A Delaware Sea Grant Technical Report

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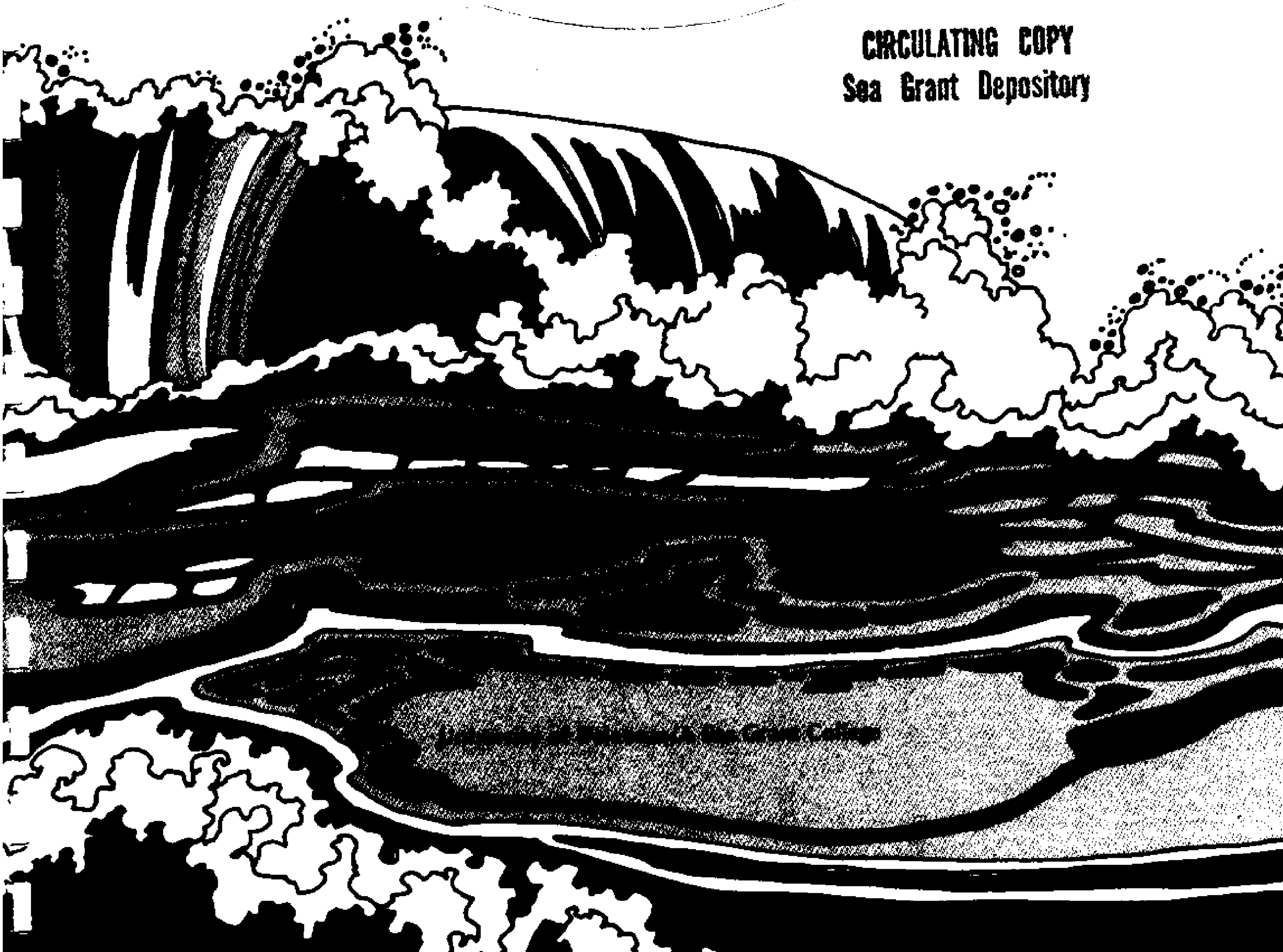
THE SHOALING OF BREAKWATER HARBOR, CAPE HENLOPEN AREA, DELAWARE BAY, 1842 TO 1971

James M. Demarest II

DEL-SG-1-78



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FOREWORD

This study is part of an ongoing geological research program in coastal processes and the evolution of coastal environments in Delaware. A number of previous projects have analyzed historical evidence of coastal change, coastal processes in the Cape Henlopen area, and the overall evolution of Delaware's coastal and estuarine geomorphic features; through these studies, a broader understanding of processes of the geology and processes of coastal Delaware has been gained.

In this report, an analysis is presented, which details the rates of sedimentation and erosion in the Breakwater Harbor area from 1842 to 1971. The analysis is based on bathymetric data available from surveys conducted by the National Ocean Survey and its predecessors. Several offshore breakwaters were constructed during this period, and Cape Henlopen built rapidly toward the northwest. As a result, the harbor has changed from an open roadstead to a semi-enclosed harbor surrounded by a breakwater and a rapidly advancing spit. Thus the sediment regime in the harbor area has dramatically altered over the past 150 years. In addition to the analysis of bathymetric change, peripheral effects of shoreline erosion, spit development, tidal flow and transport, and computer applications to bathymetric comparisons are addressed.

The information on sedimentation and erosion patterns in the harbor and vicinity gained in this study was a first step in a program to attain a precise understanding of the sedimentary processes. Under Sea Grant Project SG78-KRAFT-R/G9, suspended sediment transport through Breakwater Harbor area, sediment transport into the harbor via littoral drift and overwash processes on Cape Henlopen, and coastal erosion along harbor shorelines are being studied. An integration of this ongoing research with this study will facilitate a more precise understanding of processes both past and present, and enable prediction of future geomorphic evolution: information which is not only of interest for scientific purposes but is also useful to planners and potential users of Breakwater Harbor.

James M. Demarest II

ACKNOWLEDGMENTS

I wish to express sincere thanks to Dr. John C. Kraft for his help in planning and execution of this study. Sincere gratitude is also expressed to the faculty of the Department of Geology, University of Delaware and Mr. D. F. Belknap, Mr. W. H. Hoyt, Ms. S. D. Goodrich, Mr. D. A. Neal, Mr. J. Franks, Mr. B. F. Atwater, and Mrs. J. E. Demarest for their help during the course of this study.

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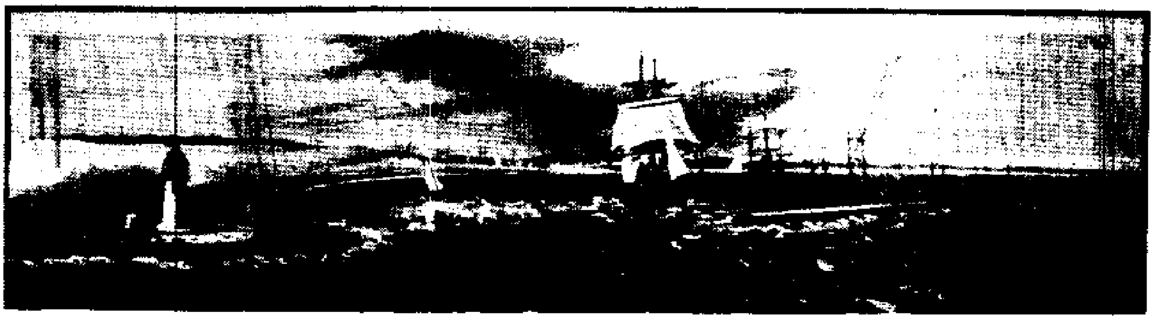

FRONTISPIECE

A sketch of the Cape Henlopen region, Breakwater Harbor and Lewestown in 1831, by William Strickland, Engineer. Taken from Kraft, 1971b (original source Eleutherian Mills Historical Library).

TABLE OF CONTENTS

TABLE OF CONTENTS
(cont.)

LIST OF FIGURES AND TABLES

FIGURES PAGE

LIST OF FIGURES AND TABLES
(cont.)

FIGURES PAGE

LIST OF FIGURES AND TABLES
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FIGURES | PAGE

TABLES

ABSTRACT

In order to understand the past sedimentary processes of the Breakwater Harbor-Cape Henlopen area, and to evaluate man's influence on these processes, two aspects of the area were studied. The present sedimentological conditions were determined through sediment sampling and current measurement, and past sedimentation was determined through the analysis of historic bathymetric data available starting in 1842.

The tidal flat on the west side of Cape Henlopen consists of coarse to medium sand, which generally becomes finer southward. Sand ridges are the dominant morphological feature of the tidal flat, and their movement is dependent on the relationships between wave energy, wave approach direction and tidal stage. The magnitude of sediment transport during times of sand ridge emergence relative to submergence is the determining factor in morphological development, migration rate, and orientation of the sand ridges. Tidal currents on the tidal flat are negligible in the absence of waves.

Breakwater Harbor is dominated by silt, and the sediment generally becomes coarser from the center of the harbor, toward shore, and into the scour hole off the east end of the inner breakwater. The coarsening seaward found on the tidal flat does not continue into the harbor. The tidal flat is prograding into the harbor, with a short transitional zone from "tidal flat" sediments to "harbor" sediments. Current data shows a strong dominance of ebb tides in the harbor, both in magnitude and duration of the currents.

In the second part of the study, seven bathymetric surveys available from NOS of NOAA, were analyzed to identify patterns of deposition and erosion as well as the effect on these patterns of breakwater construction west of the cape in 1831 and north of the cape in 1900. The data were digitized and interpolated to a grid system, from which depth changes and shoaling rates were calculated. Construction of the breakwaters, in both cases, caused a brief period of erosion in the resulting narrowed areas followed by general deposition. Average shoaling rates between survey intervals for Breakwater Harbor ranged from -0.02 ft/yr (-0.6 cm/yr) to 0.19 ft/yr (5.7 cm/yr). Rates off the spit tip were as high as 3.0 ft/yr (90 cm/yr). Cape Henlopen has grown toward the northwest 5000 ft (1500 m) since 1842, filling in a 60 ft (18 m) deep channel.

There does not appear to have been any development of an accretional spit platform as defined by Meistrell (1972). Instead, the cape has prograded with a steep leading edge extending from about the low tide line to the floor of the channel being filled. The shoaling on the "ebb-tidal-lee" side of the inner breakwater is not a result of spit growth.

Concentration of ebb tidal currents between inner breakwater and the cape has prevented the cape from recurving to the west. As a result of the narrowing of the channels between the shore and the breakwaters by spit growth and the resulting decrease in tidal flow, there has been net deposition in most of the study area. The form and rate of spit growth and associated bathymetric change appears to have been storm dominated while local bay sedimentation has been dominated by breakwater construction. These data and analysis techniques have considerable application to prediction and planning in similar areas.

CHAPTER I

INTRODUCTION AND GEOLOGICAL SETTING

Introductory Statement

Since the construction of the inner breakwater, Breakwater Harbor in southeastern Delaware Bay has filled in at a rate an order of magnitude greater than "normal" estuarine shoaling rates, as defined by Rusnak (1967). In addition, Cape Henlopen has grown toward the northwest over two kilometers, partially filling in a deep tidal channel. As a result of these and other factors, Breakwater Harbor has gradually become of little use to shipping. In recent years, the revitalization of Breakwater Harbor through massive dredging has been proposed in order for the harbor to be used as a support station for oil drilling efforts offshore. In light of these proposals and historic trends, it is important to understand marine processes in the harbor area.

Purpose of Study

The purpose of this study is to investigate sedimentary processes in the Breakwater Harbor-Cape Henlopen area. Toward this end, shoaling rates, changes in the pattern of shoaling with time, and shoreline changes have been determined through bathymetric comparison, using survey data starting with the 1842 U. S. coastal survey map. In addition, information about modern conditions and processes in the study area has been obtained through the determination of sediment distributions within the harbor and on the tidal flat, and by measurement of currents in two locations in the harbor.

From the data thus obtained, the sedimentary processes responsible for the filling of the harbor and the effects of man-made structures on normal marine processes can be better understood. Therefore, data is presented for prediction of the future of Breakwater Harbor from a geologic viewpoint and for planning of the future of the harbor from a political-economical viewpoint.

Geography

Breakwater Harbor is situated in southeastern Delaware Bay, just inside the entrance. It is bounded by Cape Henlopen on the east; the inner breakwater, built in

1831, on the north; the ferry jetty, built in 1964, on the west; and the shore of Delaware Bay on the south (Figure 1). Cape Henlopen is about 8000 feet (2500 m) long in the north-south direction, with a slight recurve at the northern end. Hen and Chickens Shoal, east of the cape, extends from the spit tip to the southeast at about a 30° angle to the Atlantic Coast of Delaware. The Harbor of Refuge is to the north of the Cape on the west side of the outer breakwater. A 60-foot (18 m) deep channel lies between the outer breakwater and the spit tip. There is a large tidal flat on the west side of the cape, with a 30-foot (9.1 m) deep channel between the edge of the tidal flat and the inner breakwater.

Historical Background

The history of the Breakwater Harbor area has been reviewed by Kraft and Caulk (1972). Those interested in details of historical aspects of construction projects of the area and/or early settlement of the area are referred to that publication.

For the purpose of this study, the history of Breakwater Harbor began in 1831 with the construction of the inner breakwater. In the early 1800s, the U. S. Congress authorized construction of the inner breakwater to protect sailing ships while they waited for favorable winds for

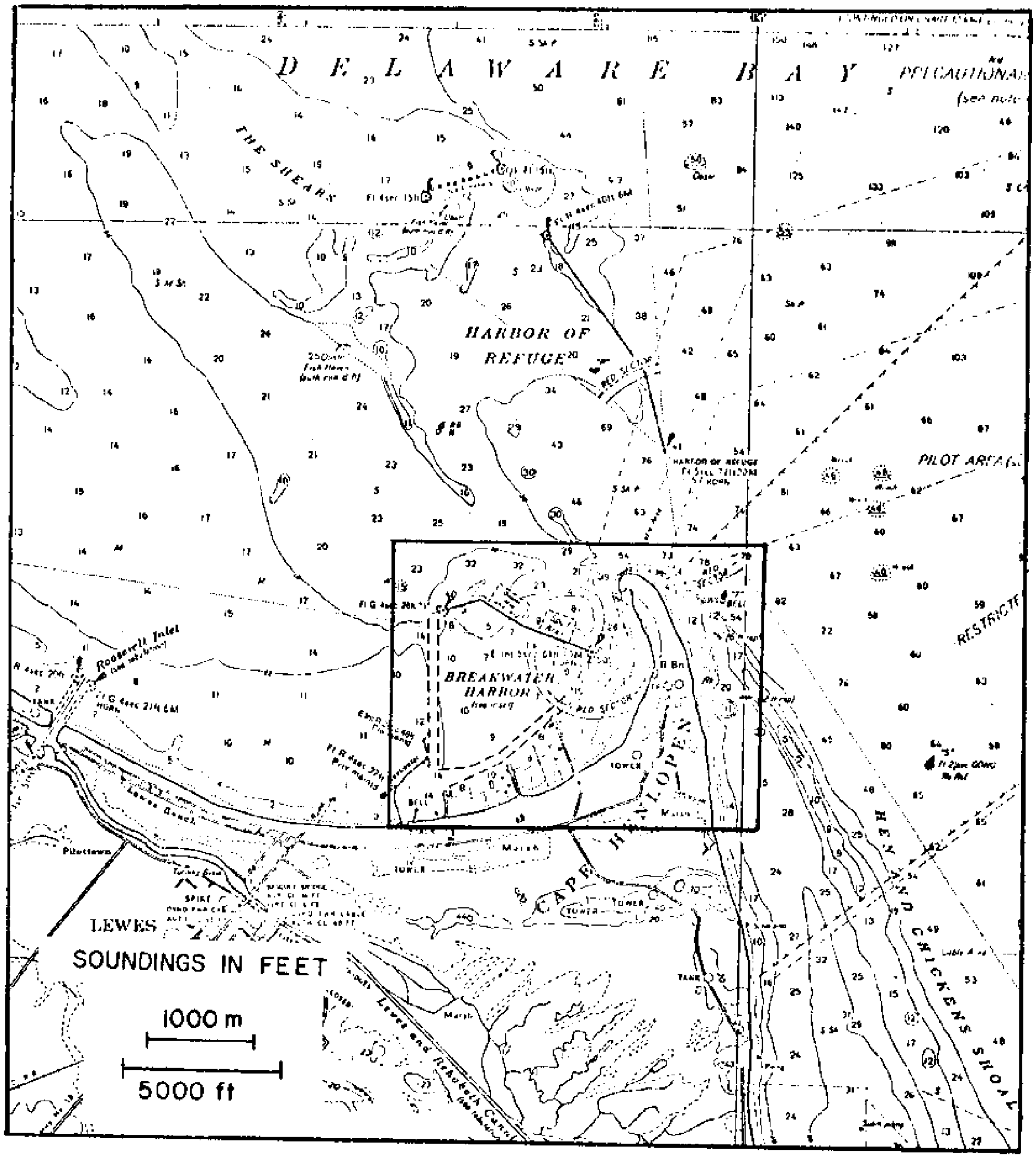


Figure 1 - Geographical index to study area. This is a reduced copy of NOS Chart 12216, (formerly C & GS 411). The study area is located in southeastern Delaware Bay, just inside the entrance. Blocked in area indicates the area studied through bathymetric analysis of historic data.

sailing up Delaware Bay or for adverse weather to clear. The breakwater was built in two sections with a gap in the center. Studies over the next few years by the Secretary of War Office, the U. S. Army Corps of Engineers, and the U. S. Corps of Topographic Engineers expressed alarm over rapid sediment infill of the harbor and attributed this increase in sedimentation to the gap in the breakwater (Kraft and Caulk, 1972). In the late 1880s the center section of the breakwater was filled. After an initial period of erosion, the sedimentation rate again increased. Because of the decreasing usefulness of the harbor, construction of the outer breakwater was authorized in 1900 (Figure 1) (Kraft and Caulk, 1972).

