8.88
7-78-3 (338-340cm)	Silty-sand	1.91
7-78-4 (710-712cm)	Clean sand	0.68
12-78-1 (375-377cm)	Silty sand	2.73
12-78-2 (552-554cm)	Sandy silt	4.31
17-78-1 (450-452cm)	Sandy	1.14
19-78-1 (90-92cm)	Organic mat	27.05
21-78-1 (600-602cm)	Sandy	0.86
22-78-1 (480-482cm)	White sand	2.55
25-78-1 (610-612cm)	Clean sand	0.93
7-78-2 (170cm)	Silty sand with coal	23.91
2-78-3 (383-385cm)	Silty	9.92
20-78 (620cm)	Sand with shells	0.90
PILOT STUDY BOTTOM SEDIMENT TRAPS		
P.S. 20cm	Silt with shells	9.44
P.S. 30cm	Silt with shells	9.17
P.S. 50cm	Silt	11.64
P.S. 60cm	Silt with shells	11.46
P.S. 70cm	Silt	12.02
P.S. 80cm	Silt	10.58
P.S. 90cm	Silt	11.81
SUSPENDED SEDIMENT TRAPS		
5/16/79 G 50cm	Silt	14.85
6/5/79 H 50cm	Silt	17.40
7/3/79 J Ferry Surf.	Silt	8.57
8/22/80 B 50cm	Silt	12.64
S.C.U.B.A. SAMPLES		
Recovery of oxidized brown-olive "fluff" layer at sediment-water interface in east-central Breakwater Harbor	Silt	5.36
"	Silt	6.65

NOTE: All samples burned at 550°C for one hour.

APPENDIX F

X-RAY DIFFRACTION MINERALOGIES

Mineralogies of selected silt and clay samples from vibracores and suspended sediment traps. Results are reported as peak height relative abundances: H = high; M = moderate; L = low; -- = absent. NOTE: 6-78-2 refers to vibracore # 6, taken in 1978, sample # 2.

VIBRACORE SAMPLE	CHLORITE	KAOLINITE	ILLITE	MONTMORILLONITE	QUARTZ	FELDSPAR
6-Biot. 205-207cm	L	--	M	--	L	L
6-78-2 298-300cm	M	--	L	--	H	L
6-78-3 520-522cm	L	--	L	--	H	M
6-78-4 750-752cm	L	--	L	L	H	H
7-78-1 28-30cm	M	--	M	--	M	L
7-78-3 338-340cm	M	--	L	L	H	L
7-78-4 710-712cm	M	--	M	--	H	L
12-78-1 375-377cm	L	--	L	--	H	M
12-78-2 552-554cm	H	--	H	--	M	L
17-78-1 450-452cm	M	--	L	L	H	L
19-78-1 90-92cm	M	--	L	--	H	L
21-78-1 600-602cm	M	--	M	--	H	L
22-78-1 480-482cm	--	H	--	--	L	--
25-78-1 610-612cm	M	--	L	--	H	L
SUSPENDED SEDIMENT SAMPLE						
8/9/79 C 50	L	--	L	--	H	L
" C 190	L	--	L	--	H	--
" C Surf.	M	--	L	--	M	--
4/25/79 C 50	M	--	M	--	H	L
" C 190	L	--	L	--	M	L
" C Surf.	L	--	L	--	L	L
8/22/80 C 50	M	--	M	--	M	M
" C 190	M	--	M	--	M	M
" C Surf.	M	--	M	--	M	M

X-RAY DIFFRACTION MINERALOGIES (CONT'D)

HARBOR BOTTOM SAMPLE	CHLORITE	KAOLINITE	ILLITE	MONTMORILLONITE	QUARTZ	FELDSPAR
A	M	--	L	--	M	L
B	L	--	H	--	M	L
C	L	--	--	--	M	L
D	M	--	M	--	M	L
E	L	--	L	--	M	L
F	L	--	L	--	H	L
G	H	--	H	--	M	L
H	L	--	--	--	M	L

APPENDIX G

GRAIN SIZE ANALYSIS DATA BOTTOM SEDIMENT SAMPLE LOCATIONS

STATION	% SAND	% SILT	% CLAY	SEDIMENT TYPE
1	71.6	18.4	10	MUDDY SAND
2	85.1	12.7	5.2	"
3	70	19.8	10.2	"
4	59.7	26.7	13.6	"
5	71	18.5	10.6	"
6	51.5	32.4	16.1	"
7	72	18.1	9.9	"
8	84	9.8	6.2	"
9	63.2	24.6	12.2	"
10	47.4	35.6	17	SANDY MUD
11	76.7	15.1	8.2	MUDDY SAND

APPENDIX H

GRAIN SIZE ANALYSIS DATA--OFFSHORE OF CAPE HENLOPEN AND HARBOR OF REFUGE

SAMPLE	% GRAVEL	% SAND	% SILT	% CLAY	$M_Z(\emptyset)$	SIZE	$\sigma_I(\emptyset)$	SORTING	$SK_I(\emptyset)$	SKEWNESS	$K_G(\emptyset)$	KURTOSIS
1	5.6	94.4	0	0	0.8	C SAND	.83	MOD	-.20	C SK	1.02	MESO
2	1.6	98.4	0	0	1.3	M SAND	.57	M WELL	-.31	SC SK	1.23	LEPT
3	50.3	49.7	0	0	-0.9	VC SAND	2.0	POORLY	-.75	SC SK	.74	PLAT
4	0	95.7	4.3		2.2	F SAND						
5	41.7	58.3	0	0	-0.6	VC SAND	1.82	POORLY	-.47	SC SK	.52	V PLAT
6	19.4	80.6	0	0	0.5	C SAND	1.80	POORLY	-.66	SC SK	1.21	LEPT
7	0	35	32.1	32.9	5.9	M SILT	4.05	EX POOR	.03	NR SYM	.72	PLAT
8	0	79.4	9.6	11	3.9	VF SAND	2.27	V POOR	.58	SF SK	3.14	EX LEPT
9	0	78.8	10.7	10.5	3.5	VF SAND	2.59	V POOR	.50	SF SK	2.11	V LEPT
11	.3	99.4	.3	0	2.3	F SAND	.52	M WELL	-.13	C SK	.94	MESO
13	0	19.8	52.2	28	6.8	F SILT	3.23	V POOR	.08	NR SYM	1.04	MESO
14	17.5	82.5	0	0	-0.2	VC SAND	.93	MOD	.09	NR SYM	1.23	LEPT
21	0.1	99.9	0	0	2.2	F SAND	.50	WELL	-.15	C SK	.88	PLAT
22	14.4	85.6	0	0	0.4	C SAND	1.09	POORLY	-.29	C SK	.82	PLAT
24	0	24.5	54	21.5	6.1	F SILT	3.16	V POOR	.17	F SK	1.27	LEPT
25	0	1.1	83	15.9	6.5	F SILT						
26	0	1.3	85	13.7	6.4	F SILT						
27	54.5	45.5	0	0	-2.0	GRAVEL	1.63	POORLY	.64	SF SK	.57	V PLAT
28	19.8	80.2	0	0	0	C-VC SAND	1.22	POORLY	.57	SF SK	1.45	LEPT
29	48	52	0	0	-1.0	VCS-GRAV.	2.03	V POOR	-.86	SC SK	.52	V PLAT

APPENDIX J

GRAIN-SIZE ANALYSIS METHODS

A variety of different procedures were followed to obtain grain-size information on the 170 sediment samples analyzed as part of this study. Samples consisting entirely of sand and gravel were analyzed either by means of brass sieves or by settling tube (R.S.A.). Samples consisting of sand, silt, and clay were analyzed by means of a hydraulic suction through stainless-steel sieves and subsequent pipette analysis of silts and clays. A summary of each procedure used follows, with appropriate references cited.

Sand Samples--Sieve Shaking Technique

Washing the cloth sample bag for two minutes removes extraneous sand and serves as a pre-wash for removal of salts. Sample is then placed in a plastic beaker and filled to one-thousand-milliliter mark with clean tap water. This is allowed to sit for at least six hours to allow settling of fines and solution of salts. Carefully siphon water off of sediment and transfer to a glass beaker for drying in an oven at 70°C. When dry, disaggregation is achieved with a rubber-tipped pestle and plastic bowl. To assure total disaggregation, only enough sediment to just cover bottom of bowl is ground at any one time. At this time an estimate of the maximum grain size and percent coarse material should be made by visual inspection.

By using a mechanical separator, split the sample until a weight of sediment is reached appropriate to the percentage of coarse material observed in the sample. A guide for these weights was obtained from Folk (1974). The sample is then poured into a six-sieve stack at one-half-phi intervals (sieves 7.5" in diameter) from -2.5 phi to 0.0 phi. After ten minutes at half setting on a Cenco-Meinzer sieve shaker (Model #18480), the sieves are removed with material from the pan poured into the next six-sieve stack from 0.5 phi to 3.0 phi. This stack is shaken as before with the pan emptied into and shaken through 3.5 and 4.0 phi sieves if necessary. The contents of each sieve are weighed on a triple-beam balance to the nearest 0.1 gm and entered into an appropriate data table. From this a graph is constructed using phi versus cumulative percent with parameters M_Z, σ_I, SK_I, and K_G calculated as per Folk (1974).

Grain-size statistics were calculated from cumulative percent curves on the basis of the most accurate of Folk's (1974) formulas for the following four, commonly cited parameters:

Mean grain size (Folk's graphic mean) with a formula of $M_Z = (\phi16 + \phi50 + \phi84)/3$ and with verbal limits determined by the phi (ϕ) scale and Wentworth's (1922) size classes; for purposes of this study, anything larger than very coarse sand is referred to as gravel;

Sorting index (Folk's inclusive graphic standard deviation) with a formula of $\sigma_I = \frac{\phi84-\phi16}{4} + \frac{\phi95-\phi5}{6.6}$ and with indices of less than 0.35 called very well sorted, 0.35 to 0.50 well sorted, 0.50 to 0.71

moderately well sorted, 0.71 to 1.00 moderately sorted, 1.00 to 2.00 poorly sorted, 2.00 to 4.00 very poorly sorted, and greater than 4.00 extremely poorly sorted;

Skewness index (Folk's inclusive graphic skewness) with a formula of $SK_I = \frac{\phi16+\phi84-2\phi50}{2(\phi84-\phi16)} + \frac{\phi5+\phi95-2\phi50}{2(\phi95-\phi5)}$ and with indices of 1.00 to 0.30 called strongly fine skewed, 0.30 to 0.10 fine skewed, 0.10 to -0.10 nearly symmetrical, -0.10 to -0.30 coarse skewed, and -0.30 to -1.00 strongly coarse skewed (those with excess fine material, that is, a tail to the right on cumulative percent curves, have positive skewness; whereas, those with excess coarse material, that is, a tail to the left on cumulative percent curves, have negative skewness); and finally,

Kurtosis (peakedness) index (Folk's graphic kurtosis) with a formula of $K_G = \frac{\phi95-\phi5}{2.44(\phi75-\phi25)}$ and with indices less than 0.67 called very platykurtic (flat), 0.67 to 0.90 platykurtic, 0.90 to 1.11 mesokurtic, 1.11 to 1.50 leptokurtic, 1.50 to 3.00 very leptokurtic, and greater than 3.00 extremely leptokurtic (peaked).

Sand Samples--Rapid-Sediment Analyzer (R.S.A.)

The rapid-sediment-analysis system at the Geology Department, University of Delaware, consists of a water-filled plexiglass tube through which sand samples settle. The rate at which grains settle is proportional to the square of the grain diameter, but is also dependent on particle density, water density, acceleration of gravity, and fluid viscosity. Larger grains settle at quicker rates and accumulate their weight on a micro-balance pan at the bottom of the tube. This relationship governing fall rate of spherical particles in fluids is called Stokes' Law of Settling Velocity, and is written as:

$$v = \frac{(\rho p - \rho f)gd^2}{18\mu}$$

where,

v = velocity of fall (cm/sec)

d = diameter of particle (cm)

ρp = particle density (2.5 gm/cm^3 for quartz)

ρf = water density (1.0 gm/cm^3 for distilled)

g = acceleration of gravity (980 cm/sec^2)

μ = molecular viscosity (@ 22°C, 0.01 gm/sec x cm)

Distance of fall for the settling tube is 158.5 cm. The grains are mounted on a plexiglass surface at the top of the tube by means of photo-flow solution (Kodak's low surface-tension fluid). The plexiglass mount is lowered automatically onto the water surface so that all grains are introduced simultaneously. Weights are displayed cumulatively versus time on a Sargent Chart Recorder. The curve then can be used to obtain grain-size information. Alternately, a Hewlett-Packard desktop computer Model #2648-A can be used to generate grain-size statistics directly.

Use of such a rapid-sediment-analysis system requires understanding of the principles being employed, as well as a practical knowledge of equipment operation.

Sand, Silt, and Clay--Hydraulic Suction Through Stainless Sieves (Adapted from Gifford, 1978)

Samples weighed to approximately 7.5 gm are used in this procedure if the sediment appears to have no fraction coarser than approximately 0 Ø. If a very coarse sand/granule fraction (to -2 Ø) is present, a 15 gm sample is used.

The sample is suspended by mechanical agitation in about 100 ml of distilled water; it is then wet-sieved through a stack of three-inch diameter, half-height, stainless-steel sieves of .5 Ø intervals from -2 Ø to 4.5 Ø. The sieve stack is placed on an eight-inch-high, plexiglass, cylindrical receptacle having an inlet near the upper end into which a length of plastic tubing connected to a sink-type aspirator is inserted. This wet-vacuum system aids in the separation of size fractions as each is disaggregated carefully and cleaned with a spray of distilled water, which washes the finer material into the next lower sieve. That portion of the sample finer than 4.5 Ø (the silt/clay fraction) passes through the lowermost sieve and is caught in the receptacle (2,000 ml volume) for pipette analysis.

When all 12 sieves have been sprayed, they and their sediment fractions are oven dried overnight; the stack of sieves is reassembled and shaken on a small vibrating unit for 10 minutes to complete the sieving process. Any dry sediment caught in the pan below the 4.0 Ø sieve is added to the silt/clay fraction. Each sieve with its sediment fraction is then weighed to the nearest 0.001 gm on an analytical balance. In preparation for the next sample analysis, the set of 12 empty sieves is cleaned ultrasonically in a soap solution for a minimum of 30 minutes, or until all sediment grains have been removed from the mesh of each screen.

The silt/clay suspension is now in the 2,000 ml graduated cylinder, but the volume of the suspension is not up to 2,000 ml. A 40 ml aliquot of known weight (determined to four decimal places) of Calgon is added to the cylinder, and the suspension is brought up to exactly 2,000 ml with more distilled water.

When eight such mud fractions have been prepared, they are all analyzed in one operation exactly following the pipette procedure of Schlee (1957). Grain-size statistics are calculated according to the formulas cited previously from Folk (1974).

Silt and Clay Pipetting Procedure (Adapted from Schlee, 1957)

Run eight samples at once.

With a pocket knife, shave the contaminated sediment off the outside of the core sample. Soak 1 to 15 grams of sediment (15 gms normal size) in 100 ml redistilled water for at least 24 hours. Centrifuge in 250 ml redistilled water for five minutes at 2,000 r.p.m., and pour off the salt water. Disaggregate with an ultrasonic bath (or mixing blender, if bath unavailable) for two minutes. Sieve each sample through a 63 micron, 3-inch diameter, brass sieve using finger and washing with 2 gm/l sodium hexametaphosphate water (Calgon).

Washings (silt and clay) go directly into 2,000 ml plastic cylinders. Fill each cylinder to 1,000 ml with sodium hexametaphosphate water, stir, and allow to set for 2 to 3 hours to see if the sample flocculates. Wash the greater-than-63-micron fraction with distilled water into a weighed beaker. Dry and weigh the sand fraction.

Agitate each 2,000 ml cylinder vigorously with a rubber plunger or propeller for 30 seconds, insert pipette at least 25 cm below the water surface, and withdraw a 50 ml aliquot, the time zero sample. Place it in a numbered, weighed 50 ml beaker. Rinse sediment on walls of pipette (with redistilled water) into beaker for each aliquot. Agitate 2,000 ml cylinder for 30 seconds, wait 2 minutes, and withdraw a 50 ml aliquot from a depth of 10 cm below the surface. Repeat for other 7 cylinders. Then begin procedure where all aliquots are taken sequentially at carefully timed intervals. At eight minutes from time zero, agitate the first cylinder for 30 seconds, wait 30 seconds, then agitate the second for 30 seconds, wait 30 seconds, then agitate the third, etc. After the agitation of the eighth cylinder, wait 30 seconds and take an aliquot from the first cylinder at a depth of 10 cm. Take aliquots from successive cylinders at one-minute intervals. Repeat this procedure without agitating the cylinders at

times:	and depths:
32 min.	10 cm
2 hr. 08 min.	10 cm
5 hr. 38 min.	7 cm
24 hr. 00 min.	7 cm

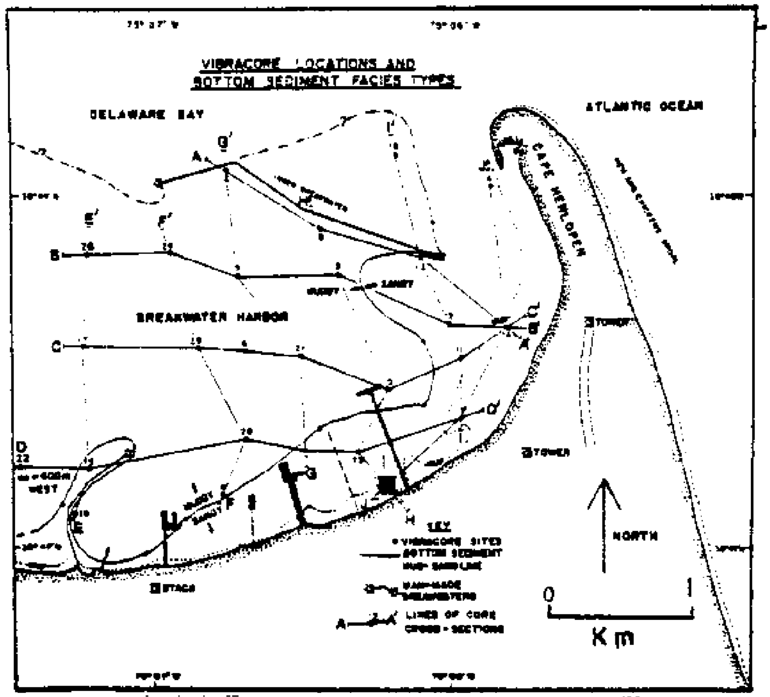
Cover the cylinders to prevent dust contamination before these last four aliquots. Weigh sediment in beakers and calculate grain-size statistics using methods of Folk (1974).

APPENDIX K

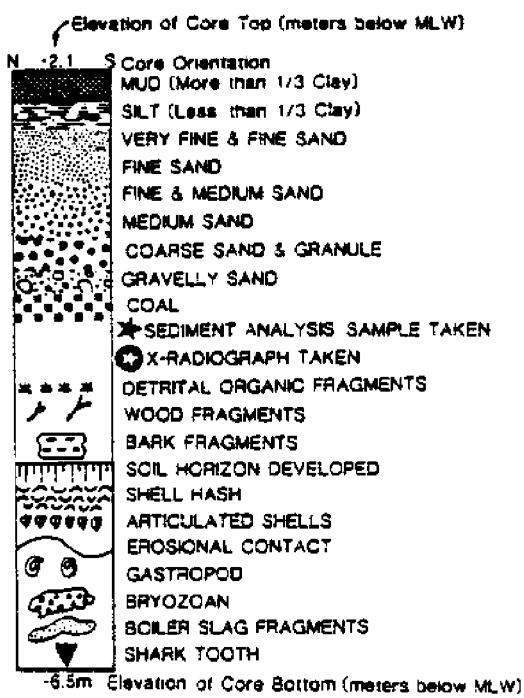
VIBRACORE DESCRIPTIVE LOGS, ENVIRONMENTS OF DEPOSITION AND ESTIMATED AGES

NOTE: More detailed lithologic descriptions are available from the author or from the Department of Geology core catalog at the University of Delaware, Dr. J. C. Kraft, curator.