With the development of steam-powered ships and the construction of the Harbor of Refuge (1900), Breakwater Harbor gradually fell into disuse except for fishing boats and, more recently, the Cape May-Lewes Ferry. In addition, during the 1940s, the harbor was used as a base for military operations because of its strategic location with respect to protection of the entrance to Delaware Bay. In 1964, the ferry terminal jetty was constructed to stop sedimentation in dredged areas adjacent to the terminal. At present, there are two ship channels within the harbor. One extends from the ferry terminal, north past the west end of the inner breakwater. The other extends northeast from the ferry terminal toward the east end of the inner breakwater (see Figure 1). The last dredging was in 1974.

At the time of the construction of the inner breakwater in 1831, Cape Henlopen was a gently rounded spit, barely extending into Delaware Bay. Since that time, the cape has continued to grow northward at an accelerating rate (Maurmeyer, 1974). The effects of the breakwaters on spit growth are difficult to differentiate from the effects of natural processes. Spits at the southern Delaware Bay-Atlantic Ocean juncture have grown more or less continuously during the last 2000 years (Kraft, 1971b). For this reason alone, growth of Cape Henlopen northward was inevitable. Man's interventions have probably affected rates of growth and shape of the spit.

Geological Setting of Coastal Delaware

Holocene Geology

The Atlantic coast of Delaware is presently undergoing a marine transgression as a result of a rise in sea level and a subsidence in the Baltimore canyon trough of the Atlantic coast continental margin geosyncline (Kraft, 1971a). Transgressions and regressions of the sea across this area have occurred several times in the geologic past, as evidence by thick sections of marine and non-marine sediments underlying the Delaware coast. These sediments range in age from Jurassic-Triassic to Holocene and represent a wide variety of depositional environments (Kraft and others, 1971).

The Holocene transgressive sequence along Delaware's Atlantic Coast, as described in detail by John (1977), generally consists of a pre-Holocene erosional surface overlaid by back-barrier sediments, which are in turn overlaid by barrier sands. The only notable exception to this is the Cape Henlopen beach-spit-dune complex, which represents a small regressive sequence, with spit sands overlaying estuarine-offshore marine sediments, which in turn overlay the pre-Holocene erosional surface (Figure 2) (John, 1977; Kraft, 1971a).

The Holocene transgression has continued for the past 14,000 years, beginning with the waning of the

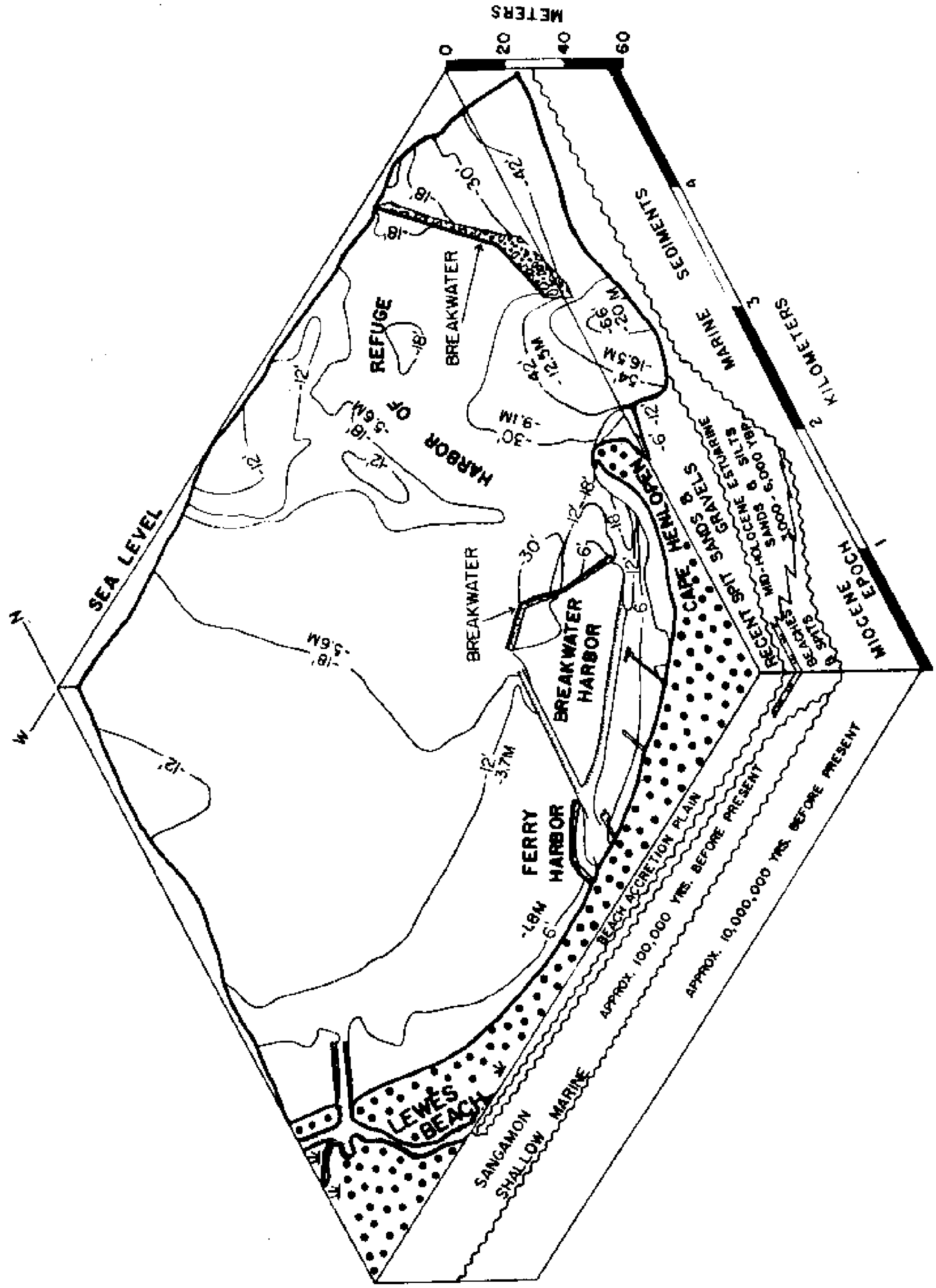


Figure 2 - Breakwater Harbor-Cape Henlopen area block diagram. The stratigraphy presented is generalized.

Wisconsin glaciation and the resulting eustatic rise in sea level (Kraft, 1971a). Ten thousand years ago, the mid-Atlantic coast of the U. S. was near the edge of the continental shelf; it has subsequently migrated over 100 miles (160 km) to its present position (Kraft, 1971a).

Sea Level Rise

A comparison of rates of relative sea level rise calculated by 1) geologic data and 2) tide gauge records shows a recent increase in the rate of sea level rise to about twice the average late-Holocene rate. Belknap (1975), based on geologic evidence, found the rate of relative sea level rise along the coast of Delaware to be 0.4 ft (12 cm) per century, averaged over the past 2000 years (also see Belknap and Kraft, 1977). Tide gauge records from 1919 to present for Breakwater Harbor show an average rate of relative sea level rise of 1.1 feet (33 cm) per century over the last 50 years. The rate based on tide gauge data was calculated by running a linear regression on the monthly means for low water, high water, and mean sea level for Breakwater Harbor. The values obtained compare very well with those obtained in a similar way for this and other east coast tide gauge records by Hicks and Crosby (1974). Figure 3 shows a plot of mean annual tide levels for Breakwater Harbor, and the regression line calculated, using mean

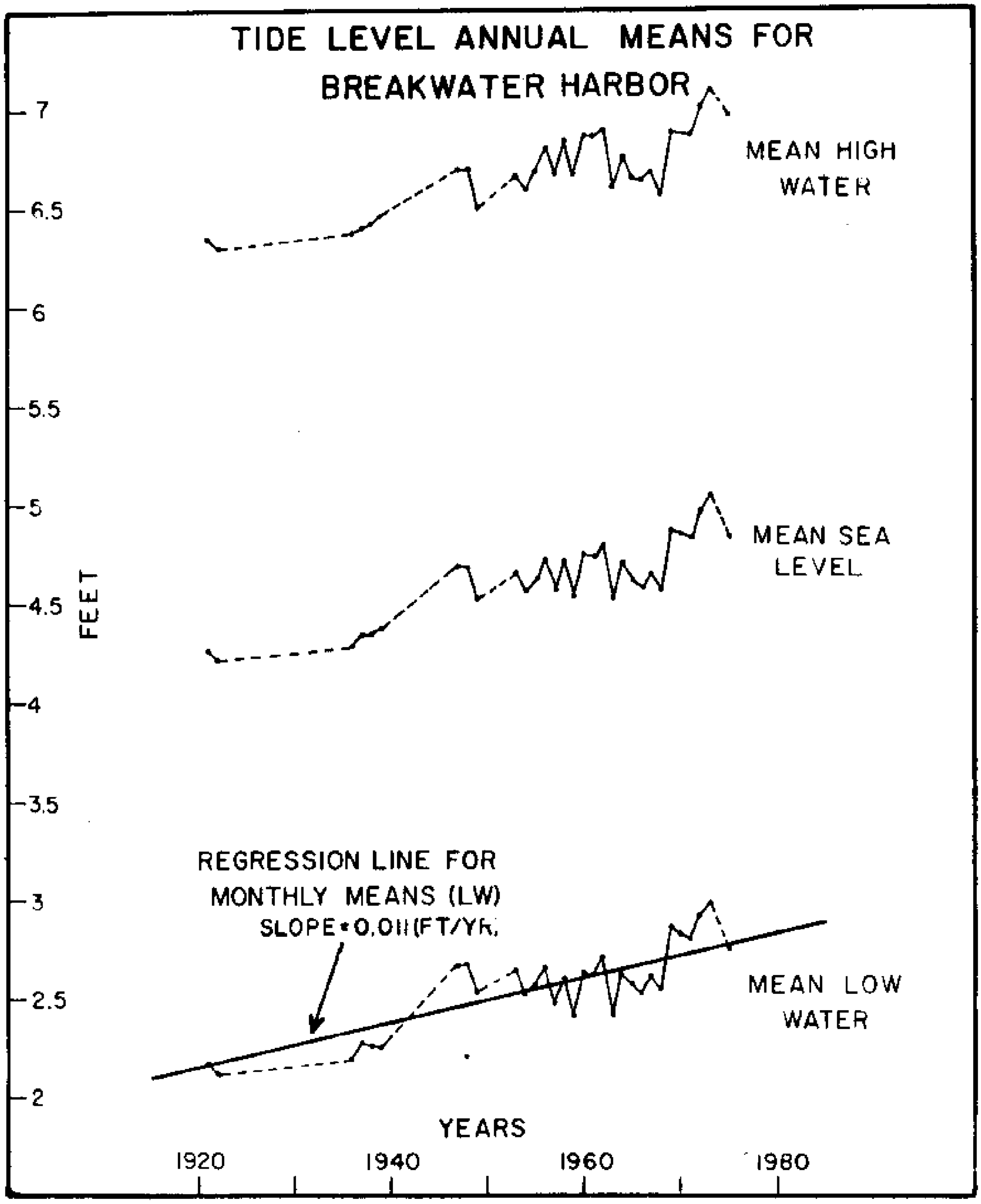


Figure 3 - Tide levels from Breakwater Harbor tide gauge records. Regression line for low water means was calculated from monthly mean low water levels. Dashed lines indicate gaps in the record. Sea level rise of 1.1 feet/century (33 cm/century) compares favorably with rates calculated by Hicks and Crosby (1974) for this and other east coast tide gauge records. This is a relative rate of sea level rise. (Source, NOAA, NOS, Tides Division)

monthly low water levels. These data were obtained from the National Ocean Survey, Tides Division.

Historic Coastal Change

Maurmeyer (1974) has determined that the Atlantic side of Cape Henlopen has been retreating at rates of 10 to 18 feet/year (3.0 to 5.5 m/yr) over the last 200 years. During that same time, Cape Henlopen has grown toward the northwest at rates ranging from 15 to 60 feet/year (4.5 to 18.3 m/yr) apparently accelerating with time. Brickman and others (1977) and Kraft (1971b) have determined that, in recent years, Cape Henlopen has accelerated to a growth rate of nearly 100 feet/year (30 m/yr).

Delaware Bay

Breakwater Harbor is part of Delaware Bay and, therefore, is affected by processes in Delaware Bay. Studies by Oostdam (1971), Strom (1972), and Weil (1977) have identified in some detail the sedimentary processes of the bay. A transgressive estuarine delta intrudes into southern Delaware Bay (Weil, 1977). Present environments of deposition and erosion are migrating upward and landward. Kraft (1971a) and Weil (1977) have traced the migration of these environments through time, and Weil (1977), Oostdam (1971) and Strom (1972) have identified the present sedimentological conditions of the bay.

Studies of Delaware Bay show that net transport of sediment in the southern portion of the bay has been landward (also see Meade 1969), because of the dominance of tidal currents over river discharge (Weil, 1977). In general Delaware Bay is not in equilibrium with present sea level rise because of an insufficient supply of sediment and the restriction of tidal currents at the mouth of the bay by Cape Henlopen and Cape May, and, more recently, by the outer breakwater. As a result, tidal currents are eroding portions of the bay floor, while waves are eroding portions of the bay shoreline (Weil, 1977).

Geological Prediction of the Future

In discussing the ability to predict future trends based on past geological history, Kraft and others (1976) state:

> The short-term geological past allows prediction of short-term (100-1000 years) future change. Our prediction of short-term change is that the marine transgression will continue at its present rate. Long-term past processes have varied. Therefore, the long-term future (thousands to millions of years) is unpredictable.

CHAPTER II

SEDIMENTOLOGICAL CONDITIONS AND PROCESSES

Methods of Study

During the summer and winter of 1975-1976, field investigations were conducted in order to characterize present sedimentological conditions and marine processes in Breakwater Harbor and vicinity. Figure 4 is an index to sample locations, sample profiles, and current meter stations. In addition, bathymetry and location of dredged channels are shown.

A plane table and an alidade were used to survey the tidal flat and to locate the exact position and elevation of sediment samples along the profiles. Samples in the tidal flat were taken by pushing a 2.5-inch (6.4 cm) O.D. plastic pipe 8 inches (20 cm) into the sand and emptying the contents into a cloth sample bag. This technique assured that the sampling procedure was consistent.

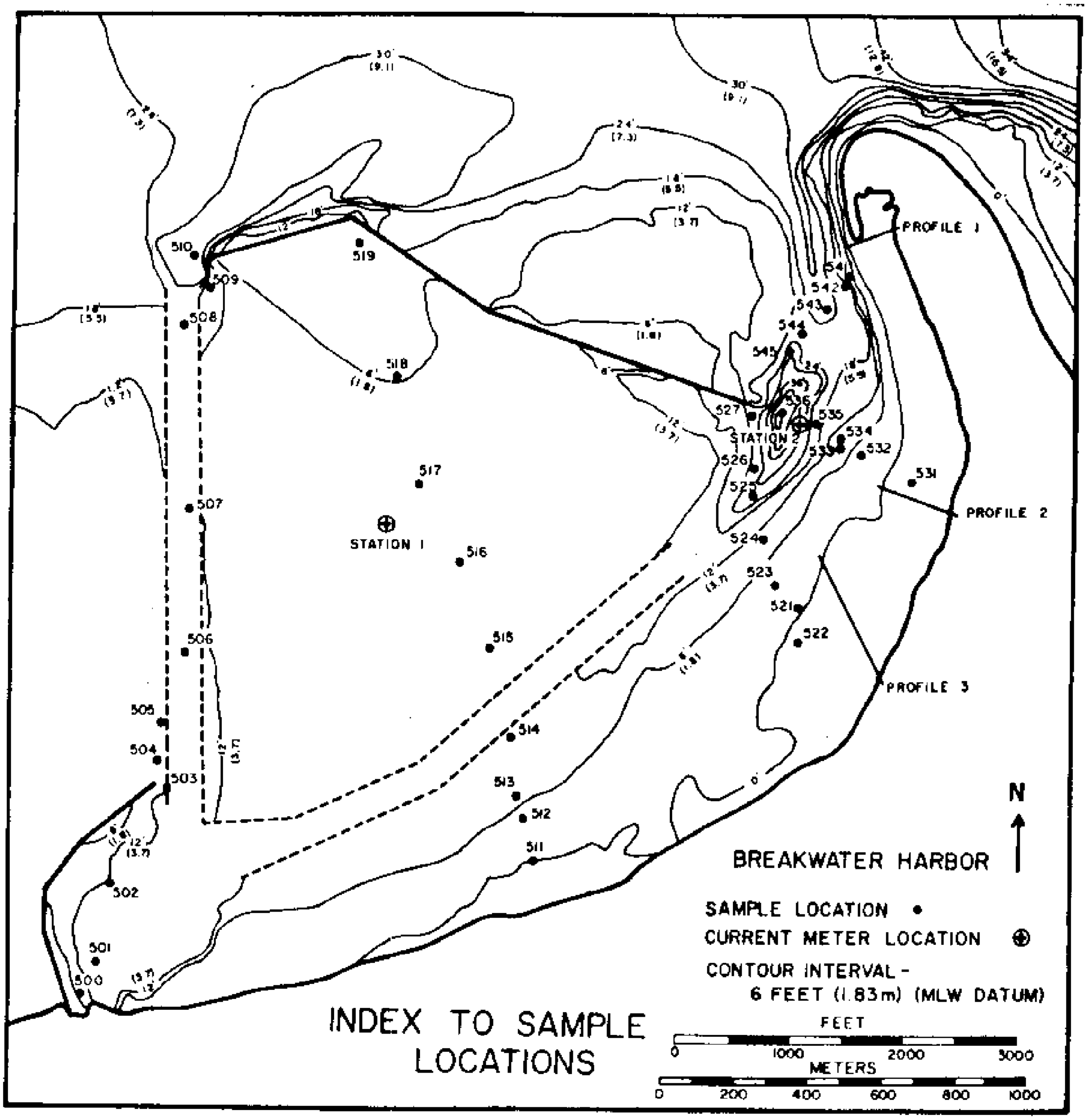


Figure 4 - Index to sample locations. Although the base map for this figure was the 1977 nautical chart (12216), the depths are valid for 1971, the date of the latest hydrographic survey. The numbers adjacent to the dots are sample numbers and refer to the data tables in Appendix A.

Sediment samples from Breakwater Harbor were taken with a modified Foster anchor dredge, except where the water was shallow enough for a small coring device. The coring device produced a sample of the top 8-12 inches (20-30 cm). Only the top 8 inches (20 cm) were kept. Muddy samples were put in plastic sample bags.

During October and November 1976, a General Oceanics Model 2010 film recording tilt current meter was placed in the center of Breakwater Harbor (Station 1, Figure 4). During April and May 1977, the current meter was placed in the channel between the inner breakwater and Cape Henlopen (Station 2, Figure 4). The speed and direction of currents were measured every 15 minutes for 23 days at Station 1 and 18 days at Station 2. Only half-hour readings were tabulated, because preliminary examination of the data showed that for the purposes of this study, 30 minute readings was sufficient to characterize current regimes. The tabulated data from each station consisted of over 1000 separate current measurements.

The Tidal Flat

Data Presentation

The tidal flat on the west side of Cape Henlopen is dominated by "sand ridges".* The orientation of these sand ridges changes from coast-parallel in the north to coast-perpendicular to the south (Figure 5). Three sediment sample and topographic profiles were made across the tidal flat approximately perpendicular to the sand ridges. The sedimentological data is listed in Appendix A and plotted in Figure 4.

A fourth profile, along the axis of a ridge, was not plotted because the elevations of the samples are unknown because of surveying problems. However, it is known from field notes that the ridge had a gradual increase in elevation from approximately one foot below low water to high water, a vertical distance of about 4 feet (1.2 m). The average mean grain size of the samples along Profile 4 was 1.03 phi. Seven of the ten most seaward samples in Profile 4 had mean grain sizes larger than the average for the profile, and all of the six landward-most samples had mean grain

*"Sand ridge" is used in this text to refer to the elongate morphological features (Figure 5) found on the tidal flat on the west side of Cape Henlopen because the term is free from genetic connotations. A theory for their genesis is presented.

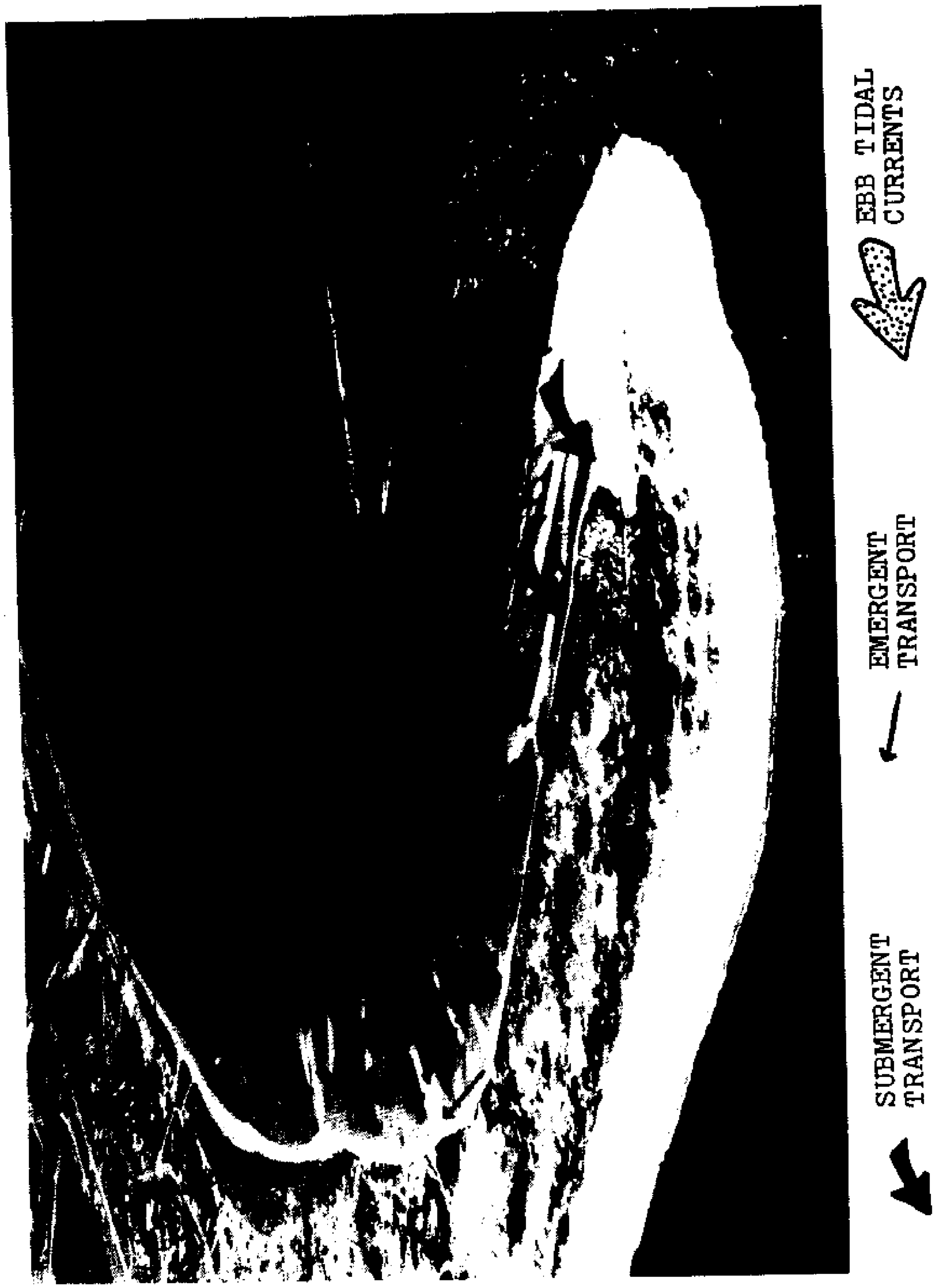


Figure 5 - Oblique aerial photograph of Tidal Flat, Fall 1976 (at mid-tide). Schematic representation of tidal flat processes. Emergent and submergent are in reference to the crests of the sand ridges. Wave fronts are generalized. Conditions are fair weather, northwest winds.

sizes larger than the average for the profile, and all of the six landward-most samples had mean grain sizes finer than the average for the profile, indicating general fining landward. All samples except one had sortings of between 0.44 phi and 0.54 phi. The sorting parameters along this profile were less variable than along any other profile.

A comparison of average mean grain size along Profiles 1, 2 and 3 (Figure 6) shows a general fining southward: 0.56 phi for Profile 1; 0.88 phi for Profile 2; and 1.08 phi for Profile 3. The fining from north to south is coupled with an increase in sorting and a decrease in elevation and relief. Direct correlation between mean grain size and elevation along each profile was not found except for an occasional slight coarsening and slight decrease in sorting immediately behind sand ridges (Sample locations 16, 21, and 61). This is more accurately described as a correlation between morphologic position of the sample and mean grain size and sorting, and is probably caused by a sudden decrease in energy as waves pass over the sand ridge during submergence.

The large "spikes" in the sorting and mean grain size at sample locations 10 and 23 were due to a gravel lag that could be found in the flat areas between many of the sand ridges, especially in the central section of the

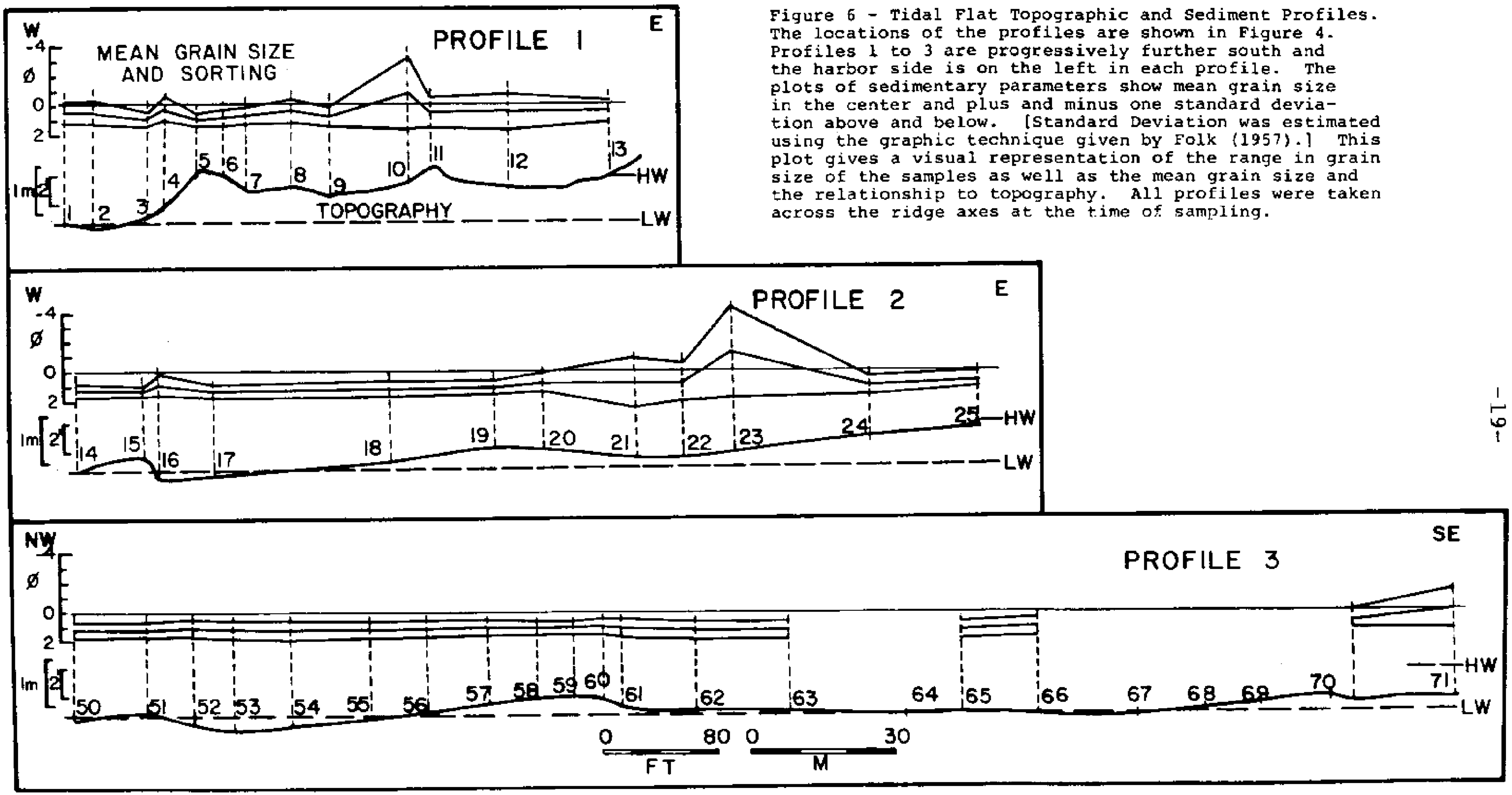


Figure 6 - Tidal Flat Topographic and Sediment Profiles. The locations of the profiles are shown in Figure 4. Profiles 1 to 3 are progressively further south and the harbor side is on the left in each profile. The plots of sedimentary parameters show mean grain size in the center and plus and minus one standard deviation above and below. [Standard Deviation was estimated using the graphic technique given by Folk (1957).] This plot gives a visual representation of the range in grain size of the samples as well as the mean grain size and the relationship to topography. All profiles were taken across the ridge axes at the time of sampling.

flat. This gravel lag is left behind as the sand ridge moves across the tidal flat and produces a bimodal distribution of the grain sizes in addition to the relatively larger mean grain size and poorer sorting.