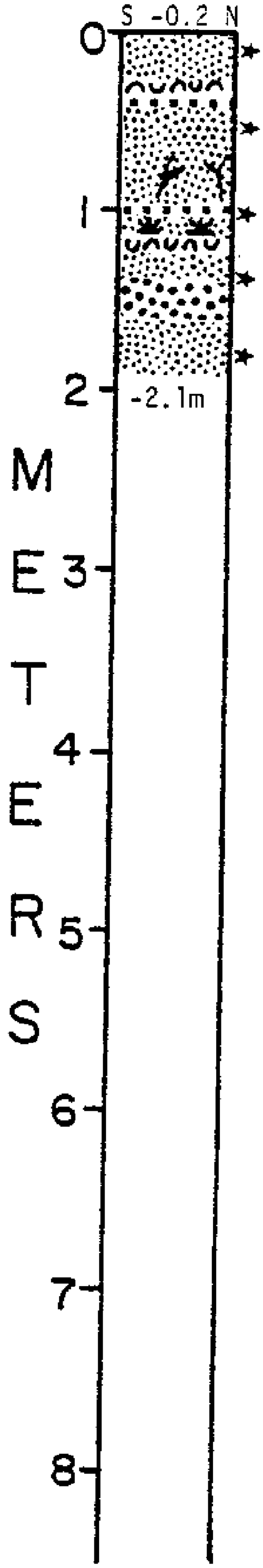
VIBRACORE I



KEY TO SYMBOLS USED IN CORE LOG DESCRIPTIONS



BREAKWATER HARBOR VIBRACORE 1 (W.H.H.-B.H.-1-'78)



Offshore bar; yellowish grey; sediments burrowed throughout

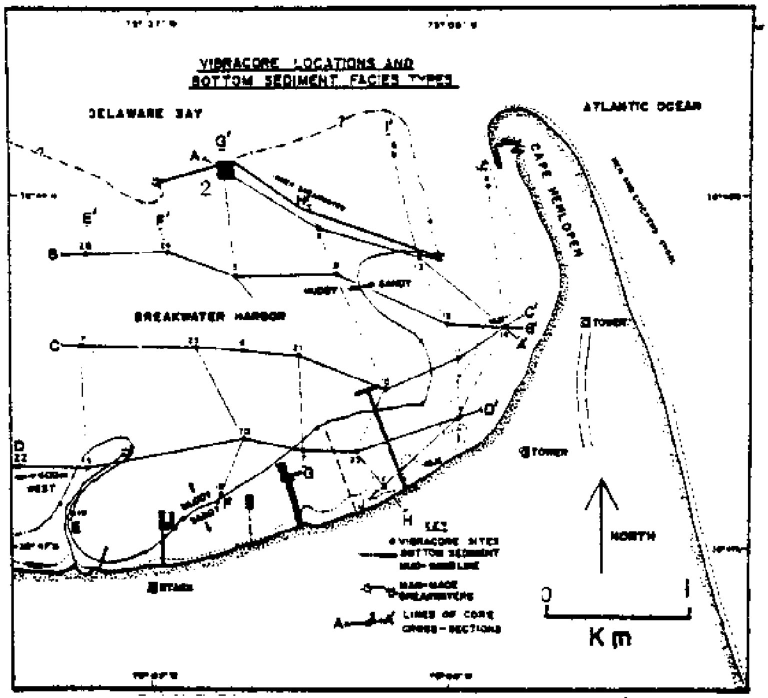
Offshore runnel; laminations dip 5° to 7° toward south; medium grey; charred wood fragments

Offshore bar; yellowish grey

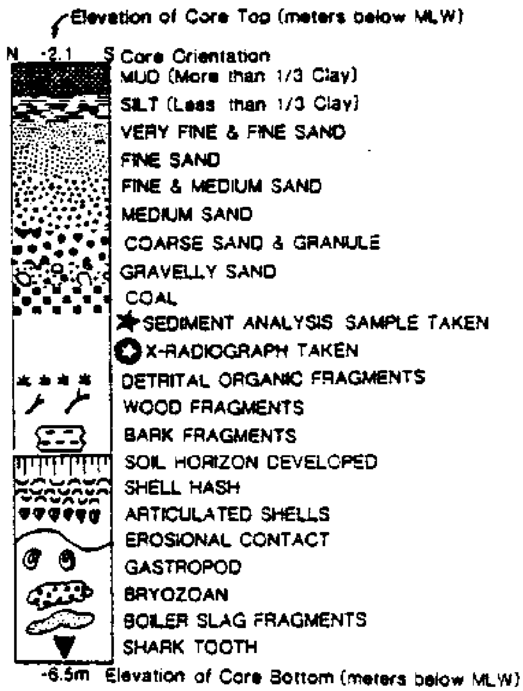
Offshore runnel

Offshore bar; light grey; 1800 or later?

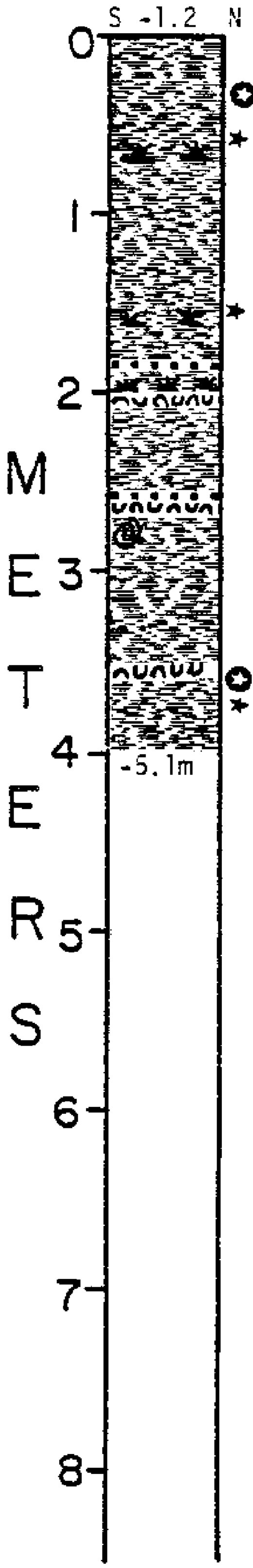
VIBRACORE 2



KEY TO SYMBOLS USED IN
CORE LOG DESCRIPTIONS



BREAKWATER HARBOR VIBRACORE 2 (W.H.H.-B.H.-2-'78)



Harbor fill silts after center section of Inner Breakwater was built in 1890's; greenish grey; sediments burrowed throughout; laminations

Light olive grey; laminations

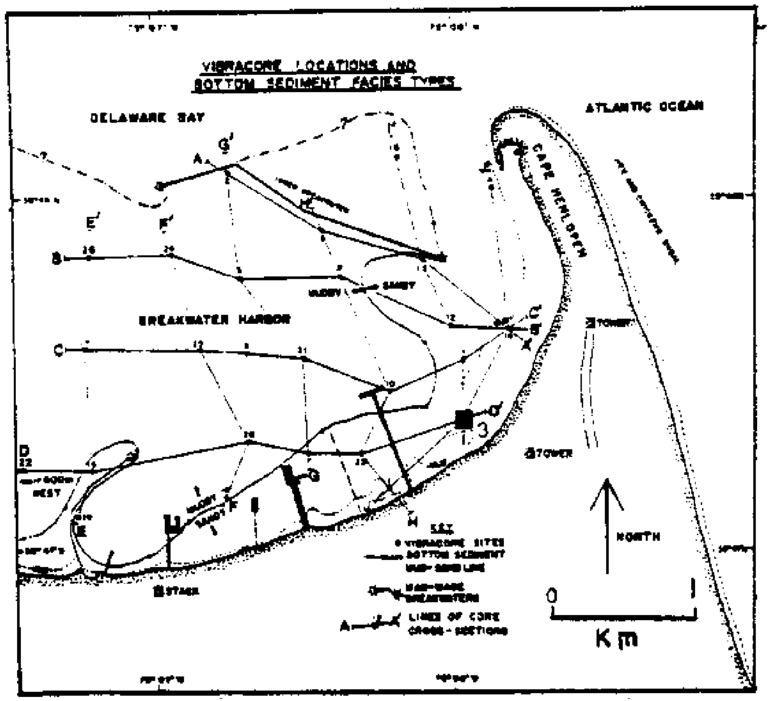
Greenish grey; laminations; coal reworked by currents through open center section of Breakwater

Gemma gemma; 1850

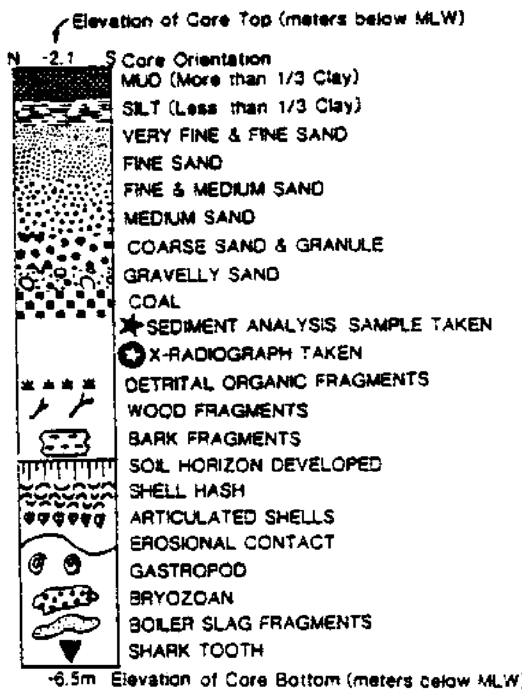
Laminations

Deposition of silts about the time of Inner Breakwater construction (1831); light olive grey; laminations

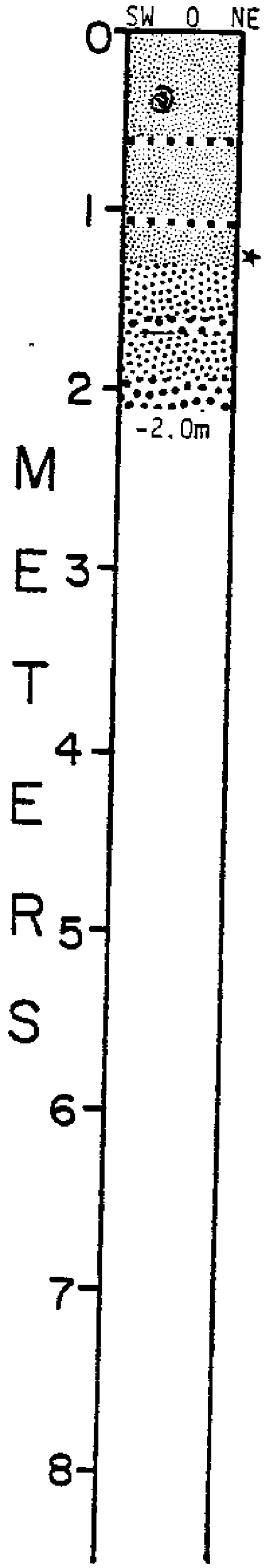
VIBRACORE 3



KEY TO SYMBOLS USED IN
CORE LOG DESCRIPTIONS



BREAKWATER HARBOR VIBRACORE 3 (W.H.H.-B.H.-3-'78)



Tidal flat deposition; burrowing throughout; yellowish grey; Tellina agilis articulated

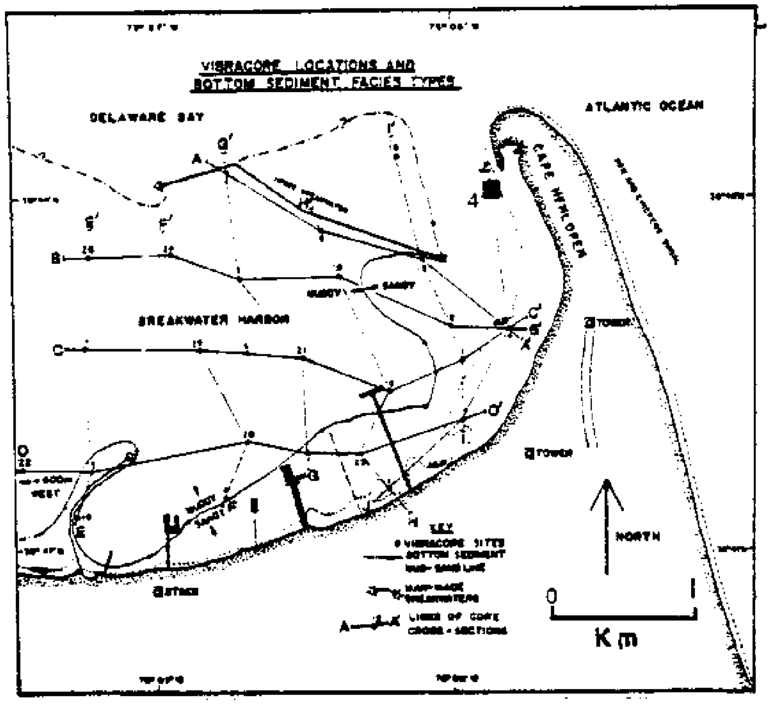
Light olive grey; 1850 or later?

Ensis directus decomposed and abraded (transported)

Mottled yellowish grey and light olive grey

Higher energy spit tip--active littoral transport; faint laminations

VIBRACORE 4



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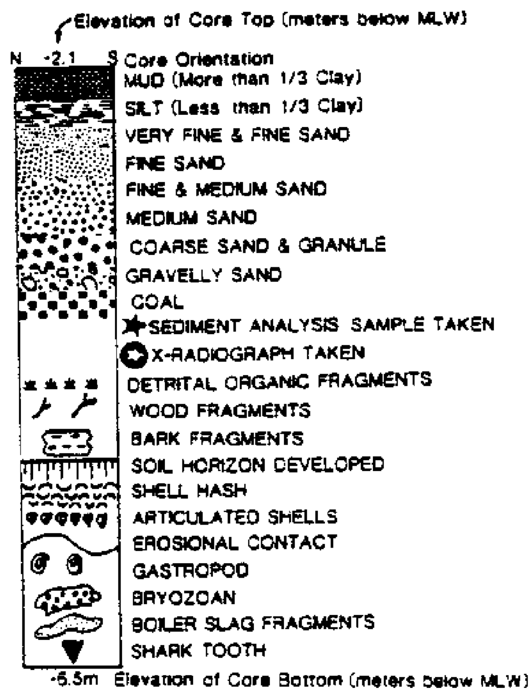
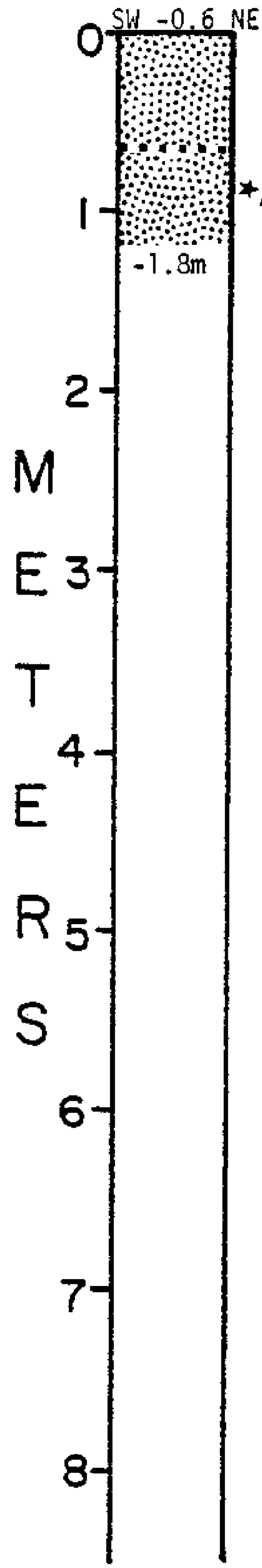


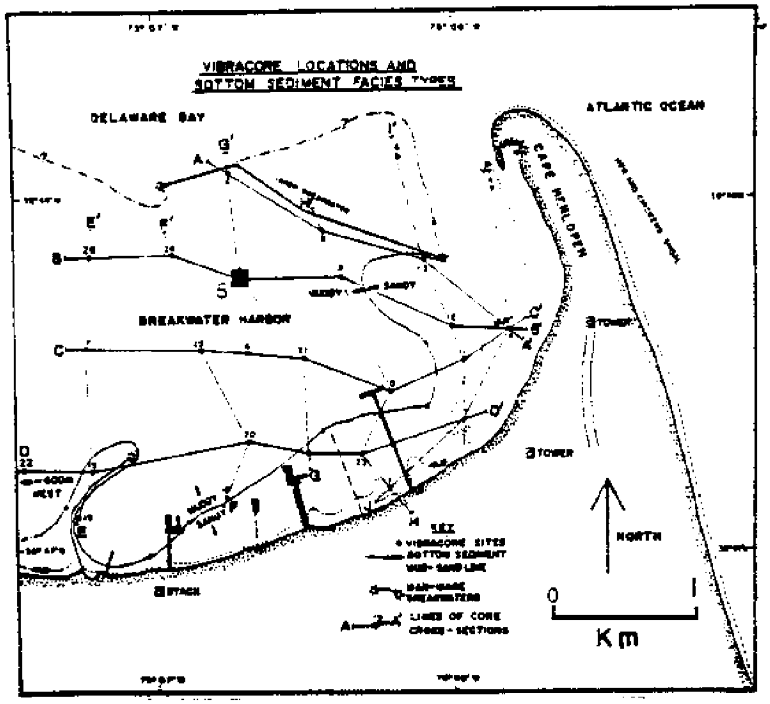
BREAKWATER HARBOR VIBRACORE 4 (W.H.H.-B.H.-4-'78)



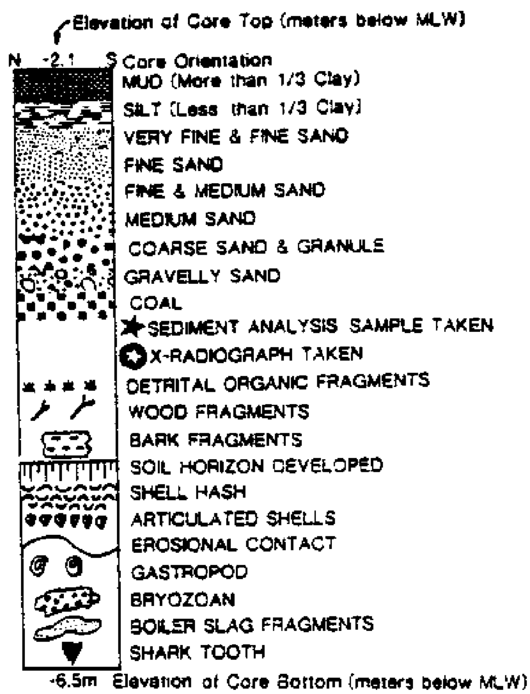
Spit tip--tidal flat deposition; yellowish grey throughout; structureless without burrows

*Age of deposition--post 1950

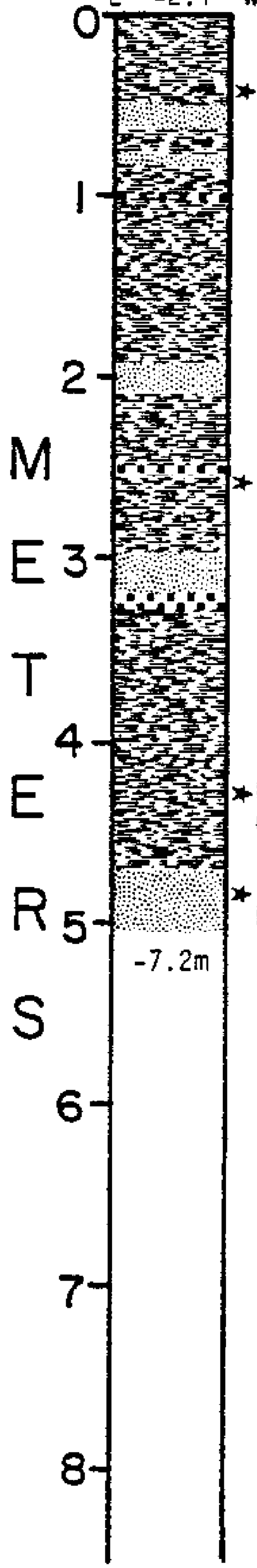
VIBRACORE 5



KEY TO SYMBOLS USED IN CORE LOG DESCRIPTIONS



BREAKWATER HARBOR VIBRACORE 5 (W.H.H.-B.H.-5-'78)



Central harbor fill silts; alternating laminations and burrowing throughout; light olive grey; iron stain; *Gemma gemma*; *Nucula proxima*

Light olive grey; laminations dip toward east (ebb-oriented) about 25° to 35°; *Tellina agilis*; cottonwood tree seeds; *Mytilus edulis*; *Ensis directus*

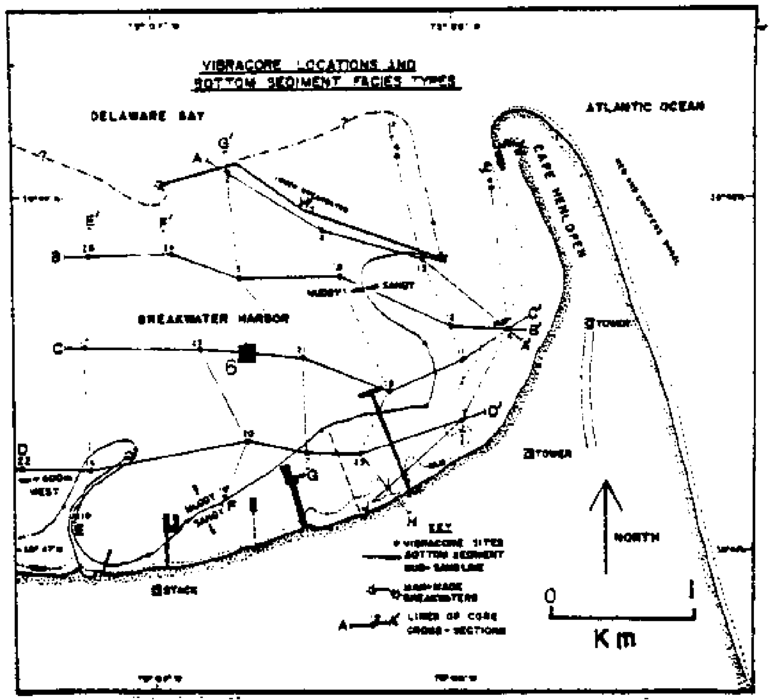
Lenticular, storm-deposited sand beds originating at Cape Henlopen spit tip to the east; horizontal burrows

*Boiler slag fragments; 1850 or later?