Profiles 1 and 2 (Figure 6) show that the amount of fine material in each sample varied little with location or elevation compared to the variability of the amount of coarse material. Mean grain size plus one standard deviation* plots as a straight line while mean grain size minus one standard deviation shows considerable range. This suggests that the size of the largest sediment deposited onto the tidal flat changes with "micro-environment," while the size of the finest material deposited on the tidal flat does not change significantly with "micro-environment."

Inferred Sediment Transport Mechanisms on the Tidal Flat

The tidal flat was sampled to characterize the general nature of the sediments and to identify the dominant processes. The discussion which follows presents some preliminary findings and a theory explaining sand ridge orientation and movement, based on the sedimentological and geomorphological data previously presented and field

*The standard deviation used was a graphic estimate calculated according to the procedure of Folk (1954).

observations by the author. A summary diagram which schematically shows the discussed processes is presented in Figure 5 as an overlay on the aerial photograph.

The decrease in elevation and relief, the decrease in mean grain size, and the increase in sorting from north to south on the tidal flat suggest that the sediment is transported from the tip of Cape Henlopen. Halsey (1971) and Kraft (1971b) have suggested the same source. The magnitude of southward transport is unknown.

Wave energy on the tidal flat decreases from north to south in part because of the configuration of the inner breakwater. Only waves produced by northwest winds approach the tidal flat directly; even then the southern portion of the tidal flat is in the "wave shadow" of the breakwater. This results in the reorientation of the sand ridges from coast-parallel to coast-perpendicular toward the south by a decrease in the energy of the waves to the point where they can no longer maintain a continuous ridge. Northwest to southeast waves are refracted around the tip of Cape Henlopen. Under these conditions the amount of wave energy on the tidal flat decreases rapidly from the spit tip toward the south.

In the northern portions of the tidal flat, the sand ridges are built by longshore transport while emergent and are built by overwash while submergent (Figure 5). As a result, they built southward or migrate landward depending on the tide level. Movement is dominated by landward overwash processes after a sand ridge first develops as a low tide spit-like "bar" connected to the tip of the cape near the low tide line. As the sand ridge moves landward, it also rises in elevation (Profile 1, Figure 6) and continues to be supplied from the north through its connection to the spit tip. As a result of an increase in the duration of emergence, the ridge grows rapidly toward the south and decreases in landward migration rate. It eventually reaches a point at which it is essentially stable at the northern end of the ridge and some eolian transport of sand on the crest of the ridge occurs since it is affected by waves for only a very short time during high tide. The southern end of the ridge is closer to the edge of the tidal flat, and at a lower elevation. As a result sediment continues to be transported southwest at the south end of the ridge but not at the north. This thins the ridge until it is breached forming an "island" of sand in the central part of the tidal flat near the low tide lines (Figure 5).

In the central portion of the tidal flat, the transport mechanism shifts, causing a reorientation of the sand ridges to coast-perpendicular. Refraction of waves around the breached portion of the coast-parallel ridge, transports the sediment landward forming a coast-perpendicular ridge, which is eventually connected to shore. The sediment is also transported southward by overwash while it is submerged at high tide. This process continues in the southernmost part of the tidal flat. Because of the decreasing energy of the waves defracted between the inner breakwater and the cape, transport by overwash becomes less significant southward but tends to maintain the orientation of the ridges. Transport by wave refraction around the end of the ridge during emergence is still significant although diminished. In the central area of the tidal flat, southward migration rates have been measured to be 0 to 7.5 meters per tidal cycle (Halsey, 1971).

Tidal current transport is insignificant compared to transport by waves. No visible sand transport occurs as a result of tidal currents on the tidal flat when there are no waves. Because of wave-induced resuspension, sediment tends to be transported off the tidal flat during ebb tide and onto the tidal flat during flood tide. Since energy decreases as waves move landward across the tidal flat, a tendency for fining landward is produced. This tendency is obvious only in the profile along the axis of a sand ridge (Profile 4, not plotted). Other profiles do not sample the same environment in relation to sand ridges and, therefore, the trend is obscured. Coarsening seaward on tidal flats has been described in other areas by Postma (1967).

This theory explains the transport processes and morphology of the sand ridges under "normal" wind and tidal conditions. During storms energies are greatly increased so that transport rates are quite different. It has been a general observation, that the overall pattern of ridges does not change although fewer, but larger ridges are present after a storm compared to prior to the storm. These ridges seem to be a product of sediment redistribution into larger less frequent ridges. This is, however, only an observation and must be proved or disproved by field measurements.

Breakwater Harbor

Data Presentation

Strom (1972) determined that the sediment from Breakwater Harbor is characteristic of sediment deposited from suspension in quiet water. This was determined by population analysis of grain size data as outlined by many authors including Pettijohn, Plumeley, and Allen (Strom, 1972). Samples used in this study were taken to identify the distribution of sand, silt, and clay (Appendix A).

The samples from the harbor were taken along five lines from the shoreline to the inner breakwater (Figure 4). Each of these samples was analyzed for percent of sand, silt, and clay. In general, the sediment becomes sandier from west to east in the harbor, into deeper water just south of the east end of the inner breakwater, and into shallower water toward shore (Figures 7, 8, and 9). An anomalous area is present north and east of the ferry terminal jetty, where slightly sandier sediment is found (Figure 7).

It is evident that the area of sand accumulation is not restricted to the tidal flat but rather extends into deeper water seaward of the intertidal zone. The area of sand accumulation was observed to extend approximately to a

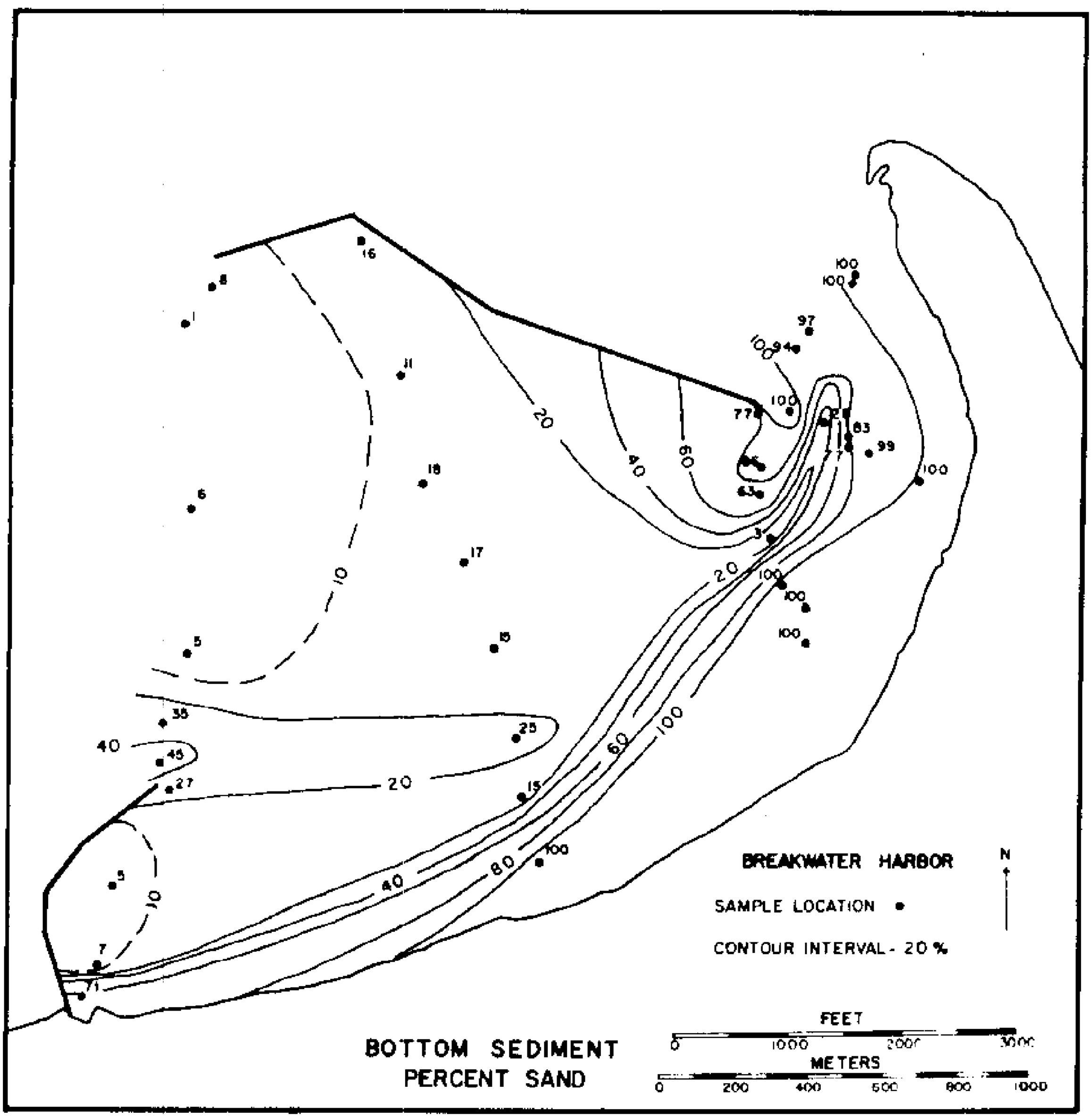


Figure 7 - Abundance of sand in bottom sediments of Breakwater Harbor.

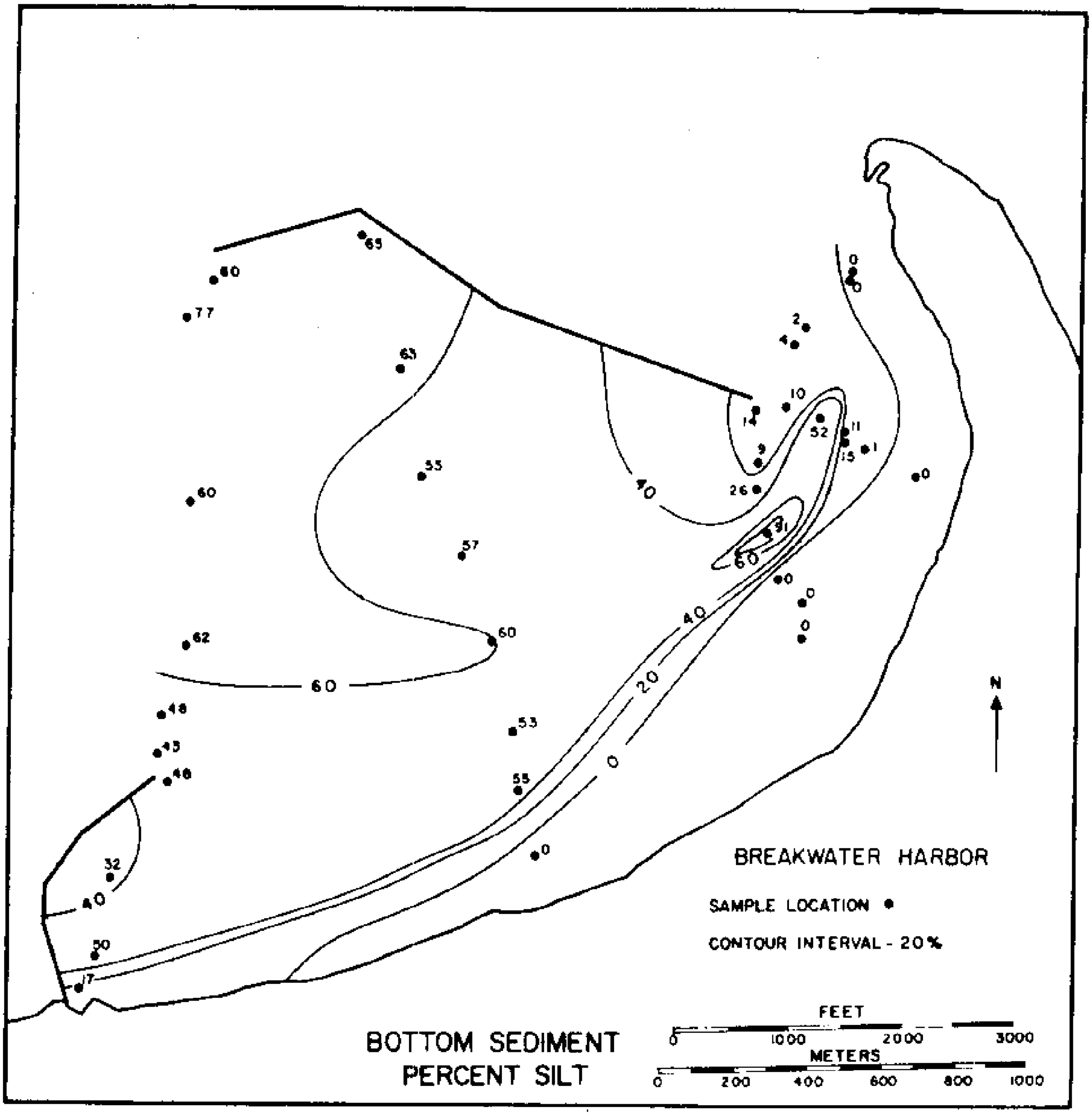


Figure 8 - Abundance of silt in bottom sediment of Breakwater Harbor.

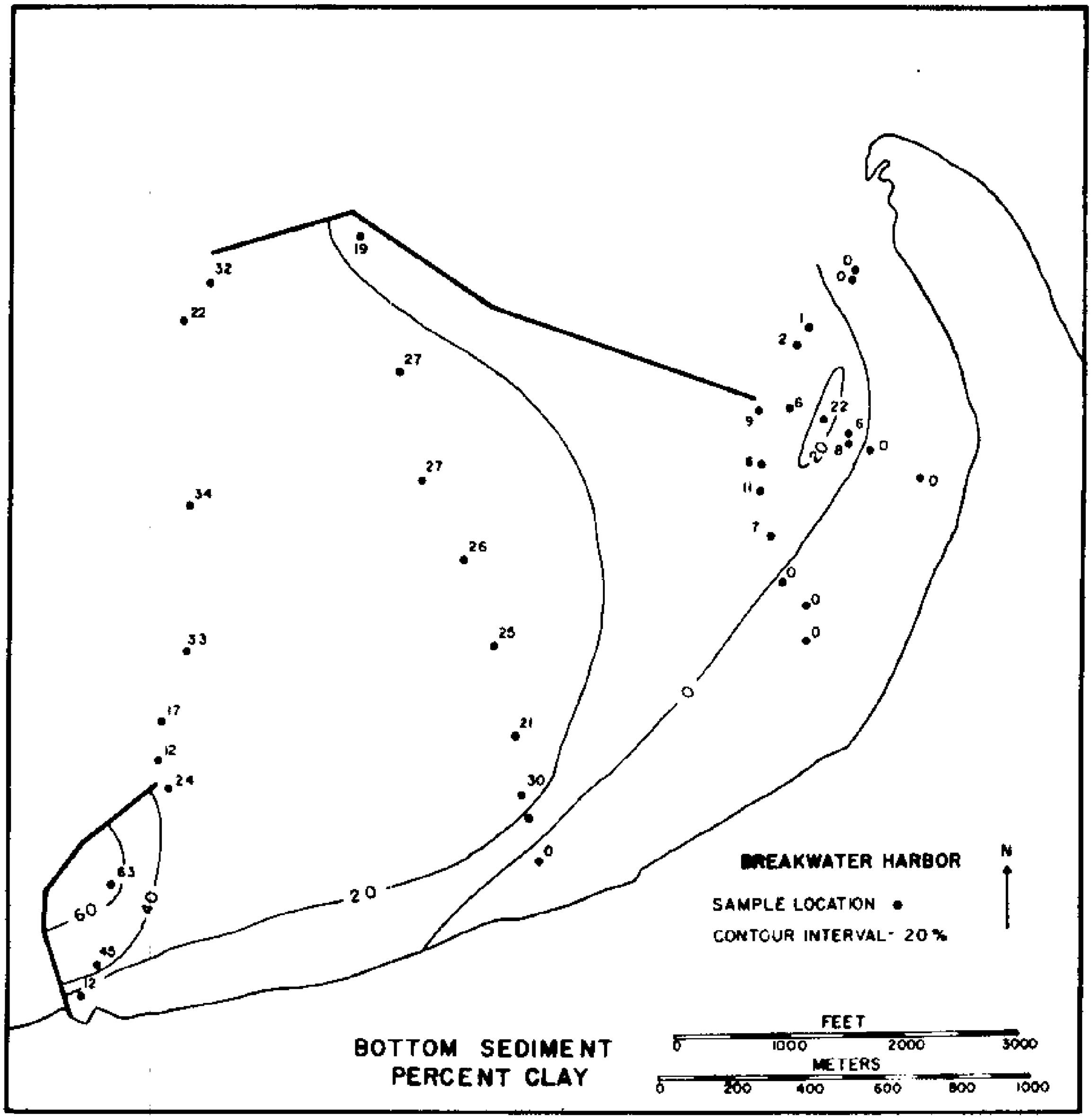


Figure 9 - Abundance of clay in bottom sediments of Breakwater Harbor.

break in slope which approximately corresponded with the six-foot contour line.