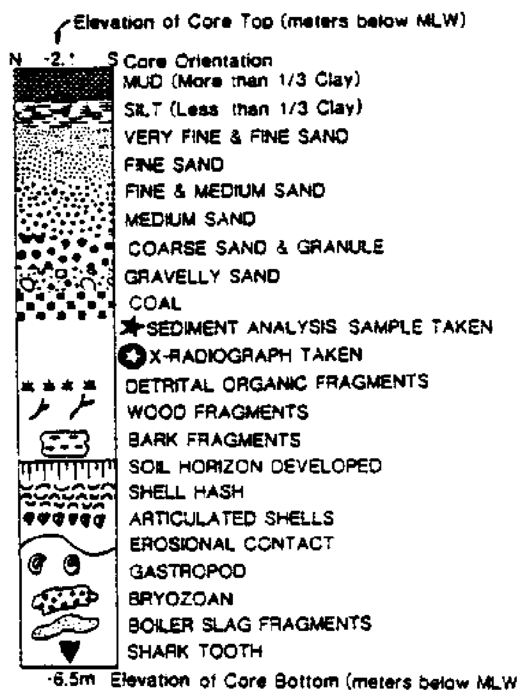
Color gradually changes downward to moderate olive brown

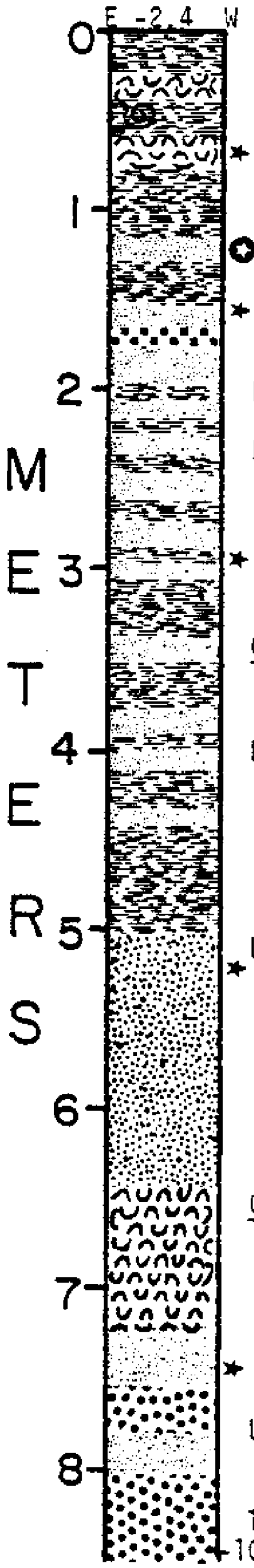
*Post-Breakwater deposition

VIBRACORE 6



KEY TO SYMBOLS USED IN
CORE LOG DESCRIPTIONS





BREAKWATER HARBOR VIBRACORE 6 (W.H.H.-B.H.-6-'78)

Central harbor fill silts; burrowed throughout; laminations dipping 25° to 35° to east (ebb-oriented); light olive grey; cottonwood tree seeds; Gemma gemma; Tellina agilis; Macoma balthica; Ensis directus; fecal pellets; insect wing fragments; parallel laminations

Pre-Breakwater deposition

Light olive grey; Ensis directus; Juanthina pallida; unidentified seeds (pollen?)

Gemma gemma

Laminations dipping 25° to 35° to east (ebb-oriented); Ensis directus

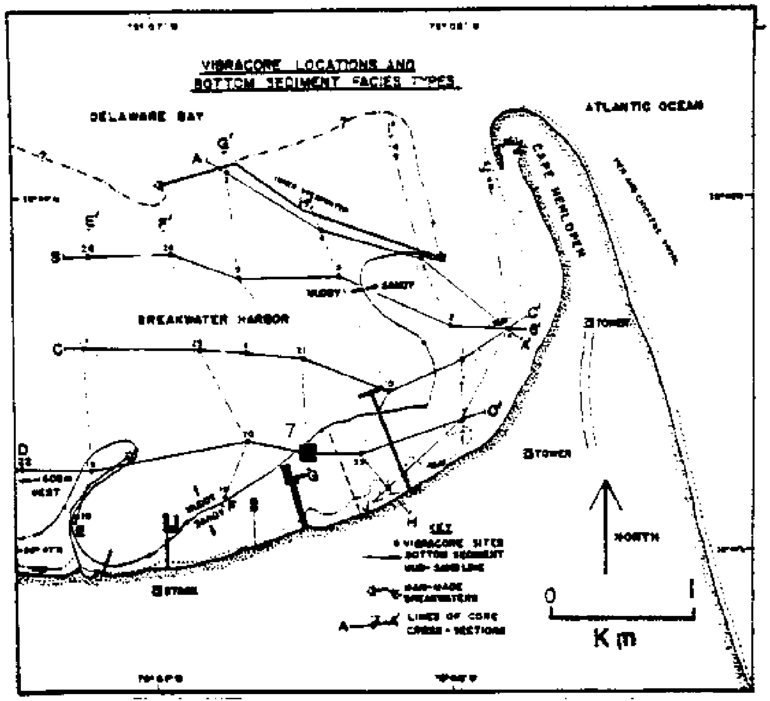
Light olive grey; Ensis directus; Tellina agilis

Gemma gemma shell hash; olive grey; Ensis directus; Crassostrea virginica; Epitonium humphreysi

Light olive grey; laminations dip 25° to 30° to east; about 6,000 yrs. B.P. in mid-Holocene Delaware Bay

Tan-orange and iron-stained Pleistocene paralic deposits

VIBRACORE 7



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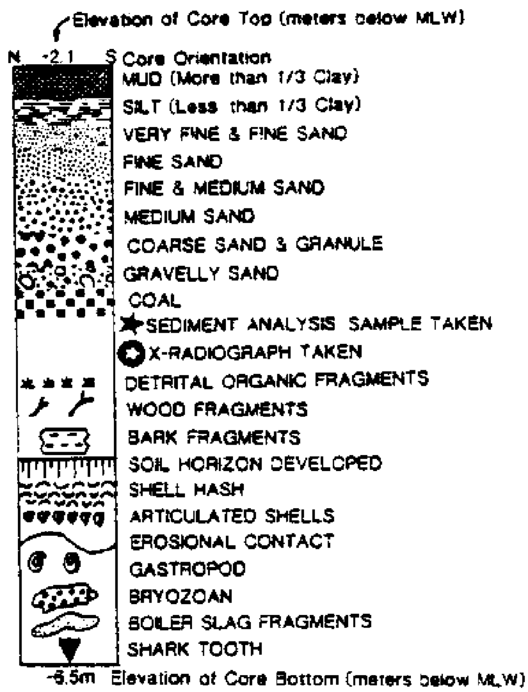
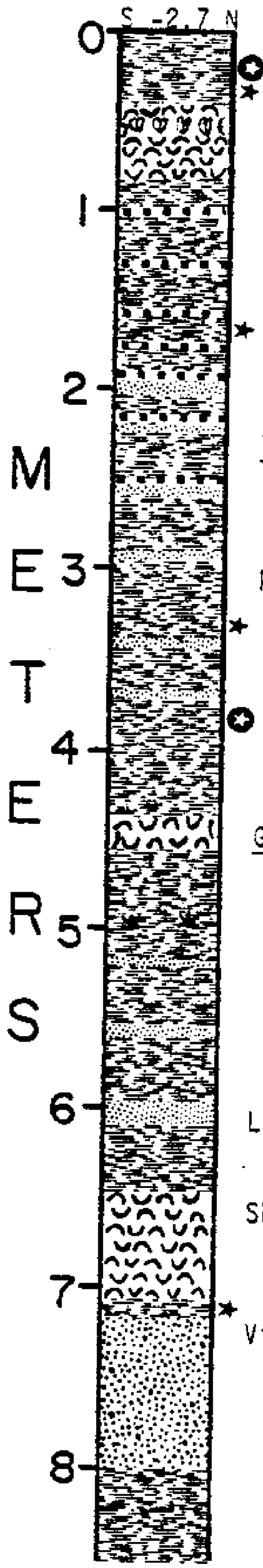




BREAKWATER HARBOR VIBRACORE 7 (W.H.H.-B.H.-7-'78)

Central harbor fill silts; light olive grey; burrowed; *Tellina agilis* (articulated and in growth position); *Nucula proxima*; *Mytilus edulis*

Greenish grey in finer laminations and light olive grey in coarser laminations; laminations are penetrative and occur as frequently as 10 in each centimeter; dip 10° to south

Tellina agilis; *Cerastoderma pinnulatum*; 1850

Pre-Breakwater deposition; very finely laminated with 10 laminations in each centimeter

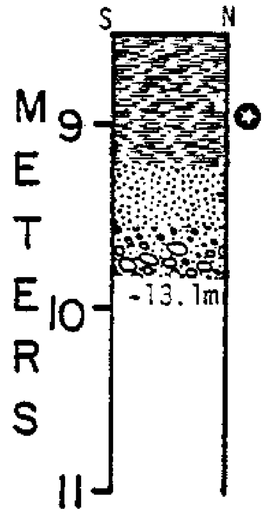
Gemma gemma; light olive brown; more abundant muscovite at laminae partings; sands are storm deposits derived from Cape Henlopen spit during northeast storms; light olive grey

Light olive brown; *Ensis directus*; *Gemma gemma*; bioturbated, with lack of laminations

Shell hash of *Ensis directus* and *Crassostrea virginica*; light olive brown; cottonwood tree seeds

Vigorous currents winnowing bottom offshore of mid-Holocene Cape Henlopen; *Ensis directus*; *Tellina agilis*

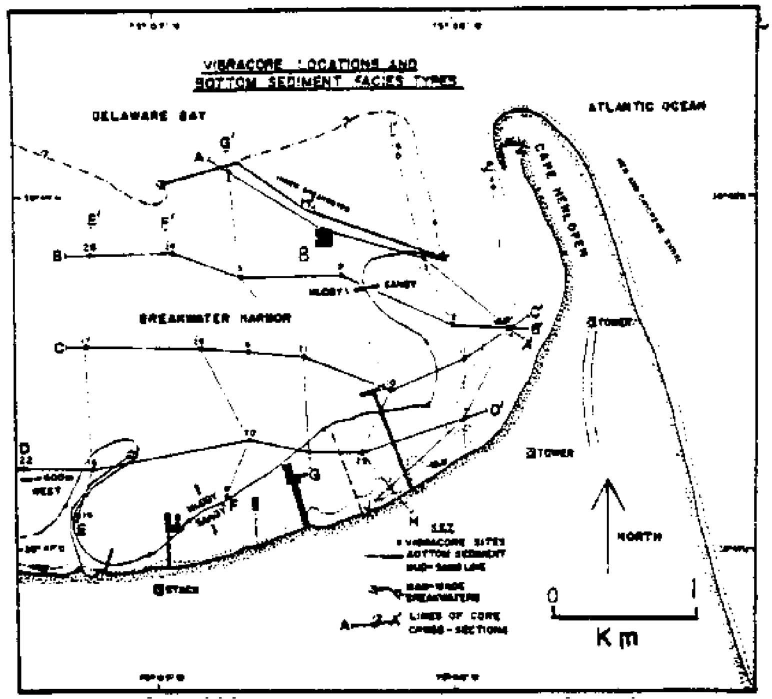
Continued Core 7 (W.H.H.-B.H.-7-'78)



Gemma gemma

Decomposed shells; light olive brown; Pleistocene paralic deposits

VIBRACORE 8



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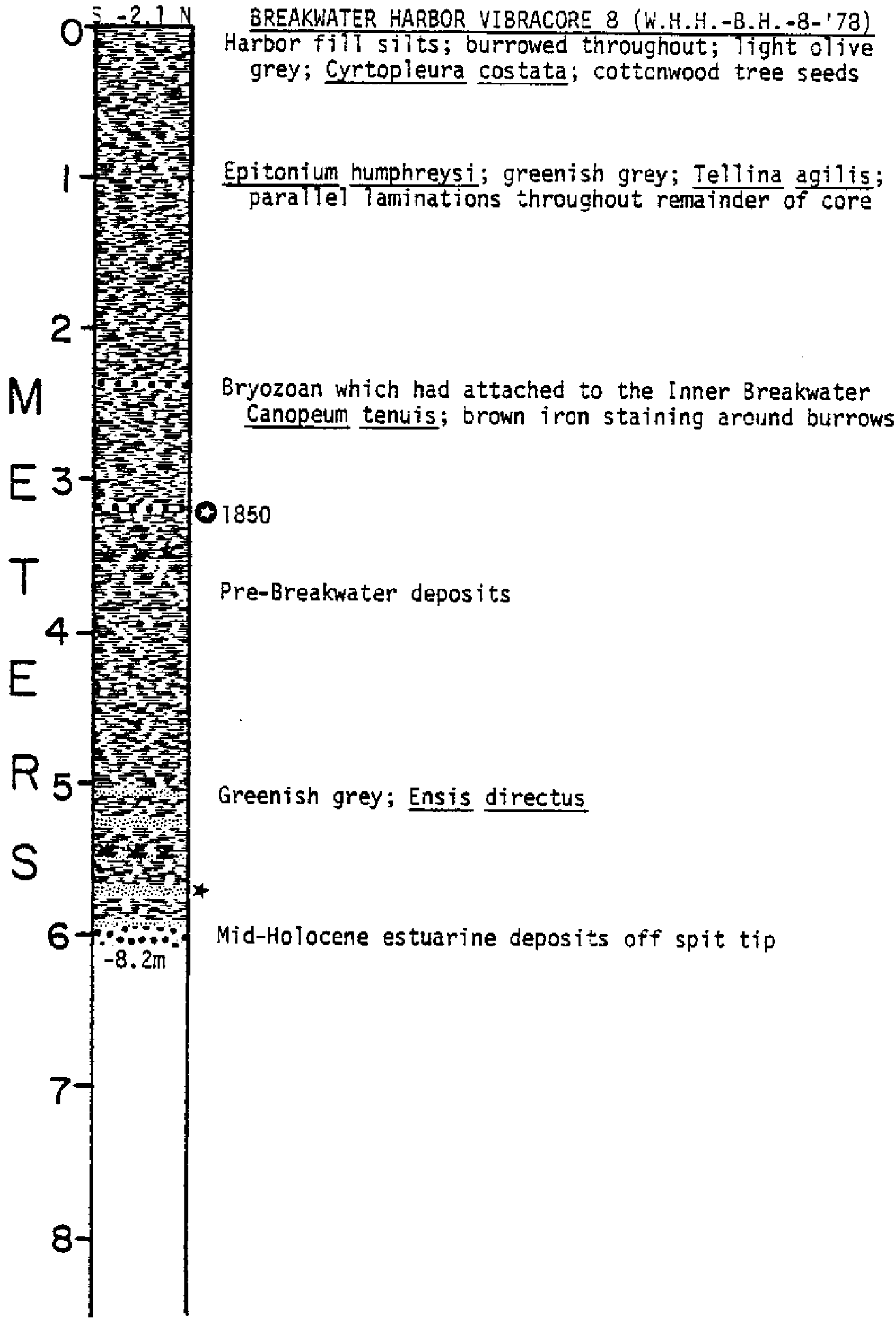
S -2.1 N
BREAKWATER HARBOR VIBRACORE 8 (W.H.H.-B.H.-8-'78)
Harbor fill silts; burrowed throughout; light olive grey; Cyrtopleura costata; cottonwood tree seeds
Epitonium humphreysi; greenish grey; Tellina agilis; parallel laminations throughout remainder of core
Bryozoan which had attached to the Inner Breakwater Canopeum tenuis; brown iron staining around burrows
1850
Pre-Breakwater deposits
Greenish grey; Ensis directus
Mid-Holocene estuarine deposits off spit tip
-8.2m
METERS
0
1
2
3
4
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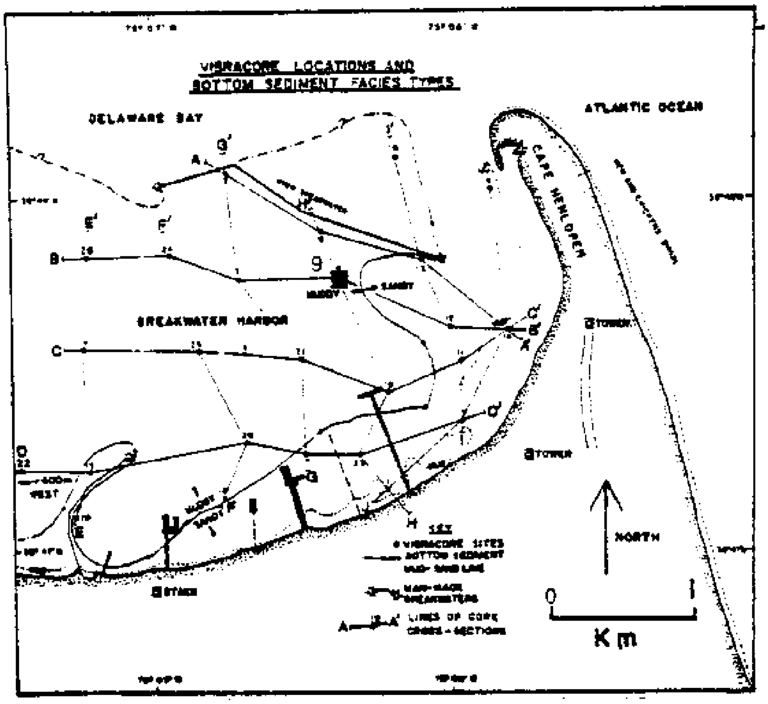
8

VIBRACORE 9



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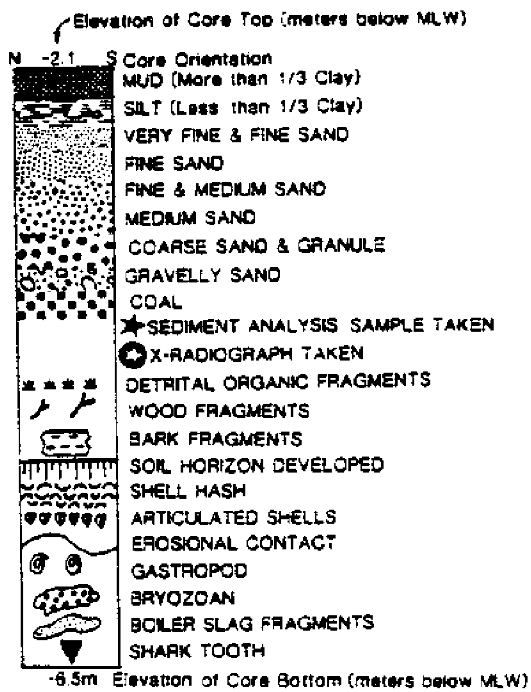
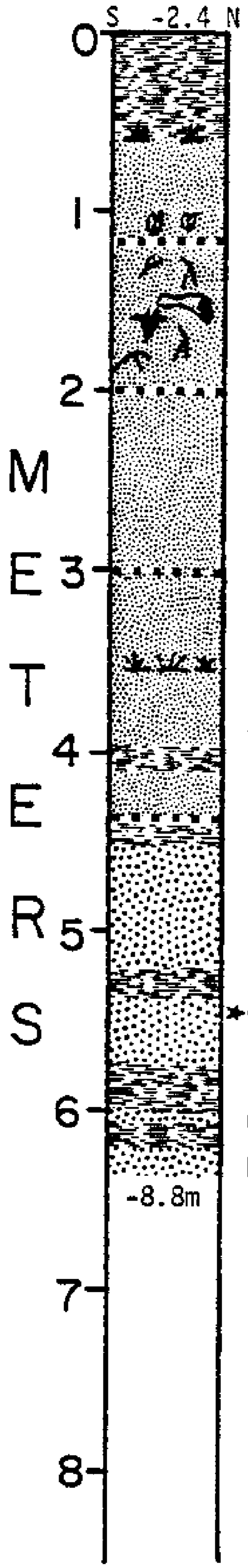


BREAKWATER HARBOR VIBRACORE 9 (W.H.H.-B.H.-9-'78)



Harbor fill silts; burrowed throughout; greenish grey; Gemma gemma; parallel laminations

Mytilus edulis; Ensis directus

Boiler slag fragment; shark tooth; light olive grey; Tellina agilis

Mytilus edulis; Epitonium humphreysi

Light olive grey; laminations dipping toward south at 30° to 40°; Spisula raveneli

Gemma gemma; Crassostrea virginica; parallel laminations

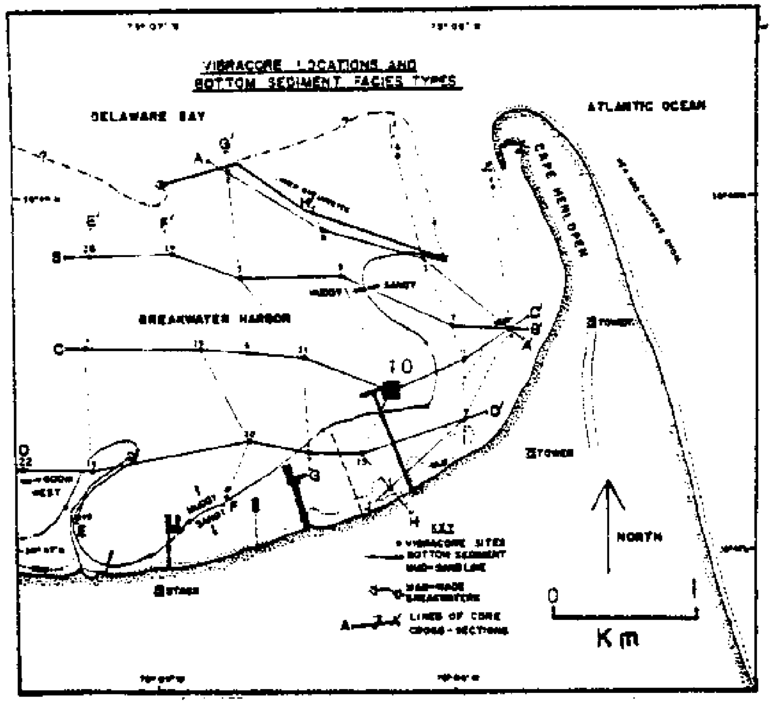
Light olive grey; parallel laminations

*Coal fragment 2" in diameter; 1850

Olive grey; Ensis directus

Pre-Breakwater deposition

VIBRACORE 10



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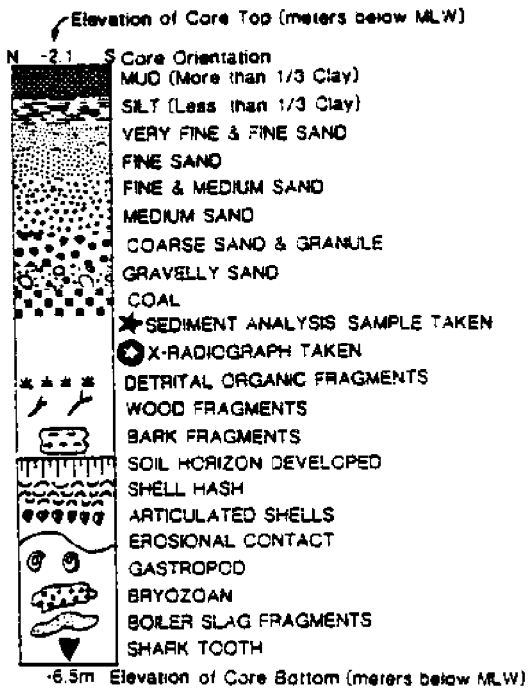
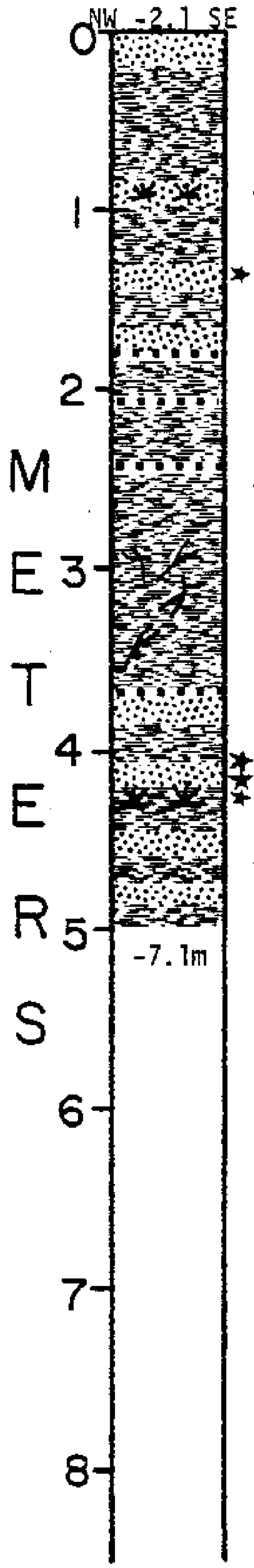


BREAKWATER HARBOR VIBRACORE 10 (W.H.H.-B.H.-10-'78)



1977-October storm deposit of sand; yellow grey; burrowing throughout; laminations throughout

Winter (storm) sandy deposits alternating with summer (low-energy) silt deposits; sands are yellow grey and silts are dark greenish grey; laminations dipping 20° toward northwest (storm-generated); sharp erosional contacts at base of sands, gradational contacts at top of sand layers

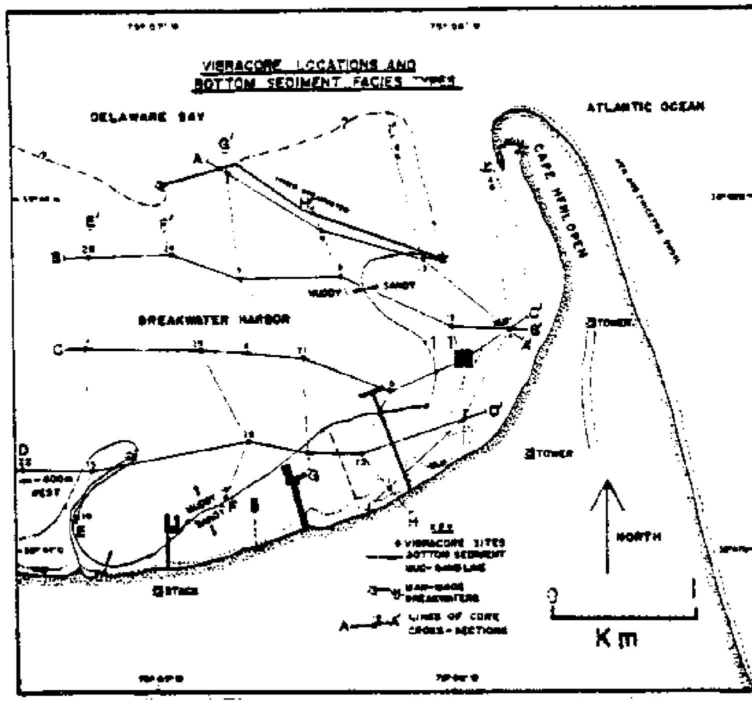
Olive grey silts alternating with laminae of yellow-grey sands, many mica-rich

Deforestation of Lewes beach associated with Inner Breakwater construction (log mats at base of Breakwater as a foundation material); 1830

Iron staining

Olive grey silts and yellow grey sands

VIBRACORE 11



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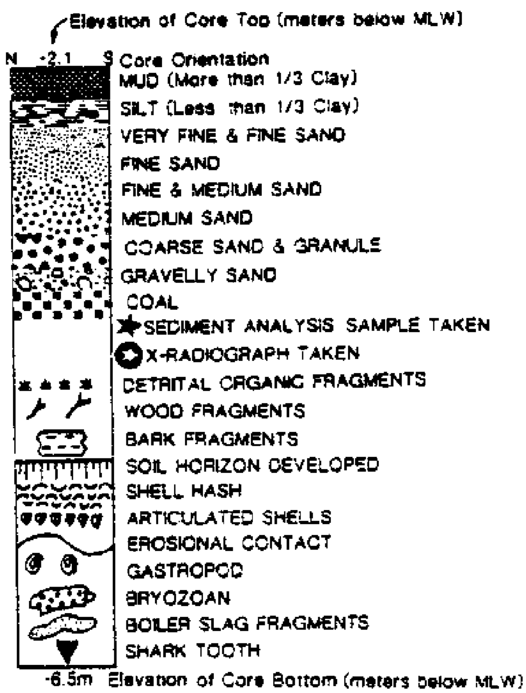
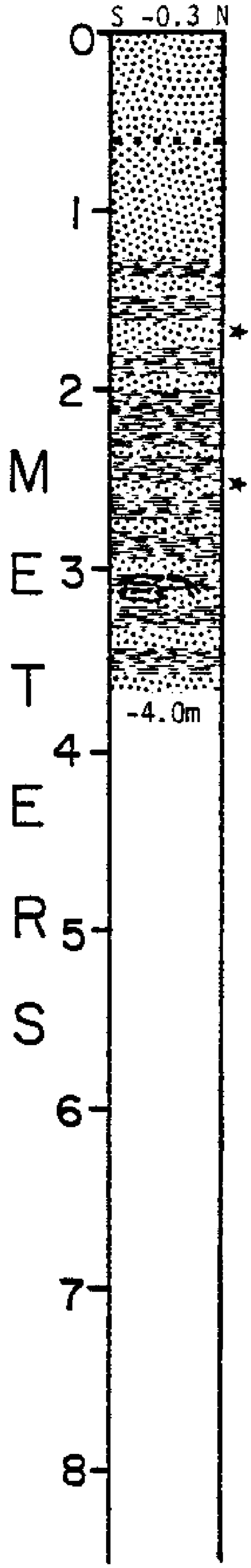


BREAKWATER HARBOR VIBRACORE 11 (W.H.H.-B.H.-11-'78)



Tidal flat sands prograding westward on top of harbor muds; yellowish grey; Ensis directus; Gemma gemma; weakly burrowed throughout; laminations

Light olive grey silts alternating with yellowish grey sands

Dark greenish grey

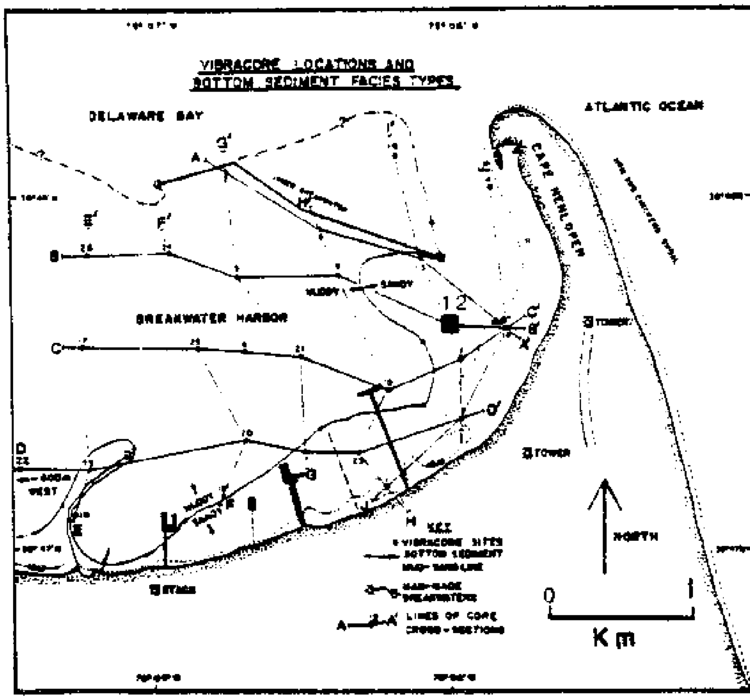
Dense laminations throughout remainder of core

* Mytilus edulis

1850

Deforestation of Lewes Beach? 1830

VIBRACORE 12



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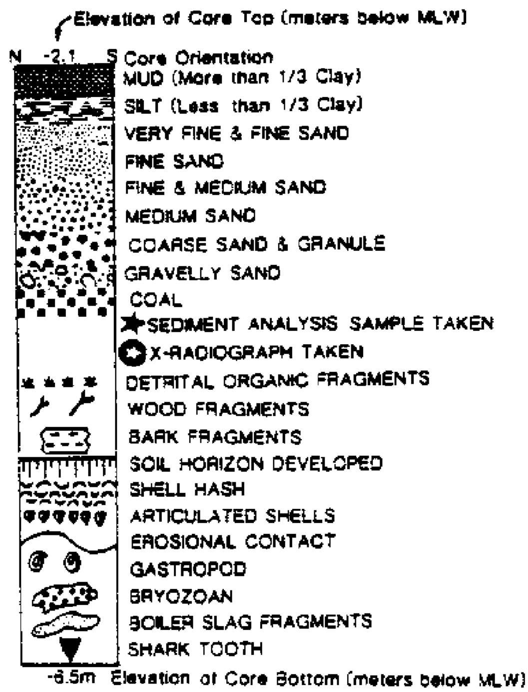
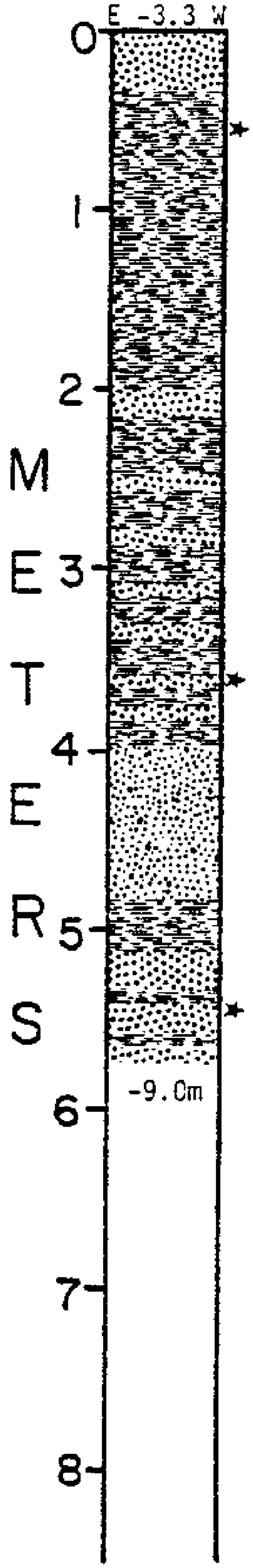


BREAKWATER HARBOR VIBRACORE 12 (W.H.H-B.H.-12-'78)



1977-78 storm deposits originating from spit to the northeast; structureless; light olive grey

Olive grey; laminations and faint bioturbations; Tellina agilis; Gemma gemma

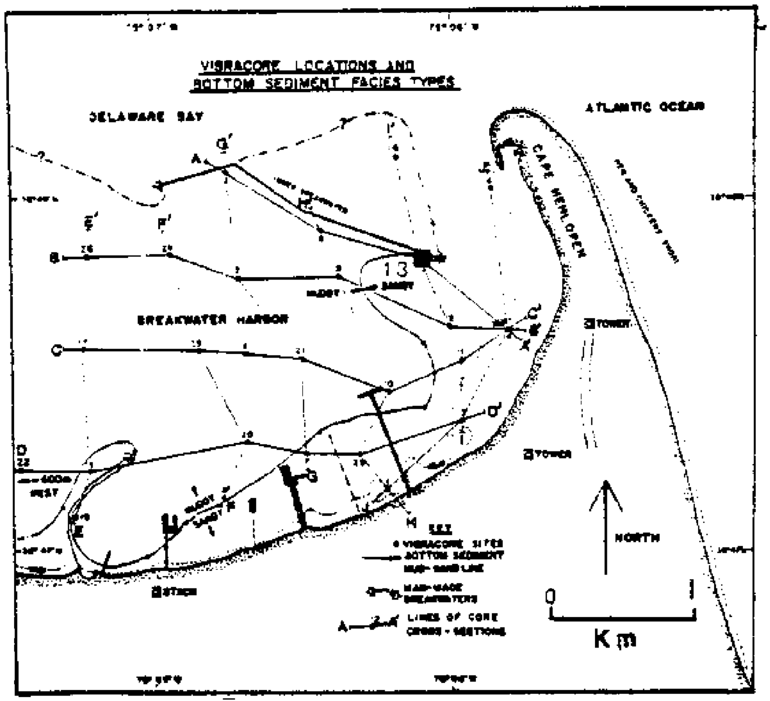
Light olive grey sandy storm deposits (winter) alternating with medium greenish grey silt deposited during lower energy conditions (summer); iron stain

Laminations; Mytilus edulis; Gemma gemma

Light grey and medium grey sands; laminations dipping 20° to 40° to west (storm deposits); other laminations dipping 10° to east (ebb-oriented)

Olive grey muds stirred up during construction of Inner Breakwater; 1830?