Figure 10 is a summary diagram showing the conversion of the percents in Figures 7-9 to verbal classification, according to Folk (1954), and points out the existence of a very narrow zone of transition from "tidal flat" sediment to "harbor" sediment. This diagram shows that a large amount of silt is present in the harbor, and that the muddy sands in the deep hole off the east end of the breakwater are the most poorly sorted of all the sediments in the harbor.

Current meter data presented in Figure 11a for Station 1, and Figure 11b for Station 2 (locations are shown in Figure 4) are a new way of presenting these data and, therefore, require some explanation. The National Ocean Survey publishes predictions for slack water times during each tidal cycle. For Breakwater Harbor, predicted times of slack surface water are a little over six hours apart. Figure 11 shows the percentage of readings taken during predicted ebb (black areas) and the percentage of readings taken during predicted flood (white areas). The percentage of readings taken during predicted flood is always plotted outside the percentage of readings taken during predicted ebb.

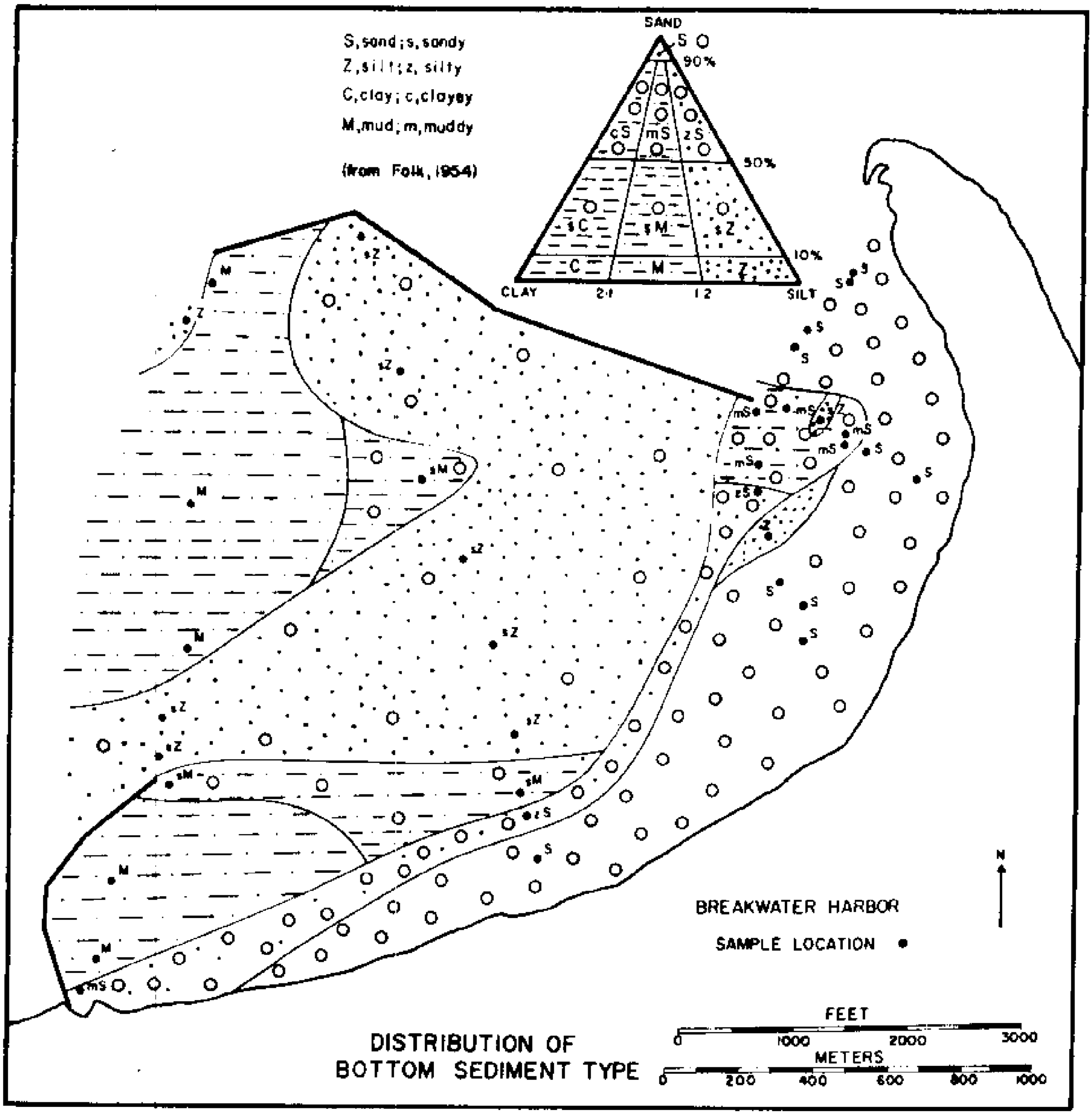


Figure 10 - Distribution of bottom sediment type. The data presented in Figure 7-9 were converted to verbal classification according to Folk (1954).

FIGURE 11 a and b

The diagrams on page 32 and 33 are plots of the current data collected at Station 1 for 23 days during October and November 1976 and at Station 2 for 18 days in April and May 1977. The radius of each pie-shaped section indicates the percentage of the readings for that station that flowed at the indicated velocity and direction. The calibration for the percentage is given in the lower left of Figure 11a. The pattern shows the percentage of readings taken during predicted ebb (black) and the percentage of readings taken during predicted flood (white). The readings during predicted flood are always plotted outside the readings during predicted ebb.

The data were collected using a General Oceanics Model 2010 film recording current meter. The readings were automatically recorded every 15 minutes, with only the 30-minute readings being compiled. The current meter was attached to a cement block, which measured 4-by-15-by-24 inches, (10-by-30-by-60 cm), and weighed about 40 lbs submerged. Two Danforth anchors were also attached to this block. The center of the current meter was about 1.5 feet (45 cm) above the bottom in both cases.

Figure 11a

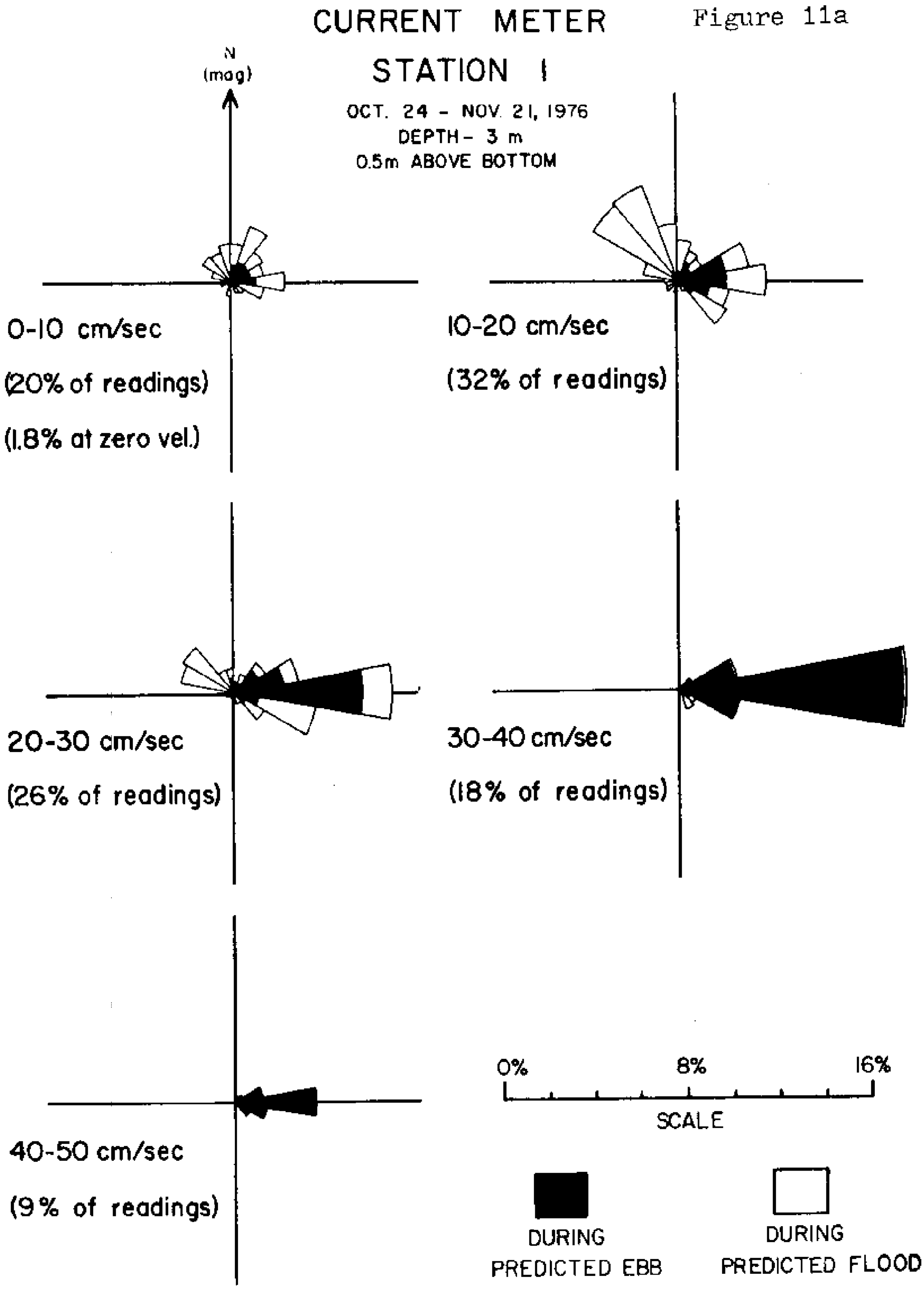
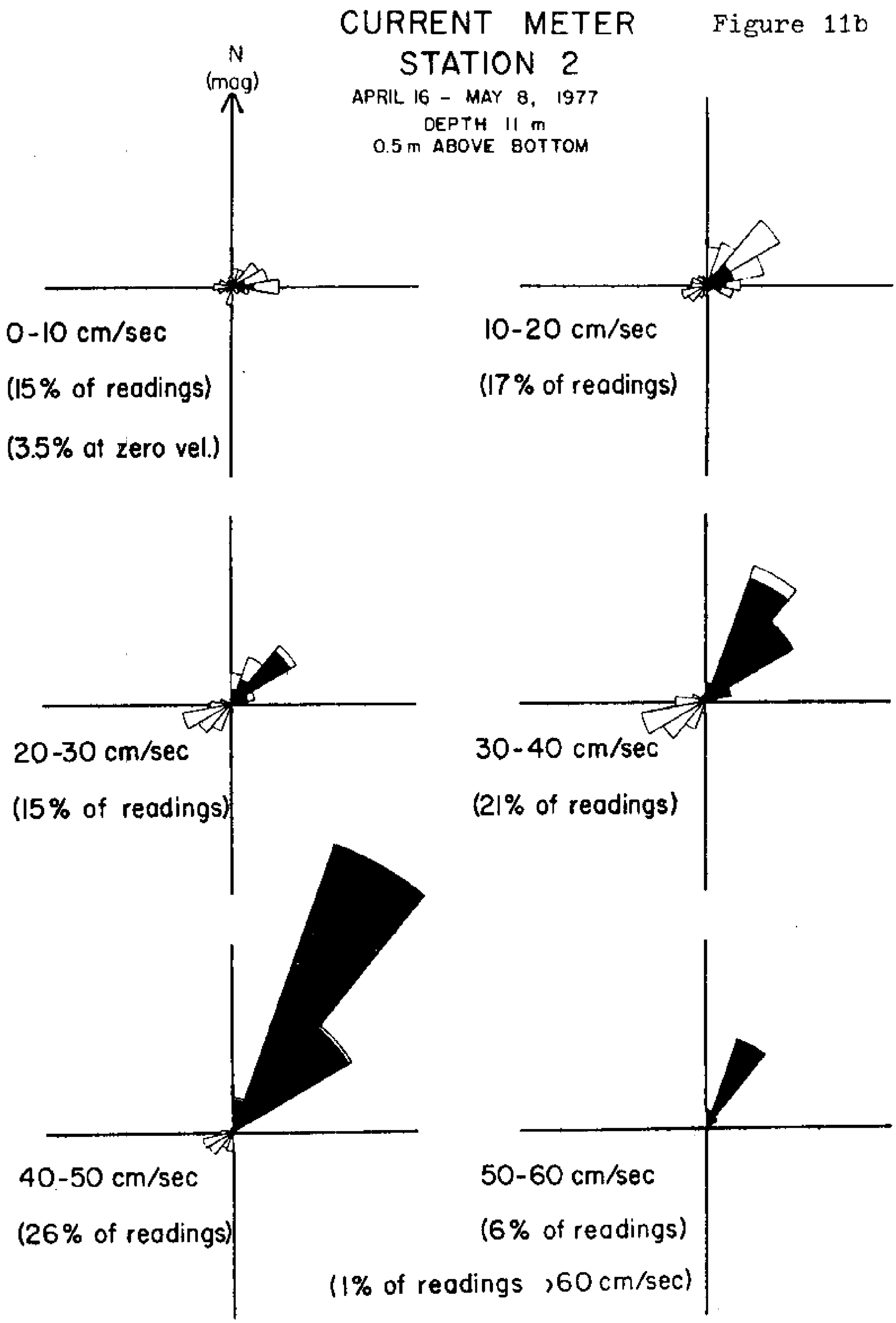

CURRENT METER
STATION I
OCT. 24 - NOV. 21, 1976
DEPTH - 3 m
0.5m ABOVE BOTTOM
N
(mag)
0-10 cm/sec
(20% of readings)
(1.8% at zero vel.)
10-20 cm/sec
(32% of readings)
20-30 cm/sec
(26% of readings)
30-40 cm/sec
(18% of readings)
40-50 cm/sec
(9% of readings)
0%
8%
16%
SCALE
DURING
PREDICTED EBB
DURING
PREDICTED FLOOD

Figure 11b

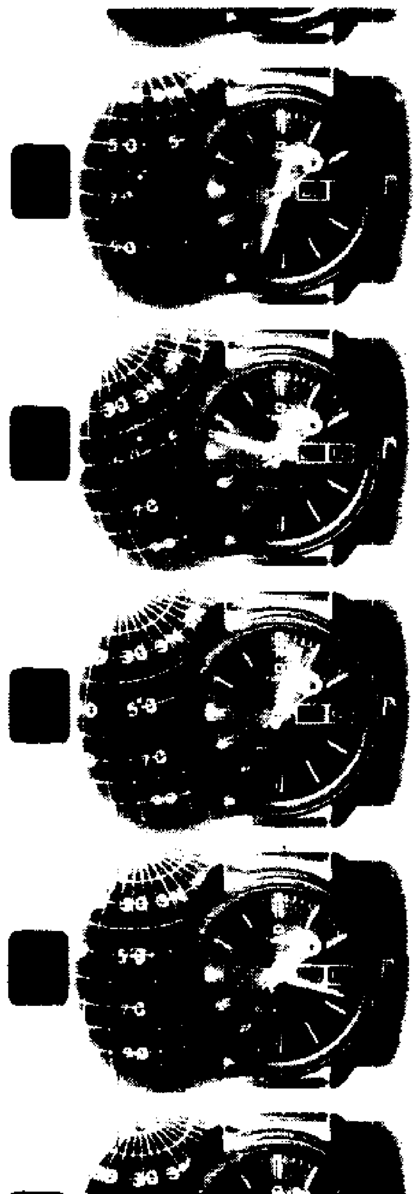

CURRENT METER
STATION 2
APRIL 16 - MAY 8, 1977
DEPTH 11 m
0.5 m ABOVE BOTTOM
N
(mag)
0-10 cm/sec
(15% of readings)
(3.5% at zero vel.)
10-20 cm/sec
(17% of readings)
20-30 cm/sec
(15% of readings)
30-40 cm/sec
(21% of readings)
40-50 cm/sec
(26% of readings)
50-60 cm/sec
(6% of readings)
(1% of readings >60 cm/sec)

The radius of each pie-shaped section indicates the percentage of readings for the station that flowed at the indicated velocity and direction. The scale for the diagrams is given in the lower right of Figure 11a. Thus, a total of 18% of the readings for Station 1 had a velocity of 30-40 cm/sec; currents were flowing between 80° and 100° magnetic for 9.8%, 0.2% were recorded during predicted ebb and 9.6% during predicted flood.