VIBRACORE 13



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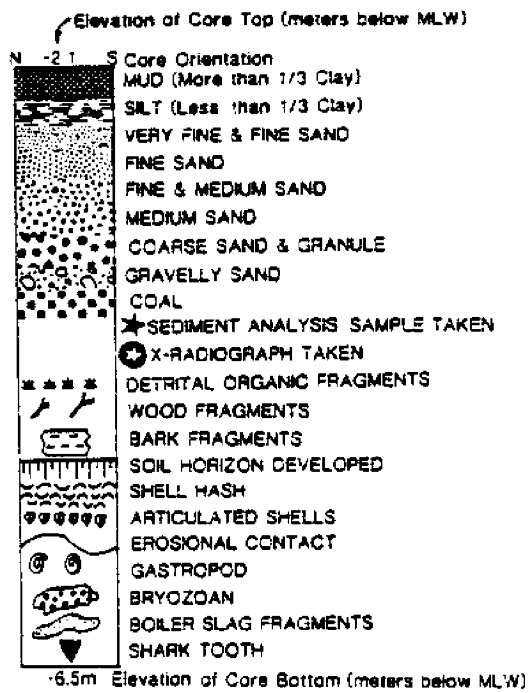
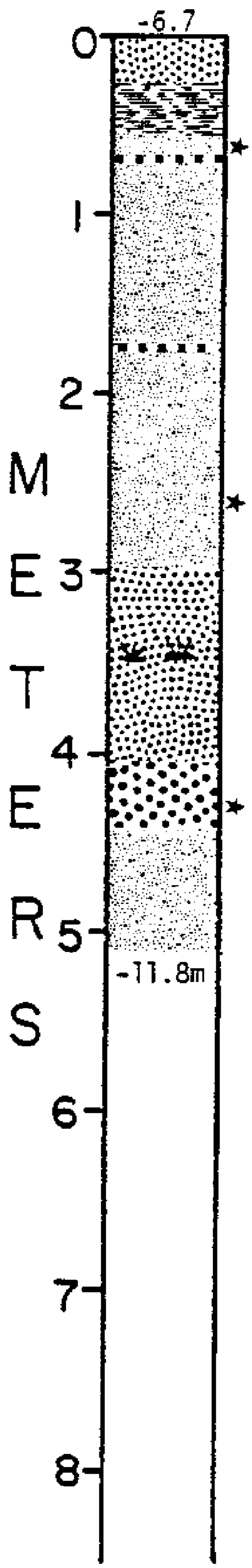


BREAKWATER HARBOR VIBRACORE 13 (W.H.H.-B.H.-13-'78)



Recent storm deposits; laminations; *Tellina agilis*; crab claw; greenish grey

Light olive grey; laminations and burrowing

Mytilus edulis; *Epitonium humphreysi*; boiler slag

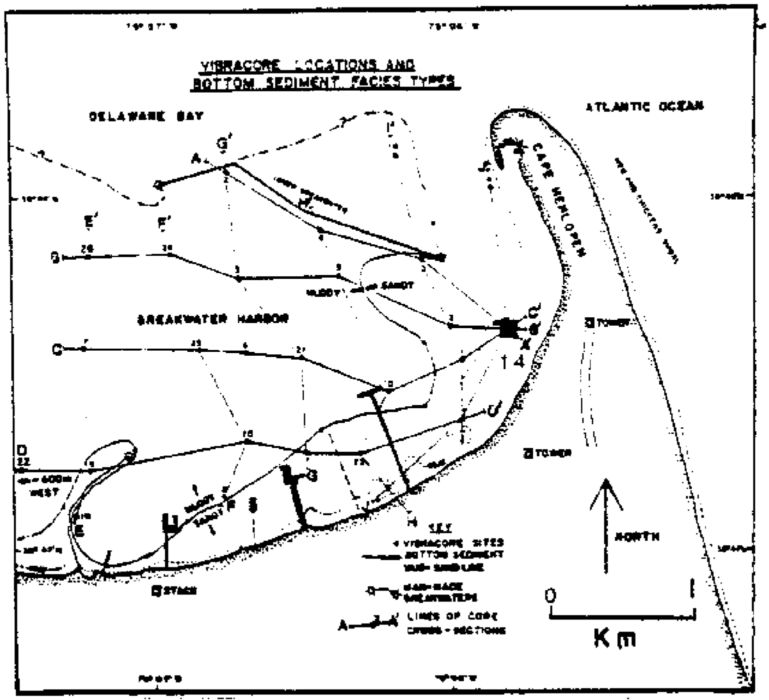
1850? or later; *Mytilus edulis* fragments which have come from adjacent Inner Breakwater; laminations dipping 10° in various directions, both storm-generated and ebb-tide generated

Greenish grey; laminations; *Ensis directus*; *Gemma gemma*

Featureless sand, possibly deposited by Inner Breakwater construction processes

Current-winnowed sediments; greenish grey

VIBRACORE 14



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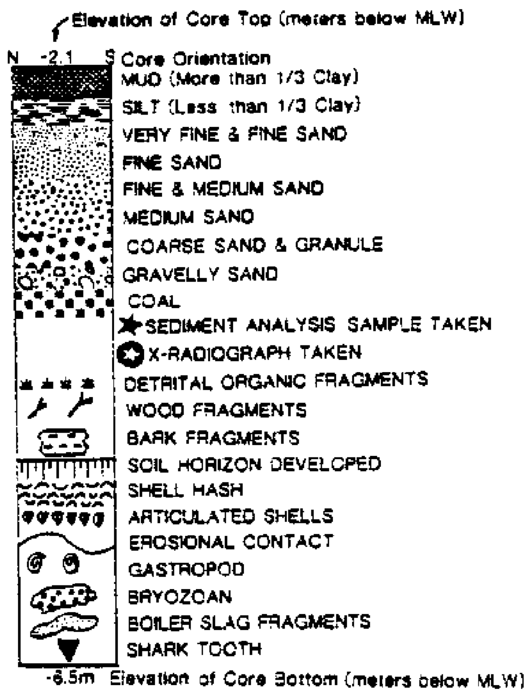
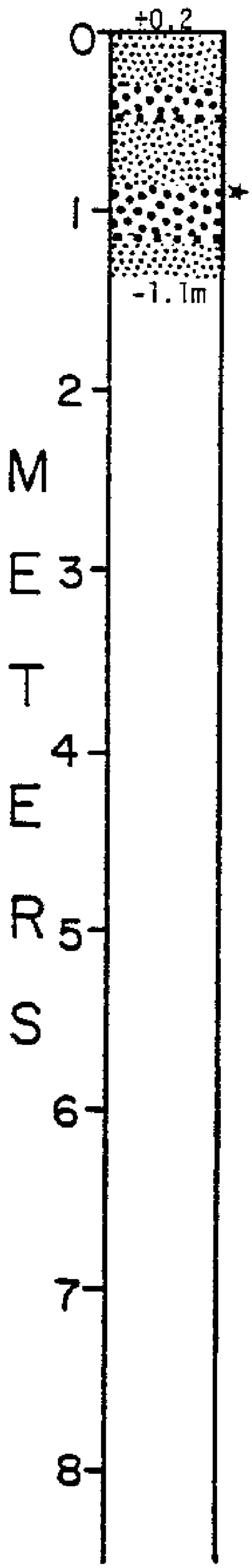


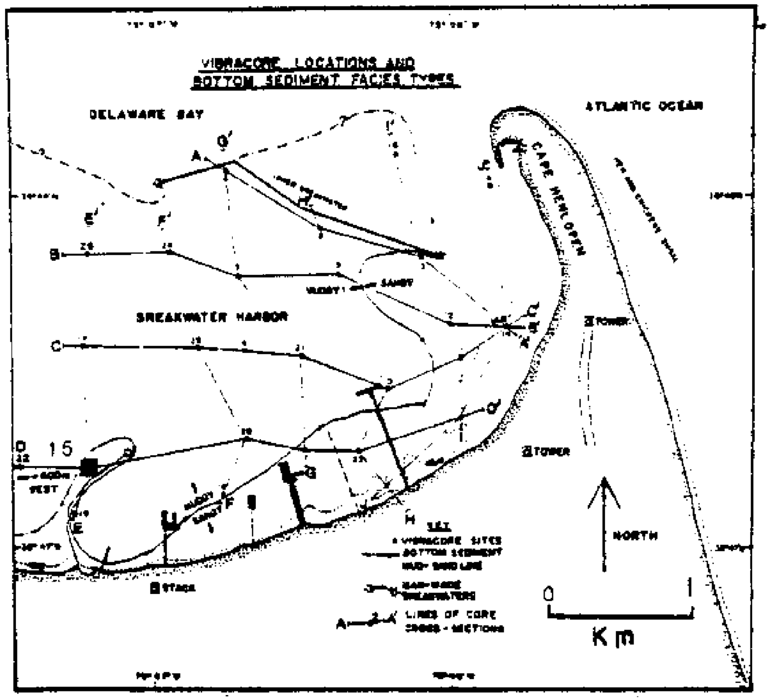


BREAKWATER HARBOR VIBRACORE 14 (W.H.H.-B.H.-14-'78)

Cape Henlopen tidal flat deposits of fine, burrowed sand (summer--low energy) and medium, laminated sand (winter--higher energy); yellowish grey; *Crassostrea virginica* fragments

Reworked coal deposit, post-1900?; very light grey sand

VIBRACORE 15



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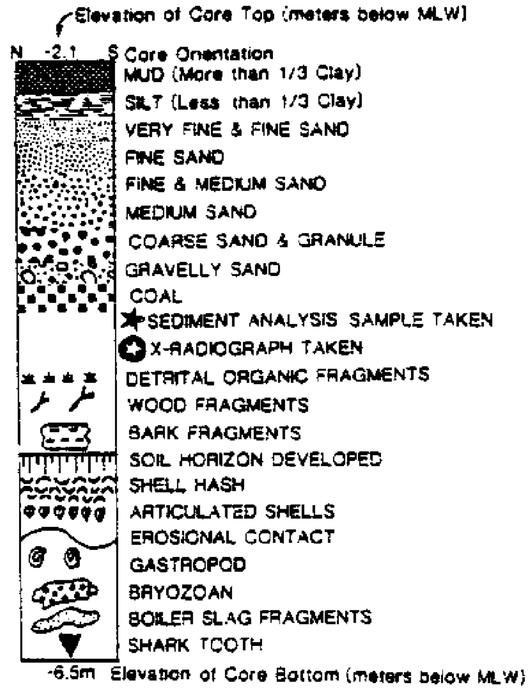
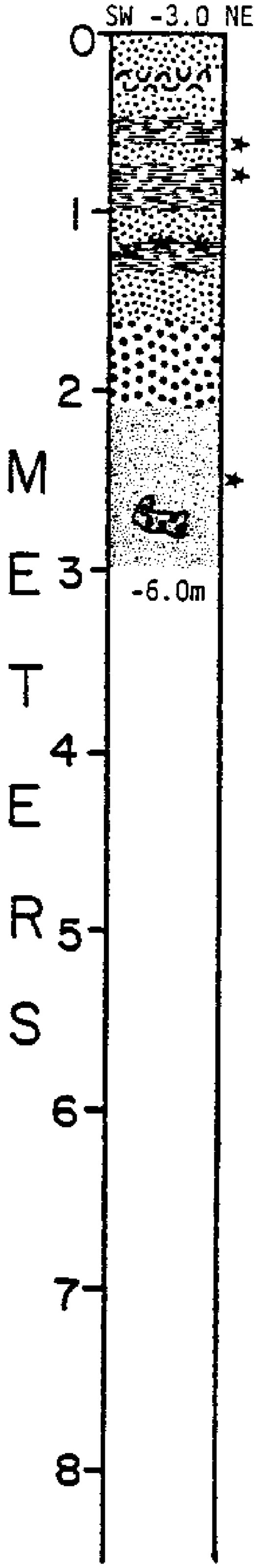




BREAKWATER HARBOR VIBRACORE 15 (W.H.H.-B.H.-15-'78)

Rapidly changing depositional environments as a result of Ferry Breakwater construction; littoral sand and shells moving over silts; light olive grey; *Tellina agilis*

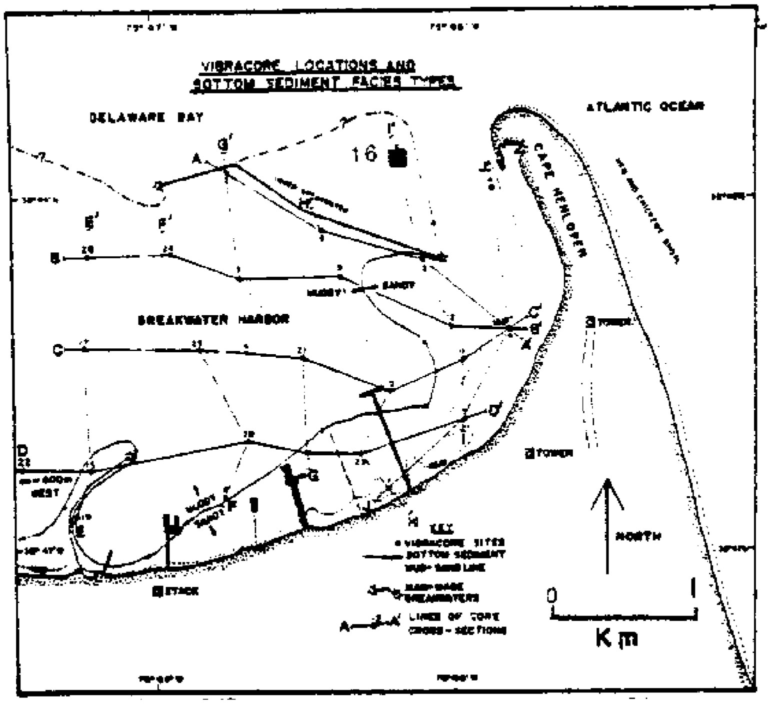
Mytilus edulis; olive grey

Timber mat base debris used in Ferry Breakwater construction; 1964; light olive grey

"Channel cut" as a result of Ferry Breakwater construction; clean sand added as a foundation material for Ferry Breakwater; laminations; *Gemma gemma*

Yellowish grey; *Tellina agilis*; pre-Ferry Breakwater deposits; *Canopeum tenuis* bryozoan; heavily burrowed and laminated

VIBRACORE 16



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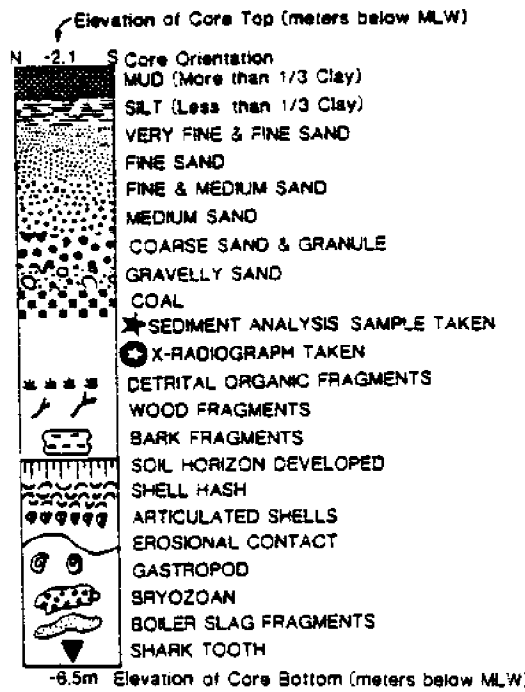
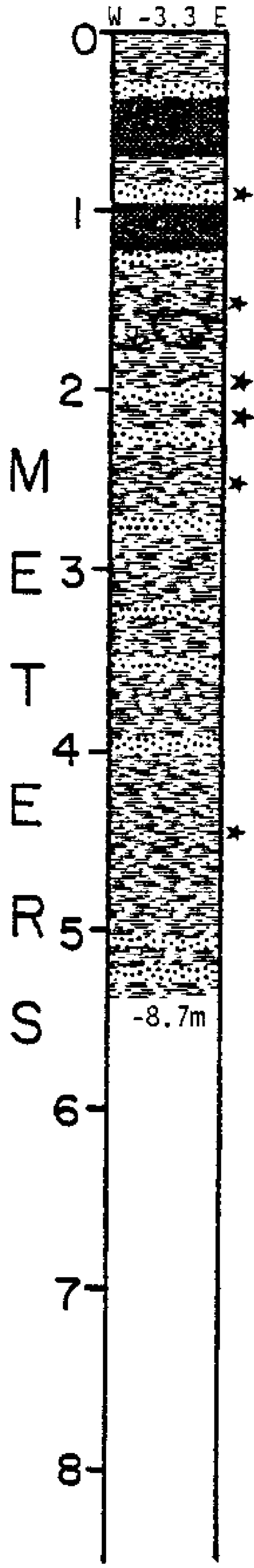




BREAKWATER HARBOR VIBRACORE 16 (W.H.H.-B.H.-16-'78)

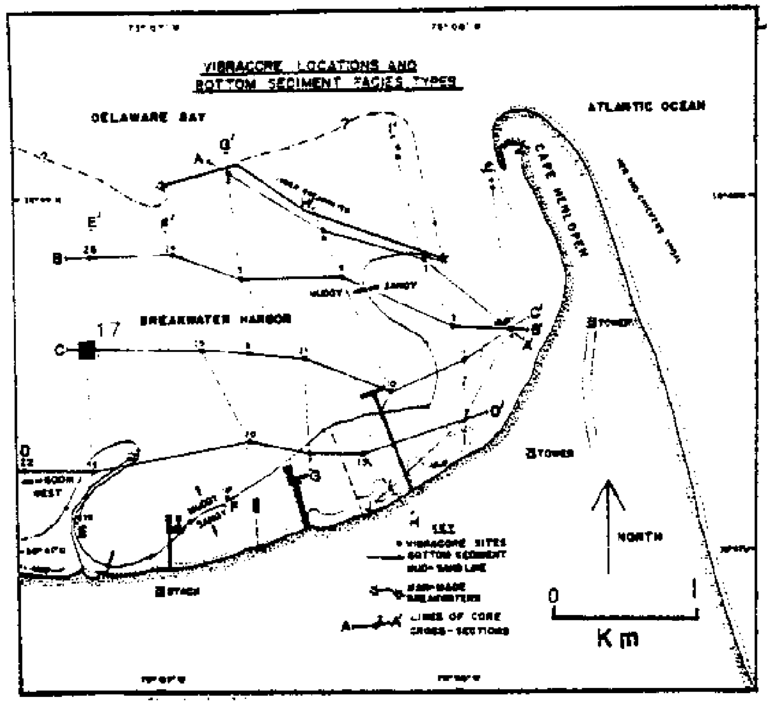
Estuarine sands (storm deposits from Cape Henlopen) are yellowish grey and alternating with light olive grey and medium grey silts deposited during times of low current velocity north of the Inner Breakwater; occasional laminations and bioturbations; silts may be deposited at times of dredge spoil deposition; Mytilus edulis; Gemma gemma; insect wing

Possible deforestation of Lewes Beach; 1800?

Abundant laminations; olive grey silt alternating with yellowish grey sand; Crepidula fornicata

Probably open estuarine deposition when Cape Henlopen spit was a broad cuspate foreland prior to 1600

VIBRACORE 17



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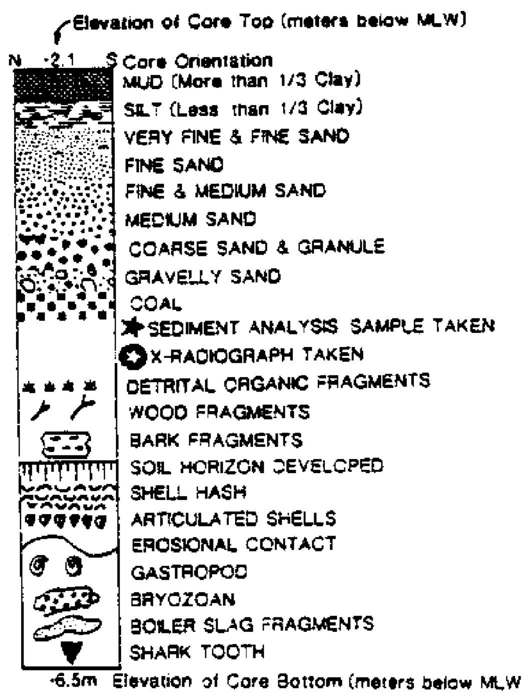
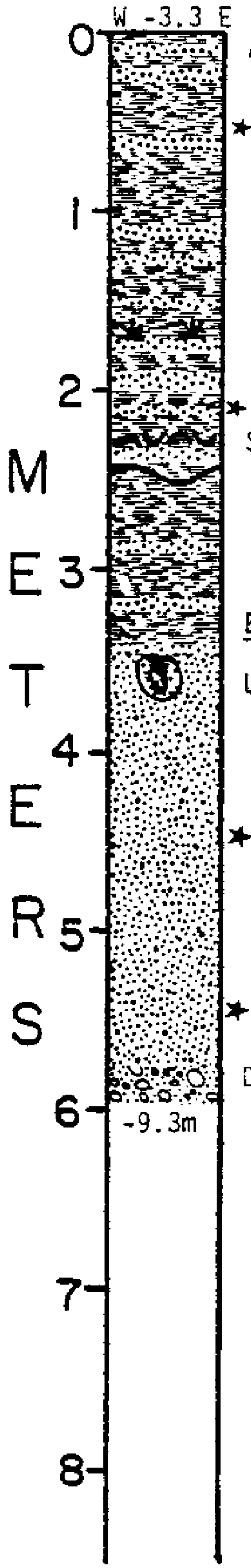


BREAKWATER HARBOR VIBRACORE 17 (W.H.H.-B.H.-17-'78)



Alternating laminations of sand and silt, all colored medium light grey; moderately bioturbated throughout; Gemma gemma; Tellina agilis; up to 15 laminations per centimeter; deposition at slack high tides and low tides during neap tides?