This procedure of plotting data was not employed to show that the predictions were inaccurate but rather to indicate irregularities in the currents of the area. The data established that either (1) actual slack water time lags behind predicted times or (2) ebb and flood tidal currents are not of the same duration as predicted. The latter is the case, as evidenced by the lack of current readings showing the water to be flowing in the "ebb direction" during predicted flood tides. That is, the duration of tidal directions is not equal.

From Figure 11a and 11b, it can be seen that velocities were slightly higher at Station 2 than at Station 1. At low velocities the direction of flow was much more variable at Station 1 than at Station 2. At higher velocities both stations had little variation in direction, although the asymmetry between duration of ebb and flood seemed to be more obvious for Station 1 than for Station 2. When compiling the data for Station 2, it seemed that the average duration of ebb tides was about 8-9 hours, with fairly short build-up times after slack water. During some tidal cycles the direction of flow did not switch at all. Velocities dropped off to near zero and remained there for several hours. For Station 1, the same type of asymmetry was found, but it was not nearly so consistent.

Much of the directional variability during low velocities at Station 1 may be explained by wave motion. The current meter cannot respond to rapid fluctuations in direction and velocity present during wave motions. For this reason, when waves were hitting the current meter at or near slack water, the photograph of the "tilt-ball" in the current meter showed the meter to be in an unstable configuration. An unstable position showed the ball tilted at an odd angle not "up" parallel to the 6-12 O'Clock line (Figure 12, Frames b). This unstable configuration of the current meter occurred quite often during low flow velocities at Station 1 and less often at Station 2. This was probably due to the shallow depth of the current meter at Station 1 (10 feet [3 m] vs. 40 feet [12 m] for Station 2), and, therefore, its greater susceptibility to waves.



Frame

a

b — Unstable orientation indicates turbulence, possibly wave induced. This frame shows this unstable orientation because the pole position on the tilt ball should always point straight up, parallel to the 12-6 o'clock line of the watch.

c

d

e

Figure 12 - This is a negative print of a section of the Super 8 Tri-x Reversal movie film (Kodak) used to record the current data. The lines of "longitude and latitude" indicate direction and tilt angle respectively. The tilt angle is then converted to cm/sec velocity by a manufacture's calibration chart.

Discussion

Very little of the sand from the tidal flat is deposited in the harbor. Sand which moves off the tidal flat is either carried out of the harbor during the strong ebb tides or is stored in deeper water adjacent to the edge of the tidal flat until such times as it can be carried out with the ebb tides. For this reason, the coarse to medium sand which is found on the tidal flat does not continue into the harbor. A minor amount of fine sand or silt may occasionally be carried into the harbor from the tidal flat during flood tides.

Silt and some sand are carried by longshore drift along Lewes Beach until they are deflected into the harbor by the ferry jetty. During slack water, silt and clay are deposited in the central areas of the harbor. This sediment may or may not be resuspended during any given maximum tidal current velocity, depending on the velocity reached during that tidal cycle and the length of time the sediment has been on the bottom.

Unpublished data (Hoyt, Personal Communication) show that, off the tip of Cape Henlopen maximum current velocity reached during ebb exceeds that of the flood, but the difference is not as great as that for the two current meter stations in Breakwater Harbor. Therefore, it appears that the configuration of the breakwater and shoreline causes a "funnelling effect" during ebb tide, tending to increase the velocities. During flood tides, the configuration of the breakwater restricts flow through the harbor. Therefore, only a small volume of water actually passes through the harbor on flood tides relative to ebb tide. Sometimes a large eddy develops on the west end of the breakwater, producing an easterly flow in the harbor during flood tide.

As a result of the continuing supply of coarse sediments to the tidal flat and the lack of these coarse sediments in the harbor in appreciable quantities, it is suggested that the tidal flat is prograding into the harbor, while building toward the south and west along Lewes Beach. Sediment moving off the flat is carried back around the tip of the cape during high flow rates during ebb tides.

Many of the low velocity currents recorded at Station 1 in the northwest and southeast directions are due to wave motion at or near slack water. The only direction from which waves can approach the station with appreciable fetch is from the northwest. This causes orbital velocities which show up as northwest and southeast currents. As a result, if the wave-affected data could be removed from the data in Figure 11a, the dichotomy between ebb and flood tidal currents would probably be similar to that found for Station 2.

Oostdam (1971) found a general coarsening of the bottom sediments with increase in depth in Delaware Bay. This coarsening trend was attributed to tidal current scouring in the channels. Tidal current scouring occurs in the deep tidal channel between the east end of the inner breakwater and Cape Henlopen.

CHAPTER IV

BATHYMETRIC COMPARISONS

Introduction

The bathymetric data collected by Federal agencies between 1842 and 1971 were analyzed to determine the rate and patterns of erosion and deposition. The first step in the analysis was the development of a computer program to do all the repetitious calculations. The procedure, digitizing the data to data display, is outlined in the flow chart shown in Figure 13. All computer work was on a Burroughs 7700.

The programming is divided into a main program and eight subprograms, each of which performs a specific function such as plotting, printing, interpolation, etc. The main program acts as the control, which calls the subprograms at the proper times and facilities direct operator control of the function and output. No calculations are performed in the main program. All FORTRAN programs are listed in Appendix B. They are completely documented

COMPUTER PROCEDURE FOR THE ANALYSIS OF MAP DATA

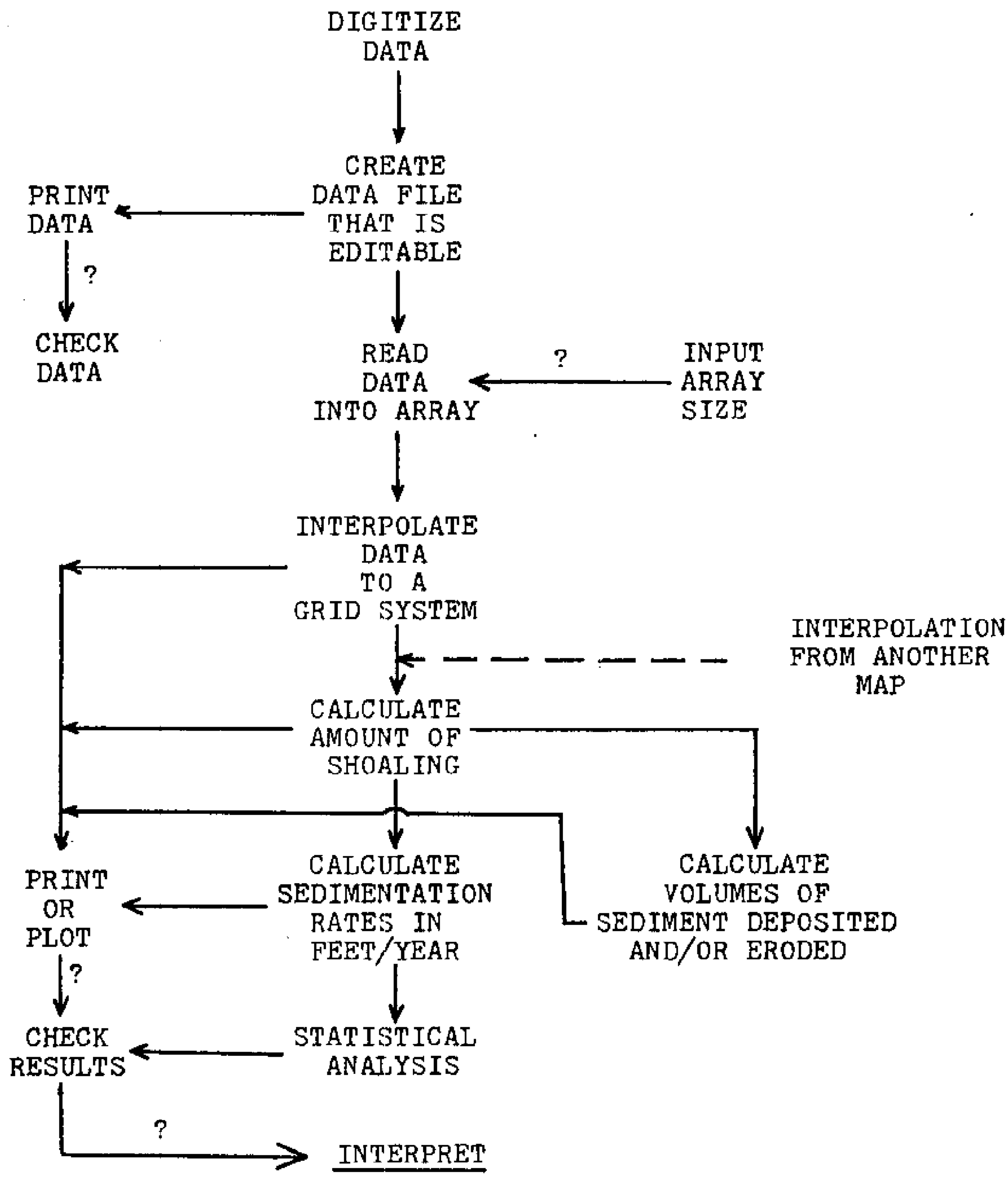


Figure 13 - A flow chart of the computer procedure used in this analysis of Bathymetric Data. This is essentially the organization and steps used in the main program of the analysis with each of the steps being performed in subprograms. The location of ? marks indicate the location of operator input or value judgments.

within the listings so that anyone with an elementary understanding of the FORTRAN language should be able to use or modify the programs as desired.

Description of Bathymetric Data

The data used in this study for the historical analysis came from the National Ocean Survey and its predecessors. Hydrographic surveys were run periodically to update published nautical charts. The first detailed survey of the Breakwater Harbor-Cape Henlopen area was in 1841 and is, therefore, used as the starting point for this study. Subsequent surveys, used in this study, were made in 1863, 1883, 1894, 1913, 1929, and 1971. In each case except 1971 the primary survey data are used. The 1971 data were taken from the published chart (NOS Chart 12216) 1977 edition. This was the first edition published with all the 1971 survey data, making the bathymetric data valid for 1971. The shoreline was for 1977. Sallenger and others (1975) discussed surveying techniques.

The bathymetric data were obtained by J. C. Kraft from the National Archives by photolithic reproduction of the original charts. The data were all hand-plotted, with soundings plotted to the nearest foot in most cases. The shorelines were the position of mean high water, while the datum for the soundings was mean low water. In some cases the mean low water line was also plotted.

The mean low water datum was originally calculated using tide level measurements made at a land station during the survey cruise. The soundings were corrected to this datum, based on the time of the sounding and measured tide level at that time. The datum was calculated by averaging the tide level for the period of data collection, and subtracting one-half the range of tides for that period.

Although the published charts were available at more frequent intervals, the bathymetric data on them were not updated unless information was available to invalidate the existing data. Sources of these data were engineering studies, reconnaissance surveying, and/or citizens. For these reasons it is difficult to know precisely the date the bathymetric data were valid on published charts. In addition, the dates of validity changed for different soundings on the same published chart. Therefore, only the information plotted on the original hydrographic surveys, which were all valid for dates within a three-or four-month period, were used. This information about charts was obtained through personal conversations with employees of the National Ocean Survey, Hydrographic Division.

This section is divided into four parts: in the first the computer programs are described; in the second the errors involved and the reliability of the data are discussed; in the third the calculated data are presented; and in the fourth the interpretation and implications of the data are discussed.

Methods of Analysis

Digitizing Procedure

All depth soundings for the harbor and vicinity were recorded on magnetic tape using a Bendix Data Grid Digitizer (Figure 14). The English measurement system was used throughout the data manipulation in order to be consistent with the original surveys. The digitizer has a square grid coordinate system, and north-south on each map was lined up parallel to the Y axis. The origin for the coordinate system of each map was established as 1500 feet (457 m) west and 2000 feet (610 m) north of the west end of the inner breakwater, with X values increasing to the east and Y values increasing toward the south. Using scaling factors the coordinate system was converted to read directly to the nearest 10 feet (3 m). To record the data, the cursor was placed over each depth, the depth value placed on a digital display box, and the "record" button pushed. This recorded the X, Y, and Z (depth) values on the magnetic tape, all in units of feet.

Figure 14 - The Bendix Data Grid Digitizer located in the Geography Department of the University of Delaware.

In addition to the depths, the position of the shorelines was recorded, using a depth of zero and the stream digitizing feature of the Bendix unit. The stream digitizer records the depth in the digital display box (in this case, zero) and the X and Y coordinates automatically every time the change in X plus the change in Y equals a given value (in this case, 50 feet [15 m]). Stream digitizing was also used to record the position of the breakwaters and jetties, using a Z value of 99, and to identify areas for which there was no data, using a Z value of 98. These values were then used in the computer programs as an indication of boundaries which should not be searched through.

Throughout this procedure, it was assumed that the position and size of the inner breakwater were correctly determined for each map. The scaling of each map was determined by measuring the distance between the east and west ends of the breakwater. The positions of the ends of the breakwater were checked for each map by triangulation from the Cape Henlopen light and the Cape Henlopen beacon, as these were the points of reference for the original surveys (until the lighthouse fell into the ocean in 1926). This procedure gave reasonable assurance that these points were in the proper spatial relationships to each other. The only thing left to be determined was the direction of true north.

Each of the original maps had geodetic coordinate systems plotted on them in several different locations, making it difficult to trust any of them. The angular relationship between the present geodetic coordinate system found on the most recent NOS Chart and the westernmost section of the breakwater was used to determine the "true" direction of north on the survey charts. If not "absolutely" accurate, this procedure was at least consistent and, as evidenced by the superposition of the bay shoreline, was adequate to assure the proper location of soundings for map comparisons. The superposition of shorelines compared very well with that of the Corps of Engineers (Hoyt, personal communication).