Shell lag deposit as result of scouring erosional contact caused by scouring event brought on by 1964 construction of Ferry Breakwater; heavily laminated

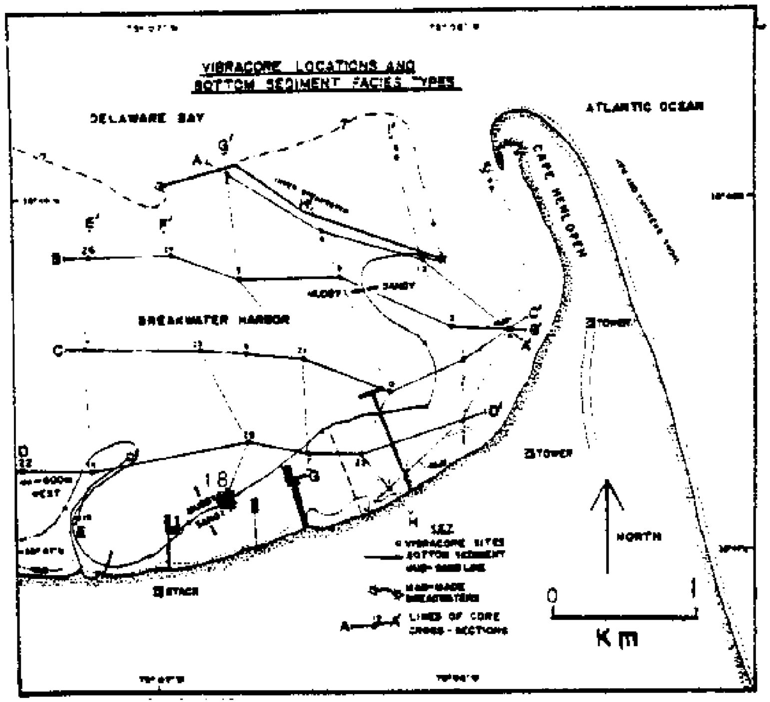
Ensis directus; Gemma gemma; heavily bioturbated

Light olive grey; deposition prior to Inner Breakwater construction; 1800

Gemma gemma; mid-Holocene deposition offshore from broad cuspate Cape Henlopen

Degraded rock fragments; Pleistocene?

VIBRACORE 18



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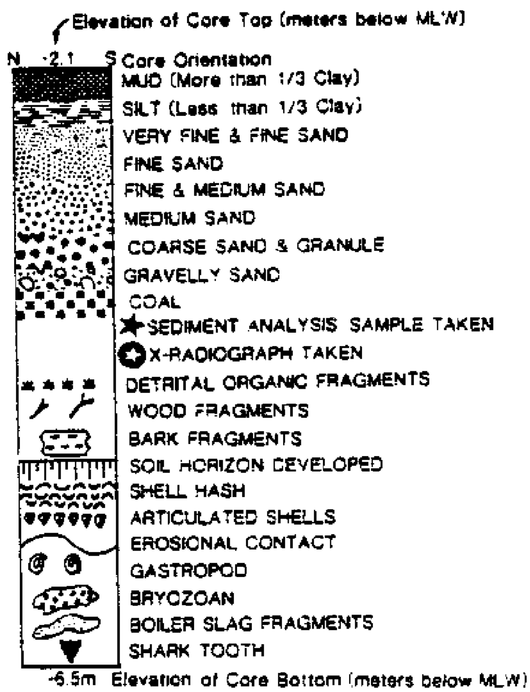
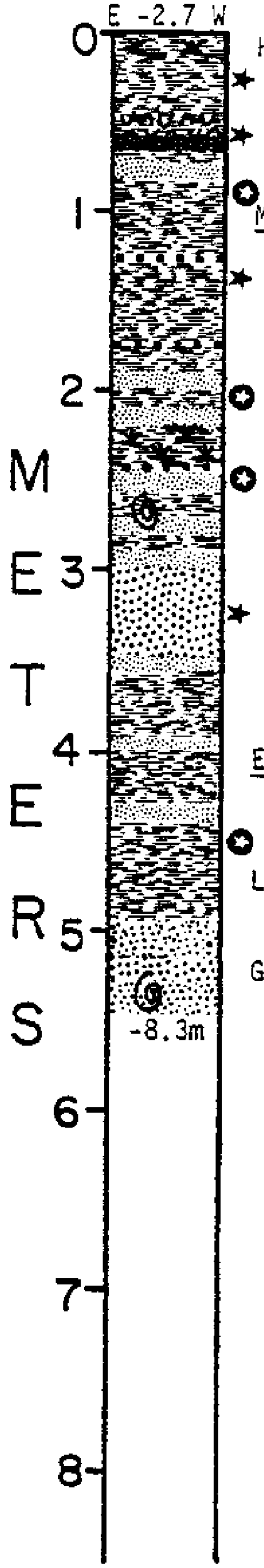


BREAKWATER HARBOR VIBRACORE 18 (W.H.H.-B.H.-18-'78)



Harbor fill silts; light olive grey; articulated, growth position Tellina agilis; heavily burrowed; heavily laminated; 1964 Ferry Breakwater construction?

Mytilus edulis; Tellina agilis; medium olive grey; iron concretion (ship debris)

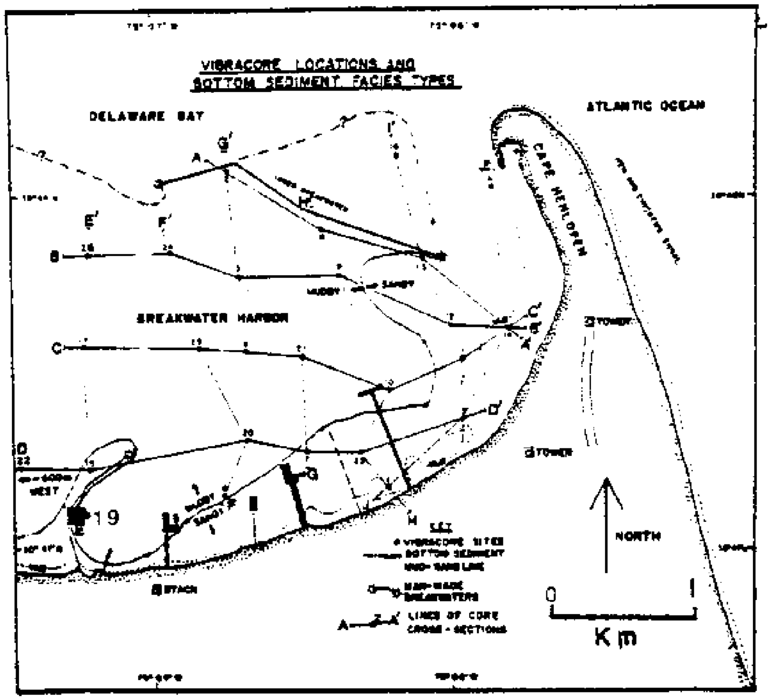
Gemma gemma; Tellina agilis; light olive grey; 1850; fecal pellets filling in burrows; bioturbation

Ensis directus; laminations and bioturbation

Light olive grey; laminations

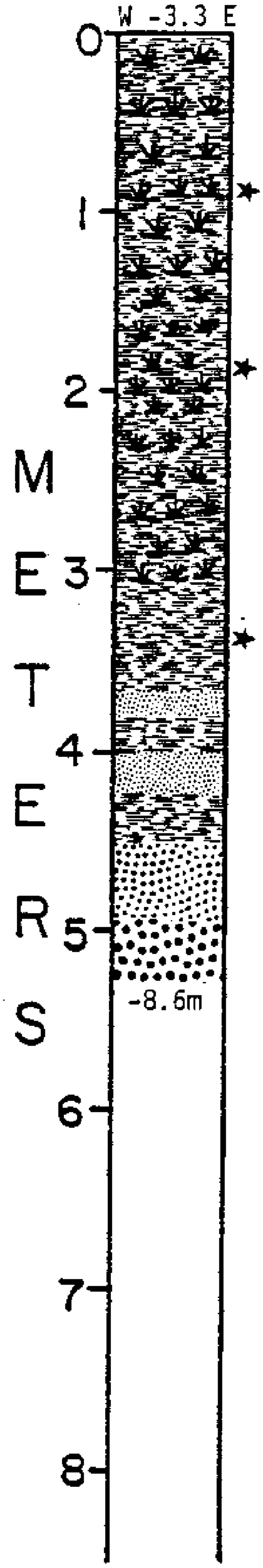
Greenish grey; laminations

VIBRACORE 19



KEY TO SYMBOLS USED IN
CORE LOG DESCRIPTIONS

BREAKWATER HARBOR VIBRACORE 19 (W.H.H.-B.H.-19-'78)



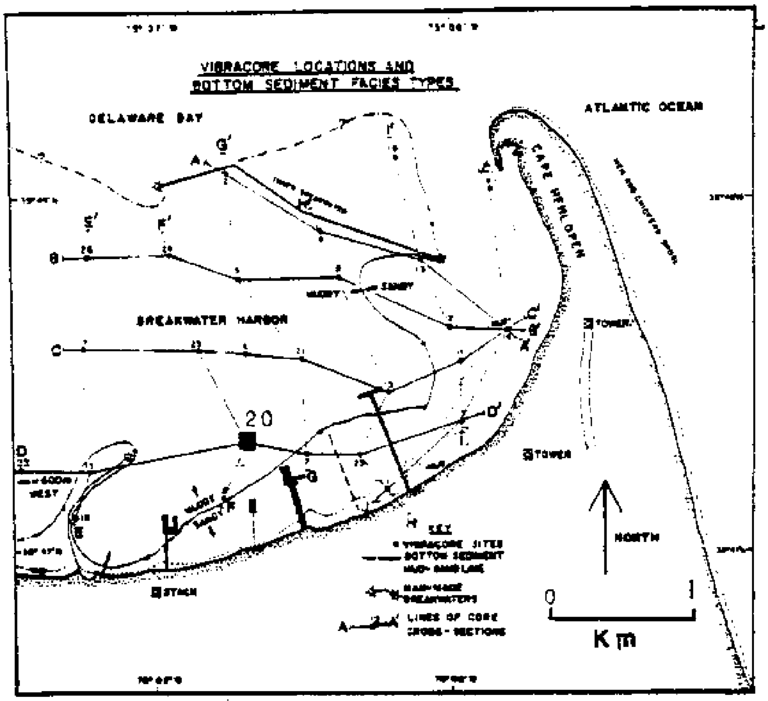
Post-1964 deposition in ebb shadow of Ferry Breakwater; olive grey; floating organic mats of predominantly salt marsh grasses settle out behind Ferry Breakwater; laminations and bioturbations

1964; Ferry Breakwater construction; harbor dredging; light olive grey; laminations dip at 30° to west; bioturbations

Bioturbations; offshore storm-deposited sands alternating with estuarine silts

Light grey; mid-Holocene deposition?

VIBRACORE 20



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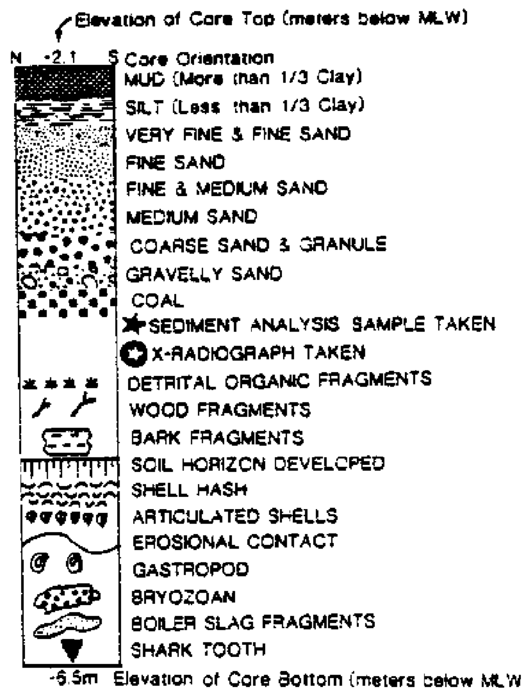

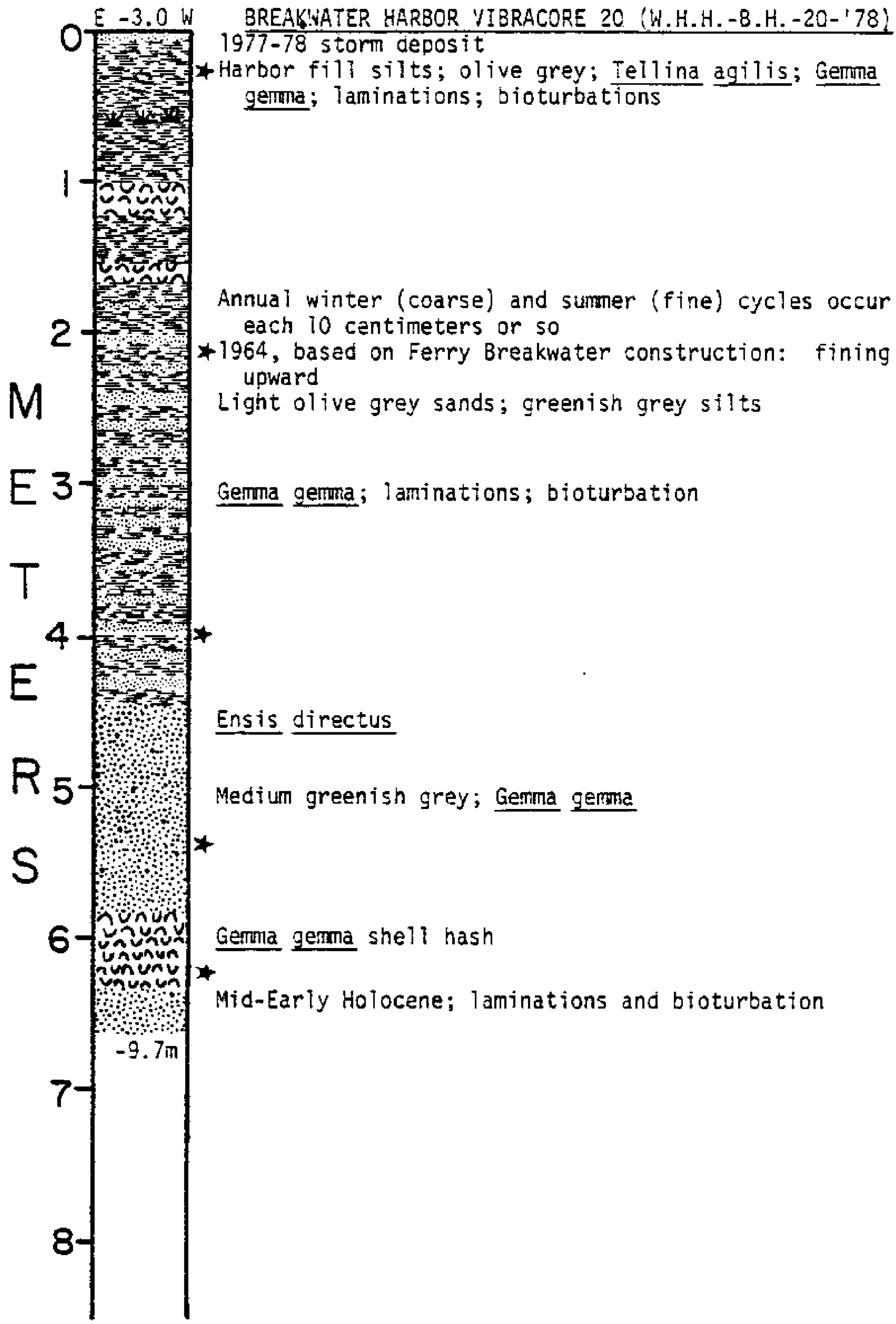
E -3.0 W
BREAKWATER HARBOR VIBRACORE 20 (W.H.H.-B.H.-20-'78)
1977-78 storm deposit
Harbor fill silts; olive grey; Tellina agilis; Gemma gemma; laminations; bioturbations
Annual winter (coarse) and summer (fine) cycles occur each 10 centimeters or so
1964, based on Ferry Breakwater construction: fining upward
Light olive grey sands; greenish grey silts
Gemma gemma; laminations; bioturbation
Ensis directus
Medium greenish grey; Gemma gemma
Gemma gemma shell hash
Mid-Early Holocene; laminations and bioturbation
-9.7m
METERS
0
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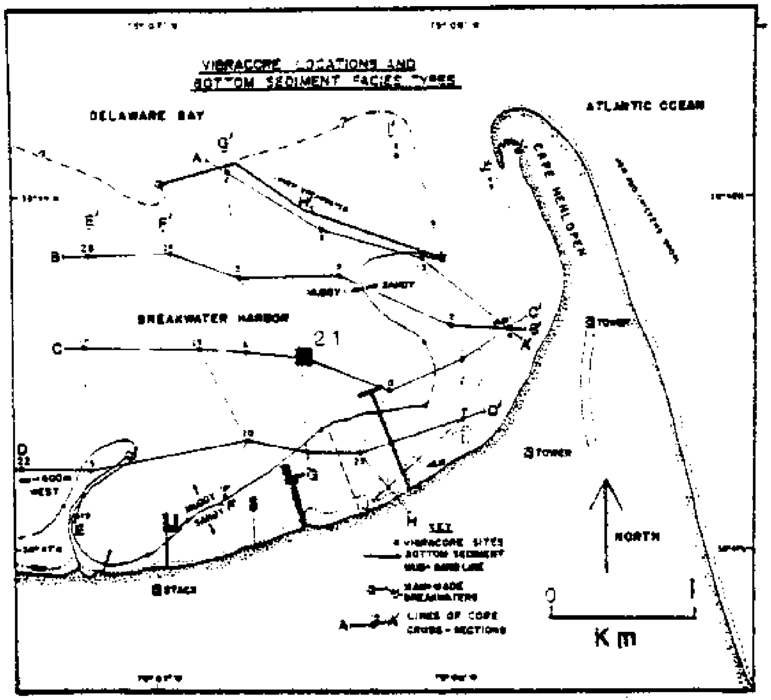
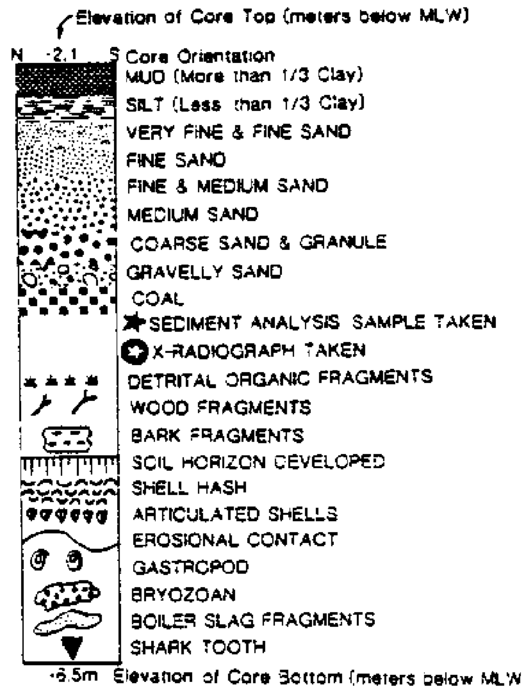
8

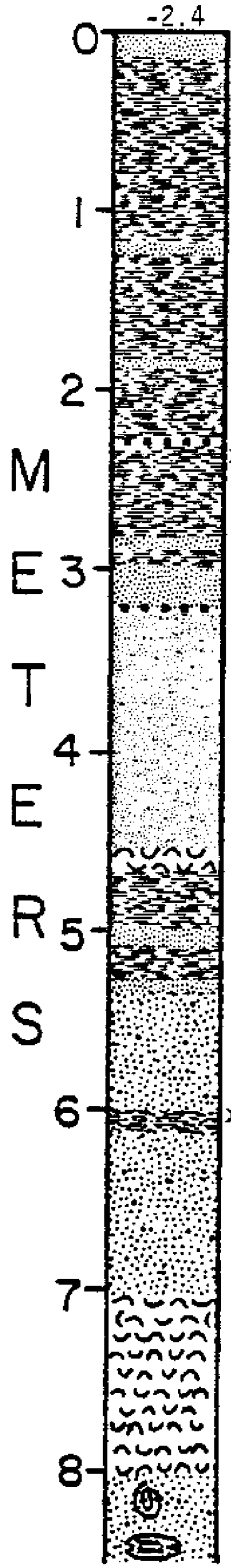
VIBRACORE 21



KEY TO SYMBOLS USED IN
CORE LOG DESCRIPTIONS



BREAKWATER HARBOR VIBRACORE 21 (W.H.H.-B.H.-21-'78)