Data Input

The data that was digitized and recognized onto magnetic tape (hexadecimal) was loaded into a memory file in the computer using one file for each map. A program, supplied by the University of Delaware computing center, was run to change the numbers from the hexadecimal system to decimal equivalents. These data were printed on the line printer and checked for errors, both machine and operator. The format of the list was two points per record (line) with values listed in the order of X_1, Y_1, Z_1, X_2, Y_2, Z_2. After necessary editing of the data file, the data were ready to be used.

After entering the necessary central parameters to the main program, the main program called subprogram 'FILL'. First, 'FILL' preset all values in the array MAP to -1 to indicate no data. It then read the two values from each record, rounded off the X and Y values for each sounding to the nearest 100 feet, and placed the Z (depth) value into the X and Y position of the 90-by-120 array MAP. Each position in the array represented a 100-by-100-foot (30-by-30 m) square box with the value in the array representing the depth in the center of the square. This procedure of filling the array in effect moved the depths, to the center square. This resulted in a maximum movement of 71 feet (21 m) for any given depth value. Looked at another way and, perhaps, more meaningfully this was a maximum movement of .084 inches (0.33 mm) on a map printed to a scale of 1:10,000. This kind of movement of the data was insignificant in light of errors in navigation and soundings, to be described later. The only places where this sort of movement may have been significant were areas that had steep slopes. However, these areas occupied a small portion of the study area and, therefore, would have had only a minor effect in the final picture presented.

The partially filled array was used as the search array for the interpolation procedure described below. It could also be printed on the line printer for a quick and inexpensive check on the validity of the data as recorded and read. The program for line printer output of this array was called subroutine 'PRTDTA' and is described later.

Interpolation Procedure ('INTERP')

In order to use the data from each map, they had to be interpolated to a grid system so that depth values were at the same points for each map. This was accomplished by using the weighted averaging procedure outlined by Davis (1975). In this procedure values are substituted in the equation:

$$Z_p = \frac{\sum_{i=1}^{n} \frac{Z_i}{S_i}}{\sum_{i=1}^{n} \frac{1}{S_i}}$$

where Z_i equals the depth at any point, S_i is the distance to that point from the grid point (Z_p) being interpolated, and n is the number of points used.

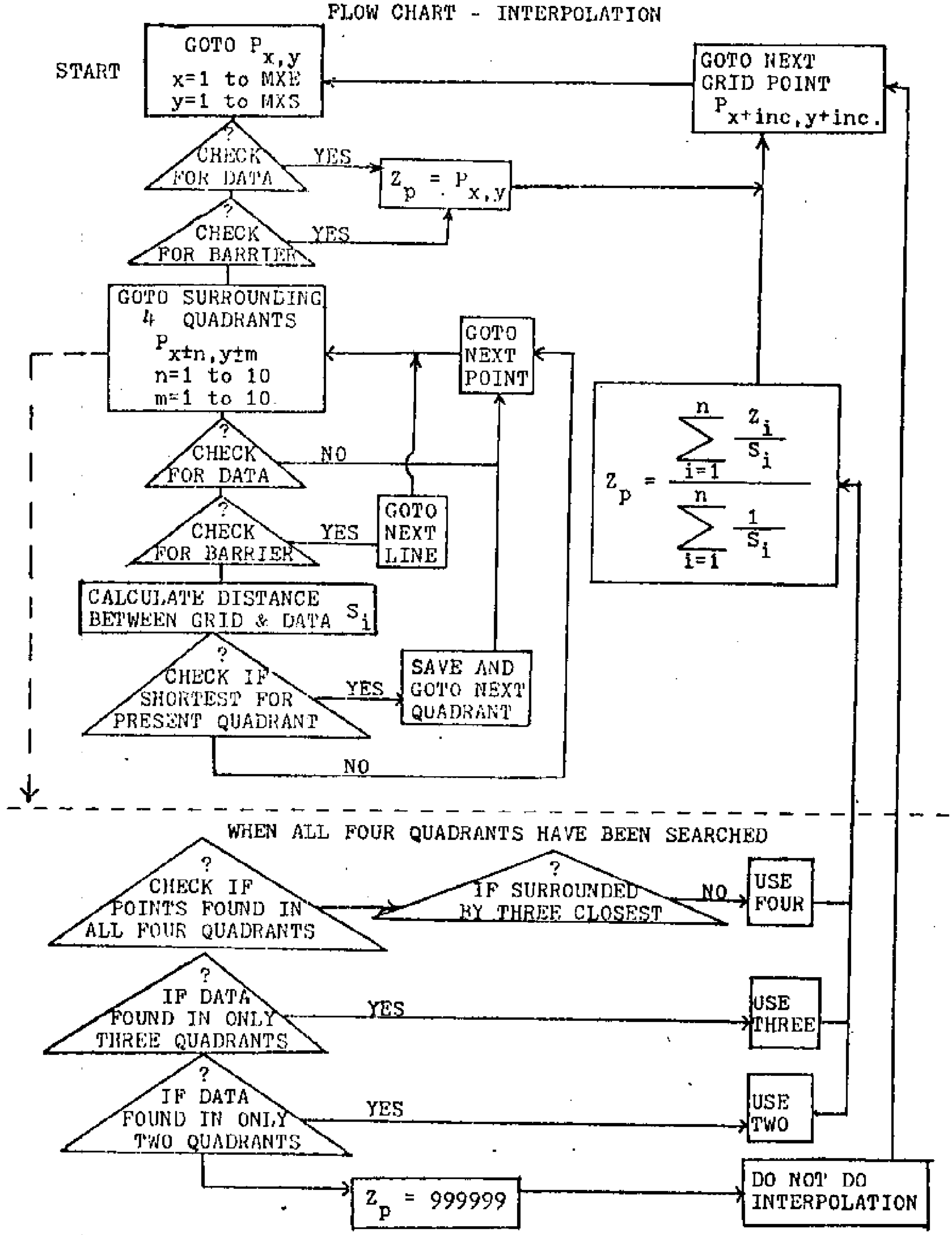
Difficulties arose in deciding which points should be used for the interpolation, how many points should be used, and how the computer should be programmed to find these points. Figure 15 is a flow chart of the interpolation subprogram. Several procedures were considered, including the simplest one of using the closest four or six (or any number) of soundings in the equation. However, in using this procedure invalid results could arise when all the closest soundings were on one side of the point being interpolated. Of primary importance in any interpolation procedure was that the interpolation be done using soundings which surround the grid point being interpolated, thereby avoiding "extrapolation" of the data. A second important consideration was the number of soundings used: if too many were used, some of the detail was lost; if too few were used, the grid depth calculated might not represent the actual depth at that point.

The program adopted assured that the grid point was surrounded by the soundings used by searching the four surrounding 1000-foot-square (300 m) quadrants (southeast, northeast, northwest, and southwest) for the closest four soundings, one from each quadrant. Providing at least two quadrants with data were found, the interpolation was done. If four points were found, a subprogram called 'DATEST' was called to test the geometric relationship of the soundings.

'DATEST' determined which of the four closest data points was the farthest away. It then tested to see if the

FIGURE 15

FLOW CHART - INTERPOLATION



data from the three other quadrants surrounded the grid point being interpolated. If the point was surrounded by the three closest soundings, then the fourth was not used in the interpolation. If it was not surrounded by the three closest soundings, then all four soundings, one from each quadrant, were used in the interpolation.

The 'DATEST' procedure was developed after 1) programming the procedure for searching the quadrants, 2) printing the calculated values, and 3) visually testing them against the original maps. It became obvious that discrepancies (i.e., the value visually interpolated did not agree with that calculated by the interpolation procedure) occurred when the three closest soundings surrounded the interpolated value, but a fourth "outside" sounding was also used. The 'DATEST' program was devised to do away with this problem.

Depth Change Calculation

The thickness of sediment deposited or eroded from a particular place was calculated by subtracting the depths in each map at each grid point, using subprogram 'MAPDIF.' At the same time that depth changes were being calculated, the average depth change, the number of points, and the area of data were being calculated. When the depth changes were calculated the values for number of points, average depth, area of data, and volume of sediment were printed on the terminal. The depth change values were stored in array DMAP for later output and/or use. Negative values for the depth change indicated net erosion during the survey interval. For efficiency, the interpolated values were stored in an array whose size was determined by the frequency of interpolation.

Shoaling Rate Calculation

The shoaling rates were calculated from the depth change array by dividing each array value by the number of years between the respective surveys, using subprogram 'SEDRTE'. These data were then stored in array RMAP for later output. As with depth change, negative values indicated erosion.

Data Display

Several different types of data display were available in this program. The data in each array could be printed on the terminal or on the line printer. Subroutine 'PRTDTA' printed the original data as they appeared in the MAP array after being read in. Subroutine 'PRTMAP' printed the data from any of the calculated arrays.

The line printer output was an inexpensive and rapid way to display the data. However, because the line printer prints eight lines per inch and ten characters per inch, it would require four sections the width of the computer paper (a total of 5 ft [1.5 m]) to make the map dimensionally square. Instead, the data were printed in two sections, with the dimensions of maps displayed on the line printer or terminal being 500 feet/inch (60 m/cm) in the east-west direction and 400 feet/inch (48 m/cm) in the north-south direction.

The calculated data was plotted, using three different devices. The first device was the Tektronix screen. This device plotted the entire map on a cathode ray tube (CRT) at the terminal. Output of the CRT was too small to be useful in analysis, although hard copies could be made. The CRT was useful for checking the form of the plot before it was sent to one of the other larger display devices.

The second display device was the Calcomp Drum plotter. This device had a maximum width of 30 inches and "unlimited" length. The maximum map size could be obtained on this unit. The drum plotter used a ballpoint and, therefore, was not as neat as the Tektronic flat bed plotter; the third device.

The Tektronic flat bed plotter used a felt tipped pen and a sheet of bond paper that had 15 by 11 inches (38 by 28 cm) usable space. This plotter was very fast and neat and, therefore, was used to display all the maps shown in this report. 'PLTMAP' and 'SHRPLT' were the subprograms used for plotted display of the calculated maps.

The plot routine 'PLTMAP' had several options that could be used at the time of plotting. Each map could be plotted with depths or depth changes in feet, meters, or centimeters. If the metric units were chosen, a metric set of axes were plotted, showing the metric equivalents to the axes in feet. If the map being plotted was shoaling rates, then the units were plotted in feet/year, meters/year or centimeters/year. For each of these units, the number of digits to be plotted to the right of the decimal point for the desired precision was also specified by the user. Care had to be taken not to overlap the numbers.

For each map used in the analysis, a string of X and Y values was stored on a "disk file" which represented the shoreline for each map. At the time of plotting, the number of shorelines desired (up to nine) was specified, and the titles of the shoreline data files were read in. Depending on the dates of the maps being plotted, the Ferry Terminal jetty and the center section of the breakwater were put on the map or left out, as appropriate. The title of the map being plotted was entered at the terminal, and the size output was designated by a scaling factor. If the scaling factor was equal to one, the map was plotted to a scale of 1000 ft/inch (120 m/cm) scaling factors less than one made the plot smaller and greater than one made it larger. This scaling factor was used to reduce or expand the map size so that it filled the usable area of the output device. The map outline used as a base for the contour maps was made, using subroutine 'SHRPLT,' which produced a map the same as 'PLTMAP' but left out the depths.

Evaluation of Errors

Errors in the analysis result from several sources. In addition to the surveying errors, they result from inaccuracies in the interpolation procedure and other data manipulation. These potential sources of error are summarized and quantified in this section.

Errors due to changes in the datum used for each map result in a constant inaccuracy either up or down, throughout the entire study area. Therefore, these errors do not change the overall pattern but simply change the value of all the contour lines. Making the assumption that the datum used for the maps has changed consistently with an average sea level rise calculated over the last 50 years, 0.01 feet/year (0.3 cm/yr) should be added to the value of each shoaling rate to correct all maps to the same datum.

Errors due to the correction of soundings on an individual map to a common datum are probably quite small because tide levels were continuously monitored for the duration of the surveying. Errors due to sounding inaccuracies and navigational inaccuracies would have been random and probably would result in an error of less than 0.5 feet (15 cm) in depth (Sallenger and others, 1975).

Interpolation of these data to a grid system resulted in a loss of some detail in bathymetry. This distance-weighted averaging over a certain area also reduced the effect of random errors. In areas of drastic variation of bathymetry, the interpolated data are probably less representative of the actual depths that were present in these positions, but would represent regional trends. Because of grid points on the fringes of available data are most likely not surrounded by the data points used in the interpolation, little weight should be given to these points, except possibly where they are consistent with local bottom trends.

When shoaling rates for a particular survey interval are calculated, some of the complexities of the map may be a result of errors in the data. The shorter the interval between surveys, the more significant an error becomes. On the other hand, with shorter intervals the greater the expected variability would be, and, therefore, the greater the expected complexity. For these reasons one must be cautious when interpreting the significance of anomalous-looking areas.

The overall accuracy of the calculated data can be estimate by determining the net errors due to surveying inaccuracies and evaluating these in light of the calculations involved. A procedure outlined by Sallenger and others (1975) estimates net error based on the average discrepancy at trackline crossings. Three maps were analyzed in this way, using between 30 and 50 crossings on each map. In all three cases the average discrepancy was around 0.5 feet (15 cm) and, therefore, was about the same as could be assumed from the fact that soundings were recorded to the nearest foot. When one map is subtracted from another, an average error of 0.5 feet (15 cm) results in a net average error of 0.7 feet (21 cm), based on statistical distributions of errors as discussed by Beers (1957). This is probably an overestimate, because of the averaging effect of the interpolation procedure in reducing the effect of random errors.

Another way to check the accuracy of the data is to compare the sum of the depth changes for each survey interval and the total depth change calculated from the first and last surveys. This was done for four points in the study area, and the results are as follows:

Point Coord. (ft)	1842-1971	Sum of Surveys
4000/1200	6.6 ft (2.0 m)	6.1 ft (1.86 m)
5200/4800	12.4 ft (3.7 m)	13.3 ft (4.0 m)
6400/3000	12.3 ft (3.7 m)	12.8 ft (3.9 m)
2000/7800	37.9 ft (11.5 m)	38.1 ft (11.6 m)

The mean discrepancy for these four points is 0.5 feet (15 cm) and the maximum is 0.9 ft (27 cm). Distributing the mean among the seven survey intervals gives an average error of 0.07 feet (2.1 cm) per interval. The 0.9 feet is probably an overestimate, while the 0.07 feet is probably an underestimate of the overall error. The 0.5 feet (15 cm) error is probably realistic and should be used. This represents a confidence of 0.05 feet/year (1.5 cm/yr) for a survey interval of 10 years and 0.03 feet/year (0.9 cm/yr) for a survey interval of 20 years. (Note that the longer the survey interval, the less significant an error of 0.5 feet (15 cm) in depth change becomes in the shoaling rate values.)

Data Presentation

Data Presentation Format

This section deals with the analysis of the computer-produced plots of depths, depth change, and shoaling rates. The English measuring system is used throughout to facilitate checking with depths as they are recorded on the original maps. It is very important that one be able to compare the depth changes and shoaling rates with the original survey data.

The interpolated point density used is every 600 feet (180 m) in the east-west direction and every 400 feet (120 m) in the north-south direction. The numbers are quite small because as much information as possible was plotted in a limited space. Considerable experimentation went into determining the best letter size and map size to use and maintain a concentrated point density.

In each of the shoaling maps the last digit is significant with caution. In addition, the last digit is more significant in maps with longer survey intervals, and, on the same map it is more significant in areas with low gradients.

The breakwaters and jetty in each depth map were plotted only if they were present during the interval. In cases where two maps were compared, such as depth changes and shoaling rates, the breakwaters and jetty were plotted only if they were built before the most recent survey used. Figure 16 shows the dates of construction for each of these features. The dates of each shoreline are given in the shoaling rate contour maps.

The area that remained above sea level for the entire survey interval is indicated by slashes about one millimeter long at a 60° angle toward the southwest. This slashing does not follow any one shoreline. It does follow the most landward of the shorelines plotted at any point along the coast.