1977-78 storm deposit

* Central harbor fill silts; light olive grey; *Tellina agilis*; *Gemma gemma*; laminations; bioturbations; annual winter (sand) and summer (silt) cycles; silts are heavily bioturbated and sands are heavily laminated, although zones of intermixing always occur

* Greenish grey sand alternating with olive grey silt

Burrowing dominant in silts; laminations dominant in sands

Ensis directus

Gemma gemma

Greenish grey sand alternating with olive grey silt; *Mytilus edulis*

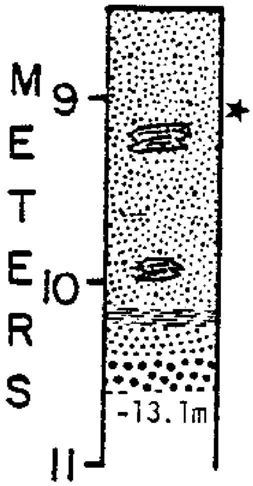
Ensis directus

* Heavily bioturbated zone

Gemma gemma shell hash; laminations

Epitonium humphreysi

Continued Core 21 (W.H.H.-B.H.-21-'78)

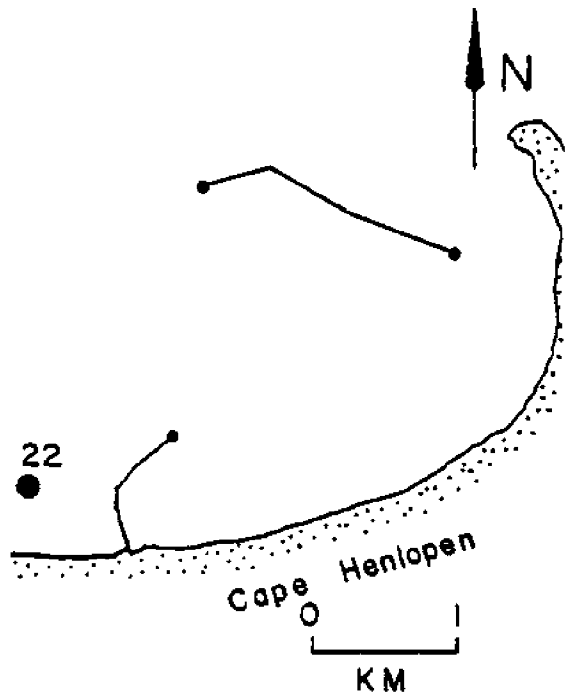


Tellina agilis; *Anomia simplex*; *Gemma gemma*; *Natica pusilla*; laminations and bioturbations

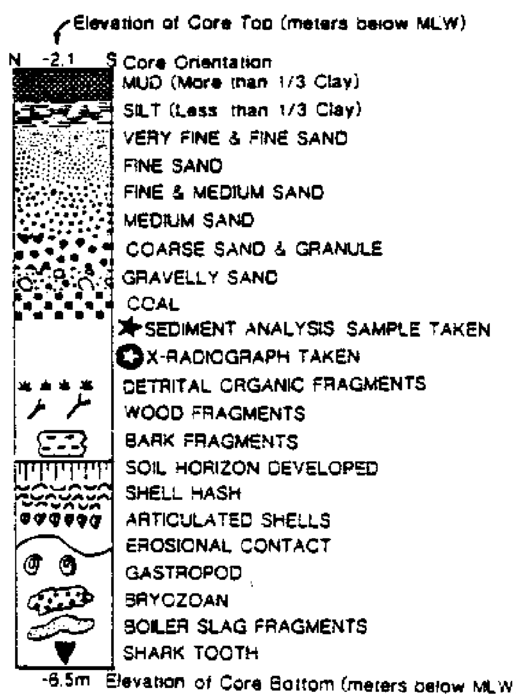
Olive grey; *Tellina agilis*

Greenish grey; Pleistocene paralic deposits

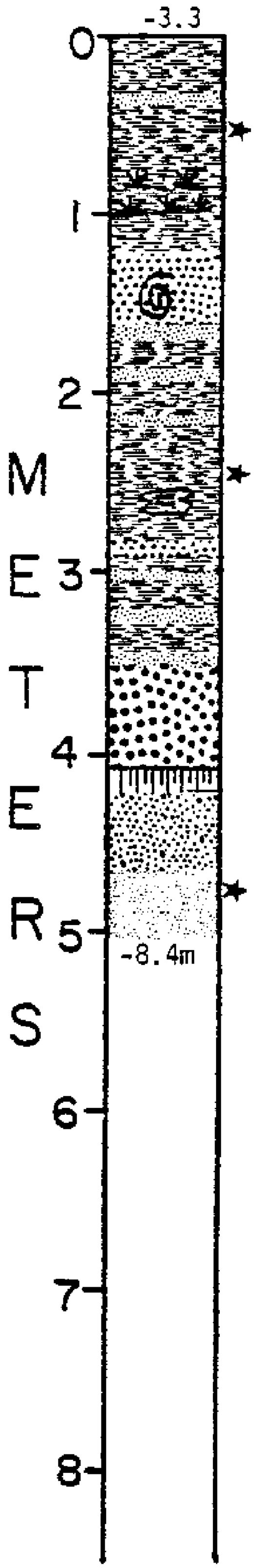
VIBRACORE 22



KEY TO SYMBOLS USED IN CORE LOG DESCRIPTIONS



BREAKWATER HARBOR VIBRACORE 22 (W.H.H.-B.H.-22-'78)



Heavily laminated estuarine silts; olive grey; Tellina agilis; Mytilus edulis; Gemma gemma; laminations and bioturbations

1964? sudden change in lithology associated with construction of nearby Ferry Breakwater; yellowish grey sand

Light grey

Deforestation of Lewes Beach, 1800?; greenish grey

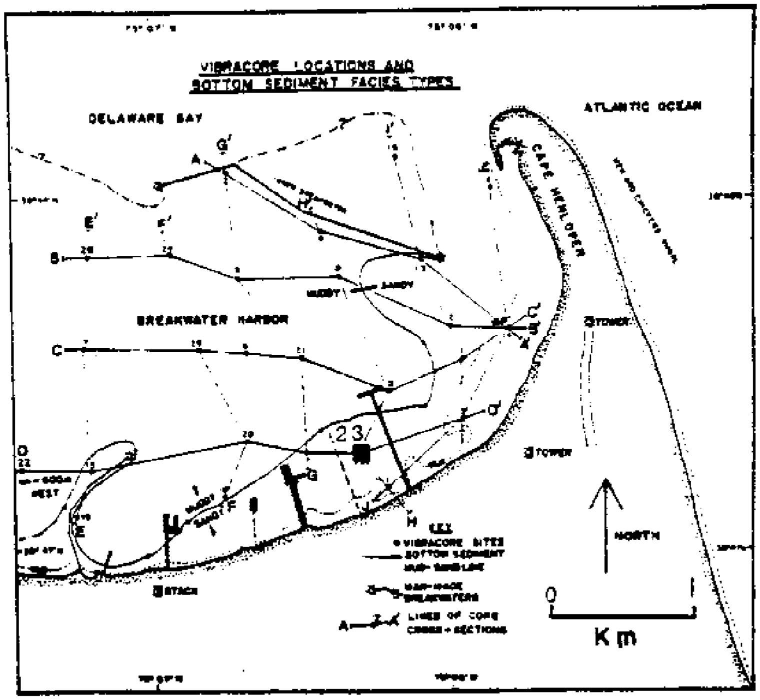
Gemma gemma; bioturbations; laminations

Very light grey

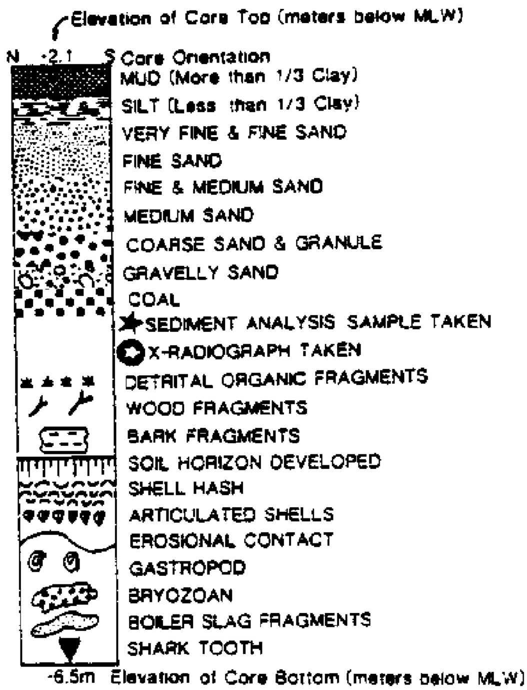
Soil hardpan ("B" horizon); Pleistocene emerged surface

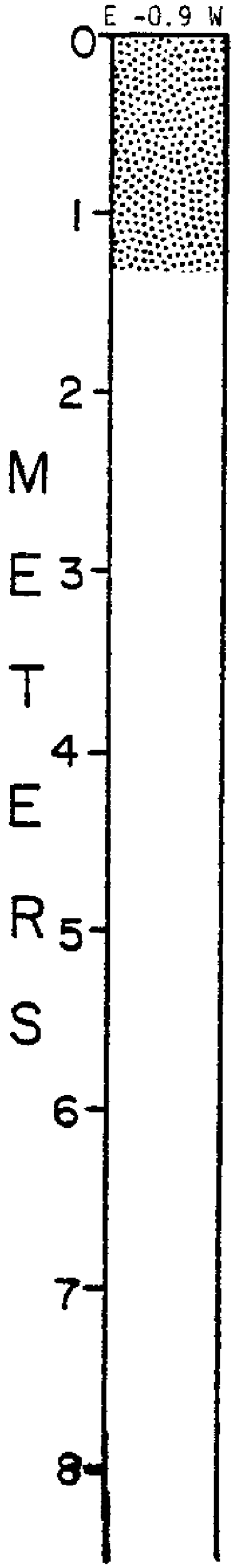
Greenish yellow
White; heavy minerals; laminations; fluvial channel?

VIBRACORE 23



KEY TO SYMBOLS USED IN
CORE LOG DESCRIPTIONS





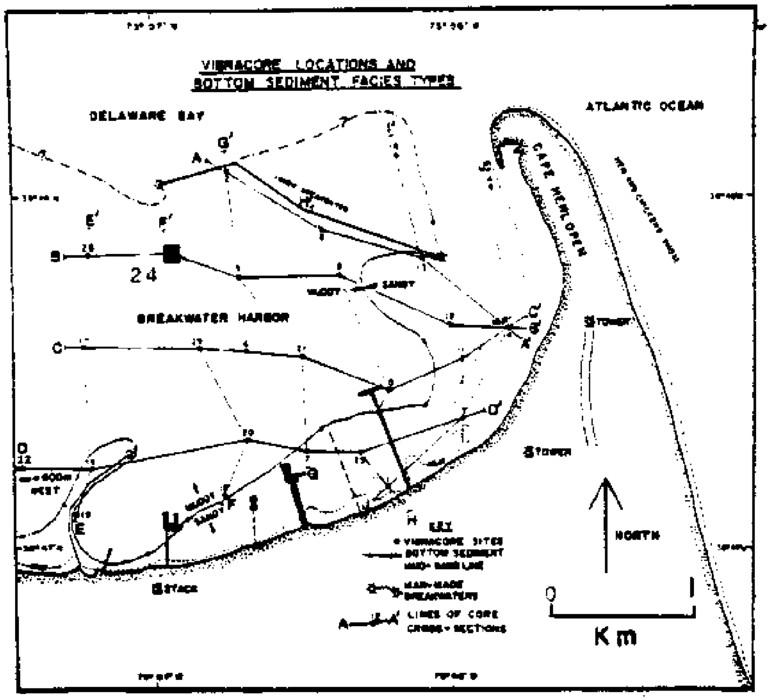
BREAKWATER HARBOR VIBRACORE 23 (W.H.H.-B.H.-23-'78)

Cape Henlopen tidal flat deposits; light olive grey; faintly laminated and bioturbated; reduced

Oxidized; yellow grey; bioturbations

Reduced; light grey; laminations; 1900?

VIBRACORE 24



KEY TO SYMBOLS USED IN
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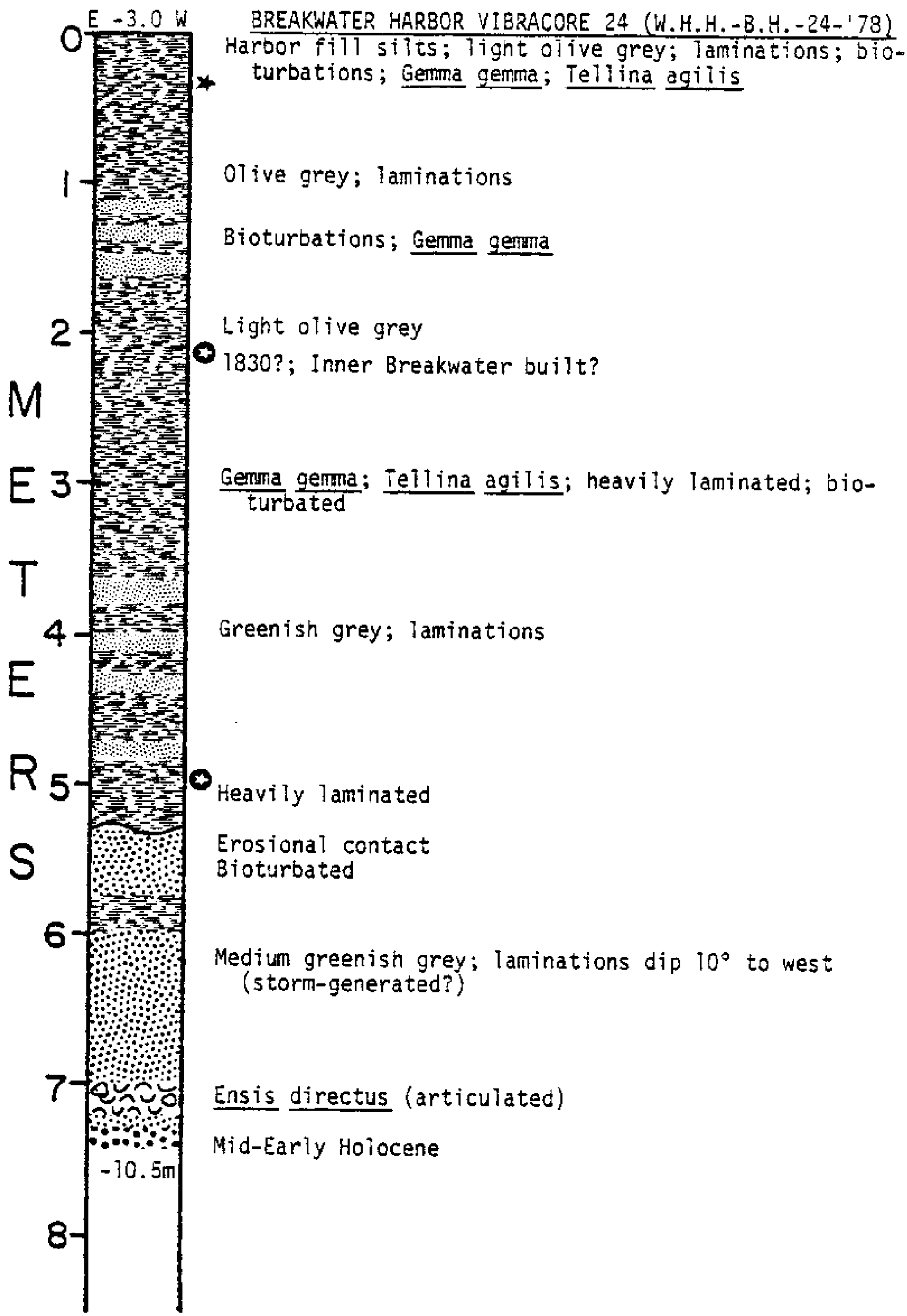
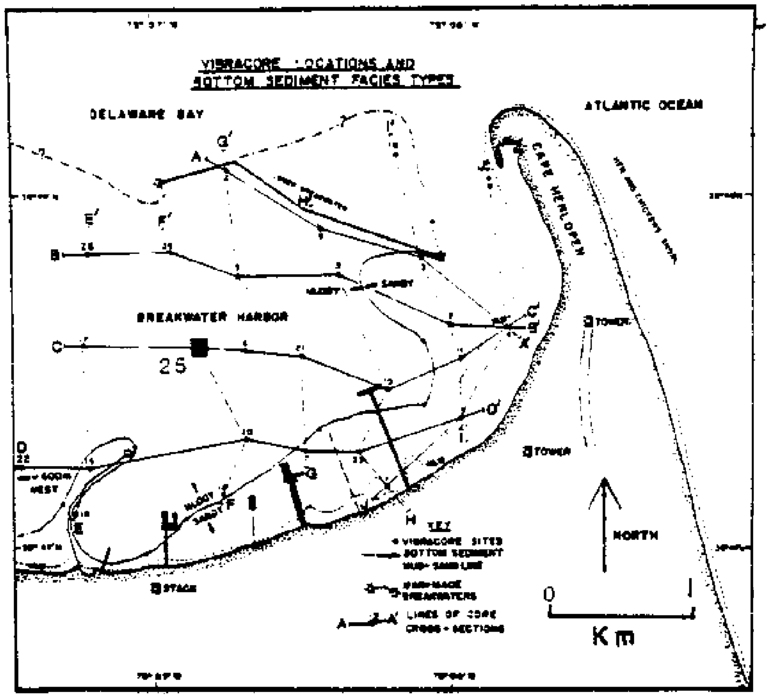

BREAKWATER HARBOR VIBRACORE 24 (W.H.H.-B.H.-24-'78)
E -3.0 W
Harbor fill silts; light olive grey; laminations; bioturbations; Gemma gemma; Tellina agilis
Olive grey; laminations
Bioturbations; Gemma gemma
Light olive grey
1830?; Inner Breakwater built?
Gemma gemma; Tellina agilis; heavily laminated; bioturbated
Greenish grey; laminations
Heavily laminated
Erosional contact
Bioturbated
Medium greenish grey; laminations dip 10° to west (storm-generated?)
Ensis directus (articulated)
Mid-Early Holocene
-10.5m
METERS
0
1
2
3
4
5
6
7
8

VIBRACORE 25



KEY TO SYMBOLS USED IN
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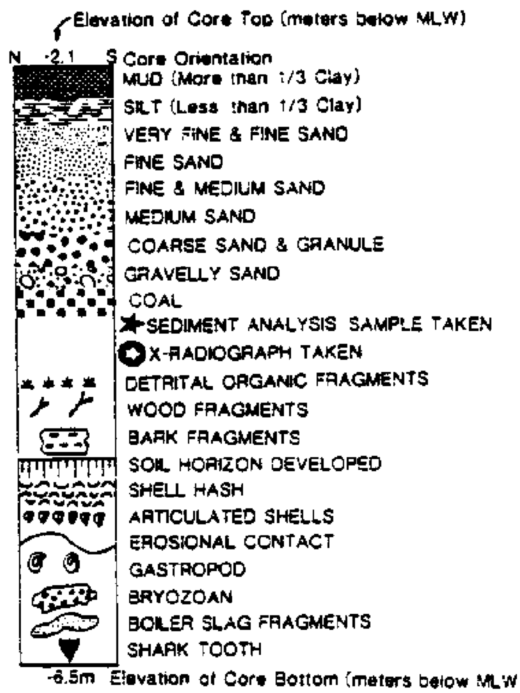
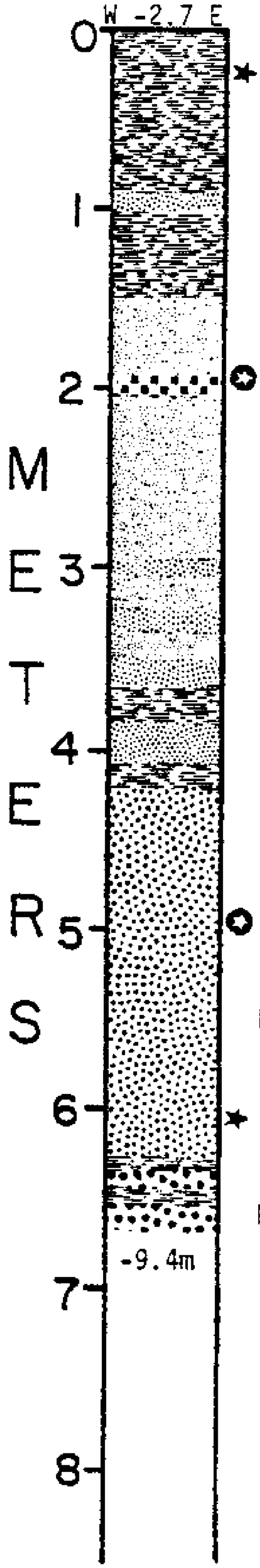


BREAKWATER HARBOR VIBRACORE 25 (W.H.H.-B.H.-25-'78)



Harbor fill silts; medium grey; *Tellina agilis*; *Gemma gemma*; bioturbations

Ensis directus, articulated

Coal is 5 centimeters in diameter--deposited from ship 1850

Heavily bioturbated

1830?; Inner Breakwater construction; heavily laminated

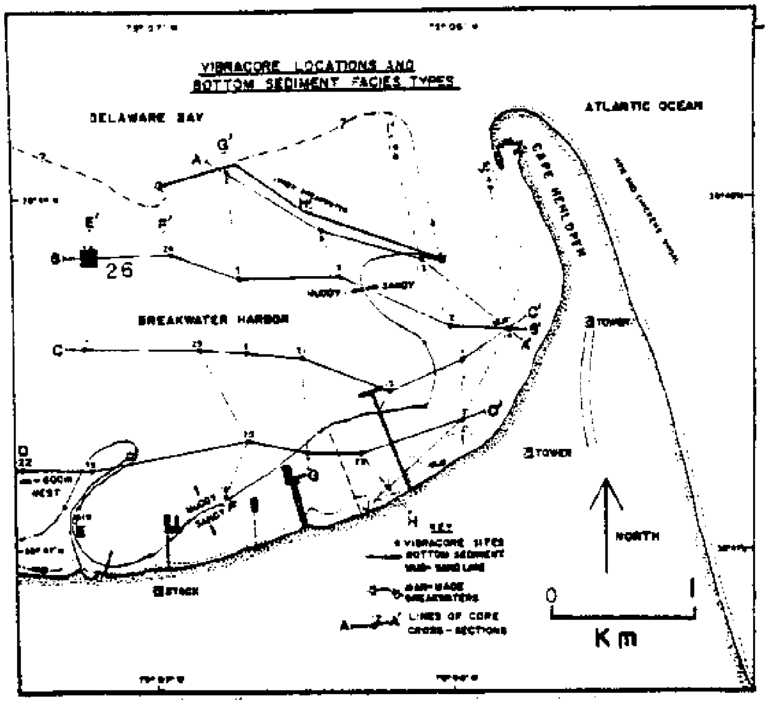
Light olive grey; *Ensis directus*; heavily bioturbated

Greenish grey; *Ensis directus*; bioturbated

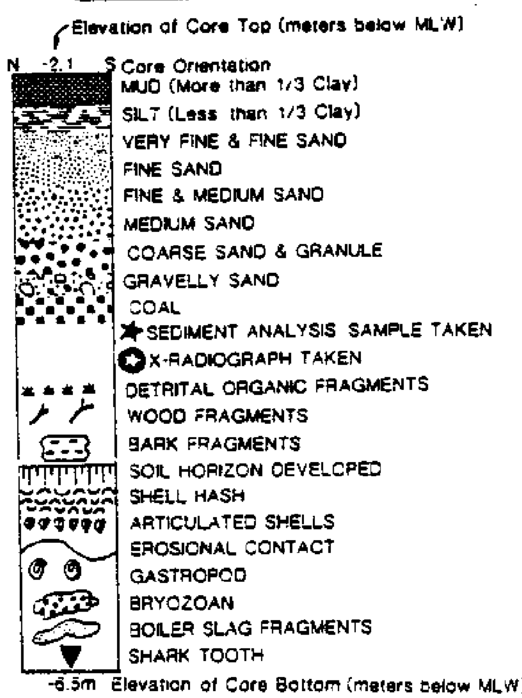
Bioturbated; greenish grey; estuarine sands winnowed by currents off of mid-Holocene Cape Henlopen

Pleistocene; cemented fluvial deposits; soil?

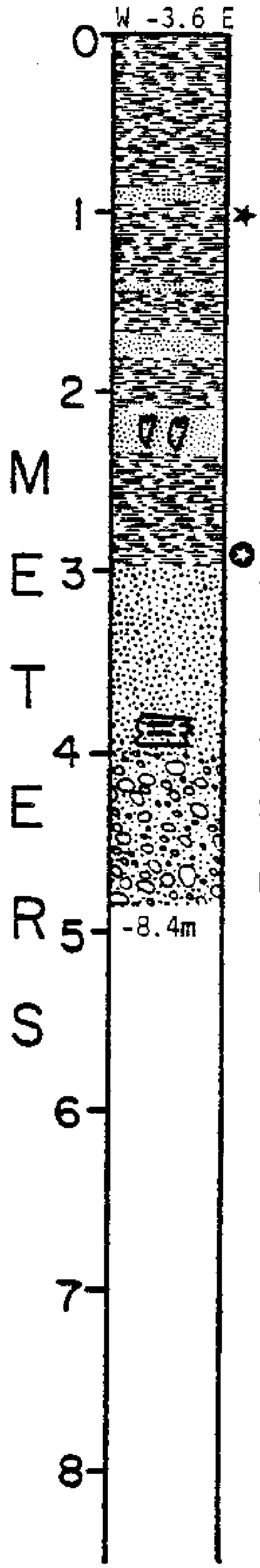
VIBRACORE 26



KEY TO SYMBOLS USED IN CORE LOG DESCRIPTIONS



BREAKWATER HARBOR VIBRACORE 26 (W.H.H.-B.H.-26-'78)



Harbor fill silts west of Inner Breakwater; olive grey; *Tellina agilis*; heavily laminated; bioturbated

Medium grey; *Gemma gemma*

1830?; Inner Breakwater construction

Ensis directus, articulated and in growth position

Laminations; bioturbations

Ensis directus, articulated and in growth position; greenish grey; bioturbations

Pine bark; *Ensis directus*

Structureless

Pleistocene paralic deposits; yellowish grey

APPENDIX L

COLORS USED IN DESCRIBING DRY VIBRACORES AND THE ASSOCIATED MUNSELL COLOR INDICIES

NOTE: Wet colors of vibracores can be obtained from the author or from the Department of Geology core catalog at the University of Delaware, Dr. J. C. Kraft, Curator.

VERBAL COLOR	MUNSELL INDEX
Yellowish grey	5Y 7/2
Light olive grey	5Y 5/2
Olive grey	5Y 3/2
Moderate olive brown	5Y 4/4
Light olive brown	5Y 5/6
White	N9
Light grey	N7
Medium light grey	N6
Medium grey	N5
Medium olive grey	5Y 5/1
Greenish grey	5GY 6/1
Dark greenish grey	5GY 4/1

APPENDIX M

FAUNA AND FLORA FOUND IN BREAKWATER HARBOR VIBRACORES

FAUNA

Identification based on information obtained from the following three sources:

1) Abbott, R. T., 1968, Seashells of North America: Golden Press, N. Y., 280 pp.

2) Stanley, S. M., 1970, Relation of shell form to life habits of the Bivalvia (Mollusca): G. S. A. Memoir #125, 269 pp.

3) Various experts in bivalves, univalves, fish teeth, bryozoans, etc. at the University of Delaware College of Marine Studies and the Geology Department.

MOLLUSKS

NOTE: Within each class, species are listed from most common to least common.

A. CLASS PELECYPODA (BIVALVES)

1) AMETHYST GEM CLAM (*Gemma gemma* Totten). Ranges from Nova Scotia to Texas. Introduced to Washington and California. The shell is very small (an average of 2.5 mm or 0.1") and the color is whitish to

tan with purplish tints. Pallial sinus is short and narrow and points toward the beak. Exterior has microscopic concentric lines. Common, usually in sand 0.3 m to 6.1 m (1 to 20 feet).

2) NORTHERN DWARF TELLIN (Tellina agilis Stimpson). The shell is an average of 1.3 cm (0.5") in length. Ranges from Eastern Canada to Georgia. Shell is fragile, elongate, glossy, and iridescent. Color varies from white to rose, mostly white and rarely pinkish hue in Breakwater Harbor vibracores. Sculpture of fine, concentric lines, but sometimes has coarse growth lines. Common occurrence, usually in sandy mud 0.92 m to 45 m (3 to 150 feet). This bivalve is a very rapid burrower (Stanley's burrowing rate index, B.R.I., is 3). Animals shift locations frequently and feed at the sediment surface with a vermiform inhalant siphon. Its life position is at a depth of about 3 cm (1.2") below the sediment surface. It has also been demonstrated that this burrowing rate goes down with increase in mud content of the substrate.

3) COMMON BLUE MUSSEL (Mytilus edulis Linne). The shell averages 5.1 cm (2") in length. Range is Artic Ocean to South Carolina and California. Shell is bluish black, often with purplish eroded areas; some specimens show brownish radial rays under the shiny, varnish-like periostracum. The ventral margin is straight or somewhat curved. No ribs are present but coarse, prominent growth lines are often seen. Interior is pearly white or greyish, much darker or purple along the border. Four small teeth are found in the margin, under the beak at the apex of the shell; the ligament is external. Common,

usually in quiet, shallow waters, attached to rocks and pilings. Occurs often in crowded colonies on intertidal rocks.

4) ATLANTIC JACKKNIFE CLAM (Ensis directus Conrad). The shell averages 15.3 cm (6") in length. It ranges from Canada to South Carolina. The shell is thin, gaping, moderately curved, with sharp edges; about six times longer than high and covered with a thin, glossy olive to brownish periostracum. Very common, usually found in colonies in sandy mud near the low water mark. This is a very rapid burrower (Stanley's B.R.I. is 6). Most common in nearshore tidal flat sand environments.

5) ATLANTIC NUT CLAM (Nucla proxima Say). The shell averages 1 cm (0.4") in length. It ranges from Nova Scotia to Florida and Texas. Exterior is smooth but may have fine grey axial lines. Ventral edge minutely scalloped. Common, usually in mud 0.92 m to 31 m (3 to 100 feet). Prefers muddy, organic-rich substrate and sheltered subtidal conditions. This species is a moderately rapid burrower (B.R.I. of 0.7). The depth of burial of the living animal is rarely greater than 1 cm (0.4").

6) BALTHICA MACOMA (Macoma balthica Linne). The shell averages 2.5 cm (1") in length. It ranges from Artic Seas to Georgia and California. The shell is variable, often oval, moderately compressed, and dull white occasionally flushed with pink. The periostracum is thin and flakey; it is common, usually in sediments 0.92 m to 18.2 m (3 to 60 feet). It prefers muddy sands in relatively quiet water. This species

is a moderately rapid burrower (B.R.I. 0.7). The animals usually live 15 cm to 20 cm (6" to 8") down from the sediment surface.

7) NORTHERN DWARF COCKLE (Cerastoderma pinnulatum Conrad). The shell averages 1.3 cm (0.5") in length. The range is Labrador to North Carolina. The shell is creamy, thin, and inflated; it has 22 to 28 wide, flattened ribs, thinly scaled except at the central portion of the valve. The interior is brownish white. This species is common in water 6.5 m to 190 m (20 to 600 feet). These depths suggest that its occurrence in Breakwater Harbor may result from transportation primarily from deeper water.

8) ANGEL WING (Cyrtopleura costata Linne). The shell averages 12.8 cm (5") in length. Its range is from New Jersey to Brazil with the shell usually pure white, thin, moderately fragile, covered with a thin, grey periostracum. It has 26 or more well-developed radial ribs with scales where they cross the concentric ridges. Moderately common, usually found in colonies in mud and clay, living about 20 cm (8") below the surface. This species is a very deep burrower (greater than 20 cm) and often it dies because it is not able to adjust quickly enough to rapid burial.

9) ATLANTIC JINGLE (Anomia simplex Orbigny). The shell averages 2.5 cm (1") in length. Its range is New York to the Caribbean. Top valve is convex, strong, and either yellow-orange or silvery-black. The lower valve is flat and fragile, with a slotlike hole near the hinge line. It is common in depths from shore to 9 m (30 feet) in gravelly

coarse sand. It attaches to pebbles, cobbles and shell debris in moderate current flow.

10) EASTERN OYSTER (Crassostrea virginica Gmelin). The shell averages 6.7 cm (3") in length. It is found from Nova Scotia to the Gulf of Mexico. Shell is generally elongate, but is highly irregular and variable in shape. The rough, heavy, greyish shell has the upper valve smaller and flatter than the lower. Interior of the shell is white except for the purple muscle scar and edging.

11) ATLANTIC SURF CLAM--SOUTHERN SUBSPECIES(?) (Spisula raveneli Conrad). The shell averages 6.8 cm (3") in length and is found south of New England to the Carolinas. The shell is cream-tan, strong, oval, quite smooth, with fine growth lines. It is abundant in sand from shore to 30 m (98 feet) depth.

B. CLASS GASTROPODA (UNIVALVES)

1) HUMPHREY'S WENTLETRAP (Epitonium humphreysi Kiener). The shell averages 1.5 cm (0.6") in length. The range is Massachusetts to Florida and Texas. Shell is rather thick and solid, with 8 or 9 well-developed ribs, heavy and rounded on body whorl; the ribs are usually angled at the shoulder. Common, usually in sandy mud from low tide to 92 m (300 feet).

2) PALLID JANTHINA (Janthina pallida Thompson). Shell is an average of 2.5 cm (1") in length. Pelagic, worldwide with a very globose shell and with a rounded base of aperture without the slight

projection seen in the Elongate Janthina. Sinus keel or scar can be seen in whorls of spire. Color is light, whitish violet. Up to 400 elongate egg capsules are attached to the float. Capsules are about 4-7 mm in diameter, and the tentacles are pale in color. Moderately common seasonally (summer warm waters).

3) COMMON ATLANTIC SLIPPER SHELL (Crepidula fornicata Linne). Shell is an average of 3.8 cm (1.5") in length. The range is Nova Scotia to Texas. Shell is convex, slightly spotted. Interior deck is buff color. Commonly attached to each other in shallow water; abundant in water 0.3 m to 15.7 m (1 to 50 feet) deep. (Only females seen in Breakwater Harbor vibracores.)

4) SOUTHERN MINIATURE NATICA (Natica pusilla Say). The shell is an average of 0.75 cm (0.3") in length. The range is Cape Cod to the West Indes. The shell is very small and glossy, similar to the Arctic Natica. The umbilicus is almost sealed by a whitish callus. The nucleus of the shelly operculum is often stained brown. Common in depths of 0.3 m to 30 m (1 to 100 feet).

NOTE: Many gastropods found in the cores were so broken and degraded that they could not be identified to the genus and species level.

BRYOZOANS

1) Conopeum tenuis. A member of the superfamily Malcoste-goidea, order Cheilostornata, and class Gymnolaemata, Conopium tenuis is a typical box-shaped, dark colored, sedentary bryozoan which requires

firm attachment, probably rocky. It forms as a colony, as often seen in most fossils. In Breakwater Harbor, it was not found until a time when the inner breakwater rocks were present as attachment foundations.

REFERENCE: Ryland, J. S., 1970, Bryozoans: Hutchinson Univ. Library, London, 175 pp.

FISH TEETH AND MISCELLANEOUS ANIMAL REMAINS

1) Small fish teeth, probably from a small shark.
2) Crab claw, probably from a Horseshoe Crab (*Limulus*).
3) Various insect wings, not identified.
4) Tremendously abundant faecal pellets from bivalves.

FLORA

1) Cottonwood seeds from trees south of Breakwater Harbor--wind transported.

2) Twigs, wood fragments and pine bark from both natural causes (waterlogging of debris) and also from usage of trees as a mat and building material aid during construction of the breakwaters.

3) Salt marsh plant mats (primarily *Spartina alterniflora*, *Spartina patens*, *Distichilis spicata*, and *Phragmites australis*).

4) Pollen and seed materials--none were definitely identified because they were not needed for the present study.

APPENDIX N

GRAIN SIZE ANALYSIS DATA--VIBRACORES

SAMPLE	DEPTH (cm)	% SAND	% SILT	% CLAY	SEDIMENT TYPE	COMMENTS
1-78-1	10-12	100	0	0	V F SAND	
1-78-2	50-52	100	0	0	F SAND	
1-78-3	100-102	100	0	0	F SAND	
1-78-4	140-142	100	0	0	F SAND	
1-78-5	180-182	100	0	0	F SAND	
3-78-1	120-122	100	0	0	F SAND	
4-78-1	80-85	100	0	0	V F SAND	
5-78-1	38-40	57	43		MUDDY SAND	SILT & CLAY ANALYSIS LOST
5-78-4	490-492	100	0	0	M SAND	
6-78-1	68-70	83.4	10.4	6.2	MUDDY SAND	USED FOR $CaCO_3$--% SHELLS
6-78-2	298-300	61.9	25	13.1	" "	
6-78-3	520-522	81	12.3	6.7	" "	
6-78-4	750-752	84.1	9.4	5.8	" "	
7-78-1	28-30	46.5	36.5	17	SANDY MUD	
7-78-2	170	63	24.6	12.4	MUDDY SAND	
7-78-3	338-340	43.6	38.7	17.7	SANDY SILT	FINELY LAMINATED
7-78-4	710-712	84.9	9.7	5.4	MUDDY SAND	COAL ANALYSIS--% OF SAMPLE
8-78-1	580-582	48.8	33.8	17.4	SANDY MUD	
10-78-1	138-140	60.8	39.2		MUDDY SAND	SILT & CLAY ANALYSIS LOST
10-78-A	402-404	73.6	26.4		" "	" " " "
10-78-B	410-412	77.4	22.6		" "	" " " "
10-78-2	425-427	69	31		" "	" " " "
11-78-1	170-172	100	0	0	F SAND	
11-78-2	258-260	53.8	46.2		MUDDY SAND	" " " "
12-78-1	375-377	74.9	25.1		" "	" " " "
12-78-2	552-554	65.3	34.7		" "	" " " "
13-78-1	270-272	57.9	28.3	13.8	" "	
13-78-2	435-437	100	0	0	M SAND	

GRAIN SIZE ANALYSIS DATA--VIBRACORES (CONT'D.)

SAMPLE	DEPTH (cm)	% SAND	% SILT	% CLAY	SEDIMENT TYPE	COMMENTS
14-78-1	90-92	100	0	0	F SAND	
15-78-1	65-67	100	0	0	F SAND	
15-78-2	250-252	52	33	15	SILTY SAND	
16-78-C	197-200	35.7	44.4	19.9	SANDY SILT	LAMINATED ZONE
16-78-B	205-207	55.7	30	14.3	MUDDY SAND	BIOTURBATED--SUMMER DEPOSITION
16-78-2	455-457	40.3	42.5	17.2	SANDY SILT	
17-78-1	450-452	80.6	12.4	7	MUDDY SAND	
18-78-2	68-70	9.5	58.2	32.3	MUD	
18-78-3	138-140	95.2	3	1.8	SAND	BLACK ORGANIC(?) DEPOSIT
19-78-1	90-92	42.7	39.4	18.9	SANDY SILT	ORGANIC SILT
20-78-1	30-32	45.7	37.6	16.7	" "	
20-78-2	560-562	92.7	4.8	2.5	SAND	
21-78-1	600-602	77.5	14.7	7.8	MUDDY SAND	
25-78-1	610-612	84.3	10	5.7	" "	
26-78-1	100-102	33.3	45.5	21.2	SANDY SILT	