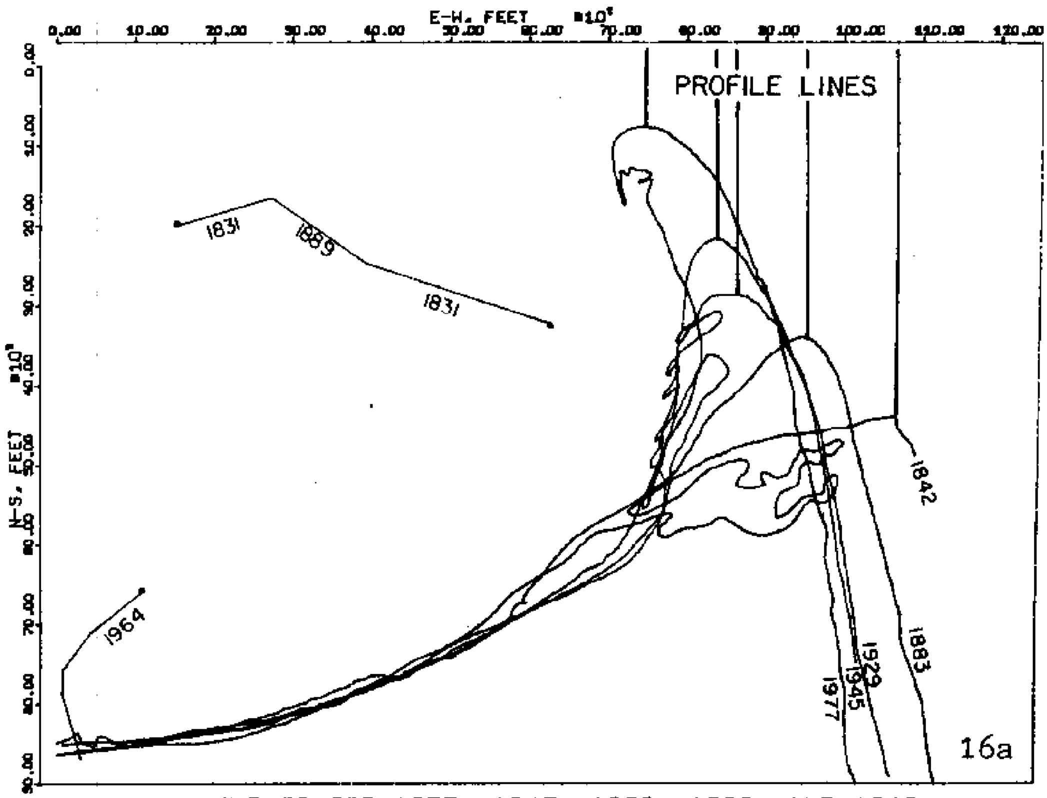
The abbreviation "ORIG DTM" stands for the original datum, indicating that the datum used for the original survey was not corrected for sea level rise. The contour interval used on the shoaling rates contour map is always 0.5 feet/year (15 cm/yr). In addition, the 0.25 feet/year (7.6 cm/yr) contour line is given in some places in order to provide more detail in otherwise empty areas.

In each plot, north-south is parallel to the Y axis, and east-west is parallel to the X axis. The depth changes and shoaling rates plots indicate the largest area for which there were data on both original surveys. There is a tendency to make assumptions by extending trends into areas for which data were not available. This should be avoided.

In the following sections, depths, depth changes, and shoaling rates that have been calculated for each survey and survey interval are described. In each case, a set of diagrams is presented with a discussion of each map. Each set consists of original depths, depth changes, shoaling rates, and manually produced shoaling rates contour maps. The survey intervals are presented in chronological order except where there is a larger interval analyzed followed by the intervening intervals. This was done for the entire study period, 1842-1971, and for the period 1883-1929, which was followed by the discussion of 1883-1894, 1884-1913, and 1913-1929. There is duplication of depth maps where necessary for completeness. After all the intervals have been described, the overall trends and conclusions will be presented with some summary diagrams.

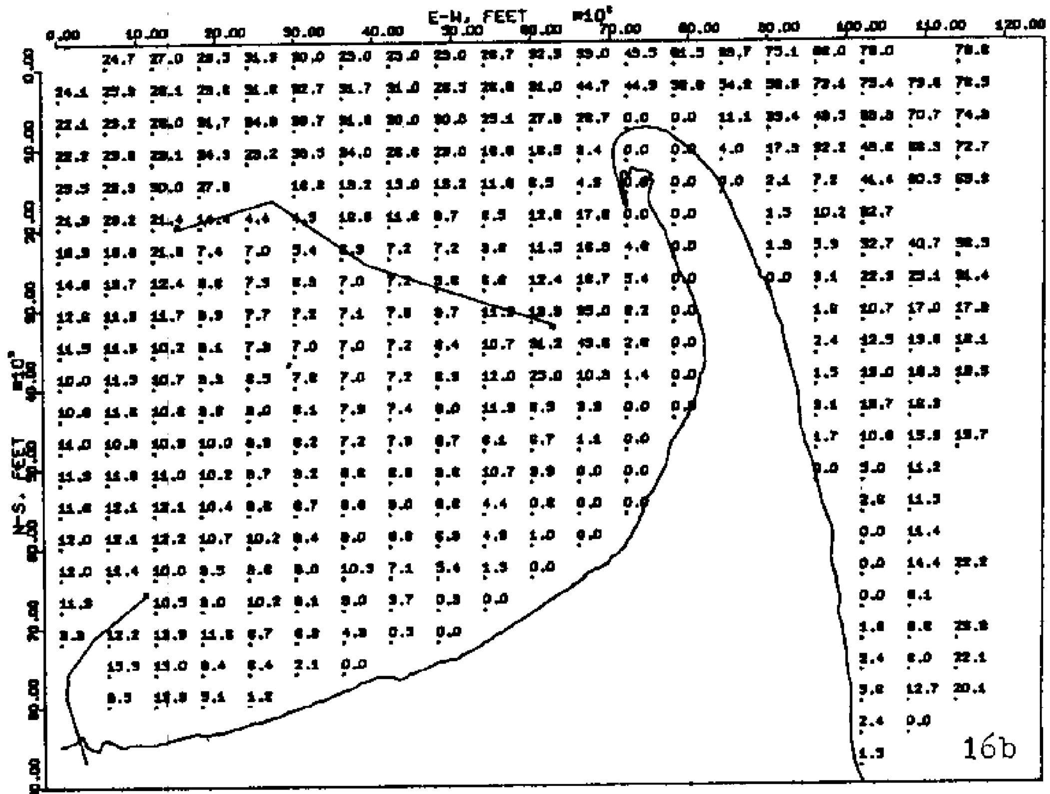
Shoreline Changes and Depths

Figure 16a shows the shoreline changes that have occurred in the study area during the last 129 years. In addition, the dates of construction of the breakwater and ferry jetty are given. Figures 16b-i give the interpolated depth values calculated from each of the hydrographic surveys. These maps have not been corrected to the same datum, because the assumed correction factor based on average sea level data from tide gauge records would not significantly change the bathymetric differences and shoaling rates presented later.

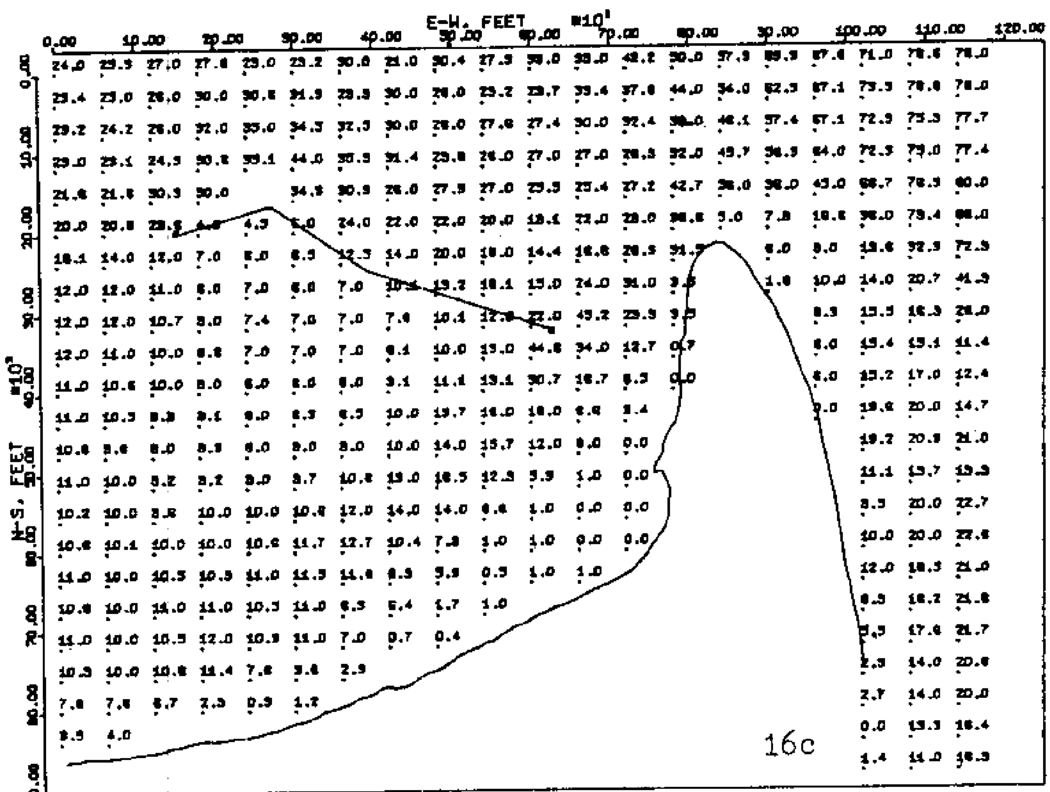


SHØRELINES FØR 1977, 1945, 1929, 1883, AND 1842

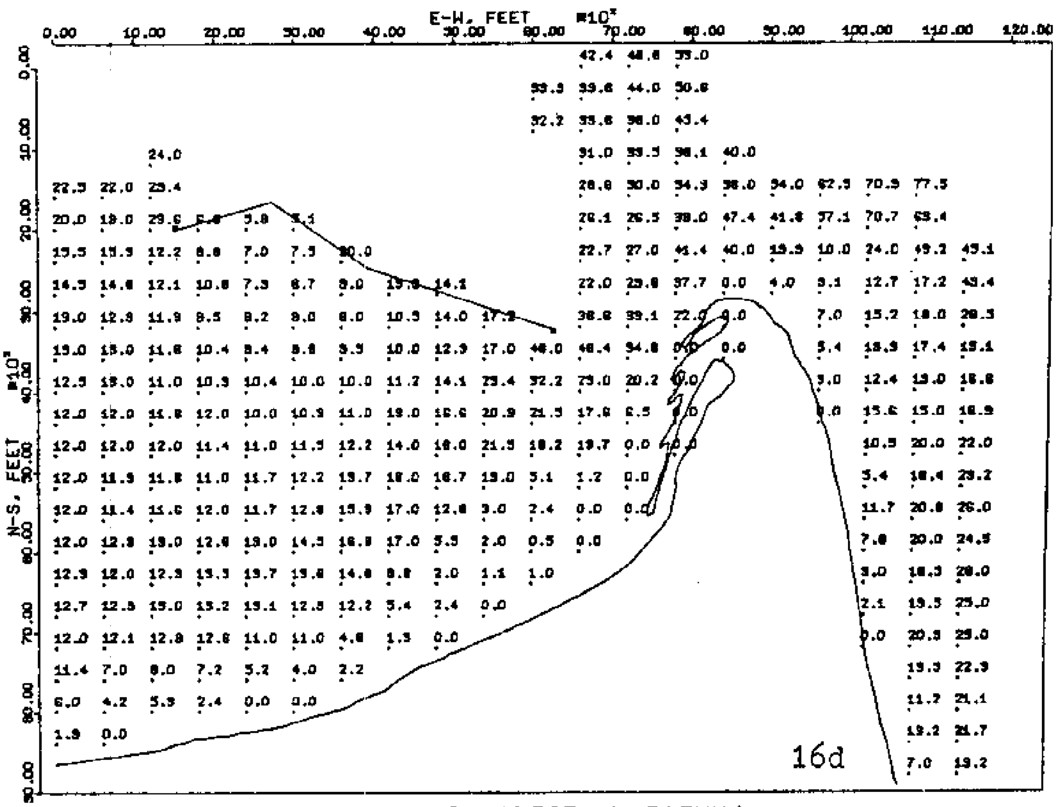
Figure 16 - Shoreline and Depths, 1842-1977. Figure 16a, shows the position of profile lines, the dates of construction of breakwater and the jetty, and the shorelines for 1977, 1945, 1929, 1883, and 1842. Figures 16b-16i show the computer-interpolated depths for each of the available survey maps; 1971, 1945, 1929, 1913, 1894, 1883, 1863, 1842. These data were used to calculate the difference maps shown later. The bathymetric patterns shown in this figure are discussed later with depth change data and shoaling rate data.



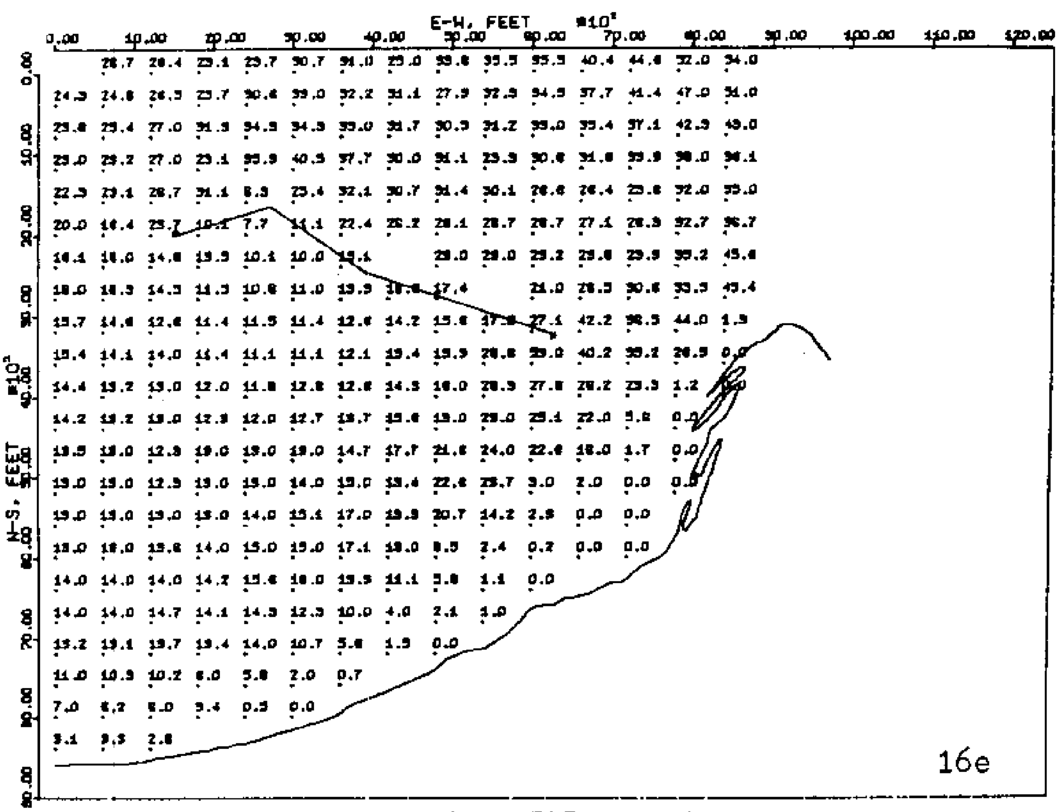
1971 DEPTHS IN FEET (ØRIGINAL DATUM)



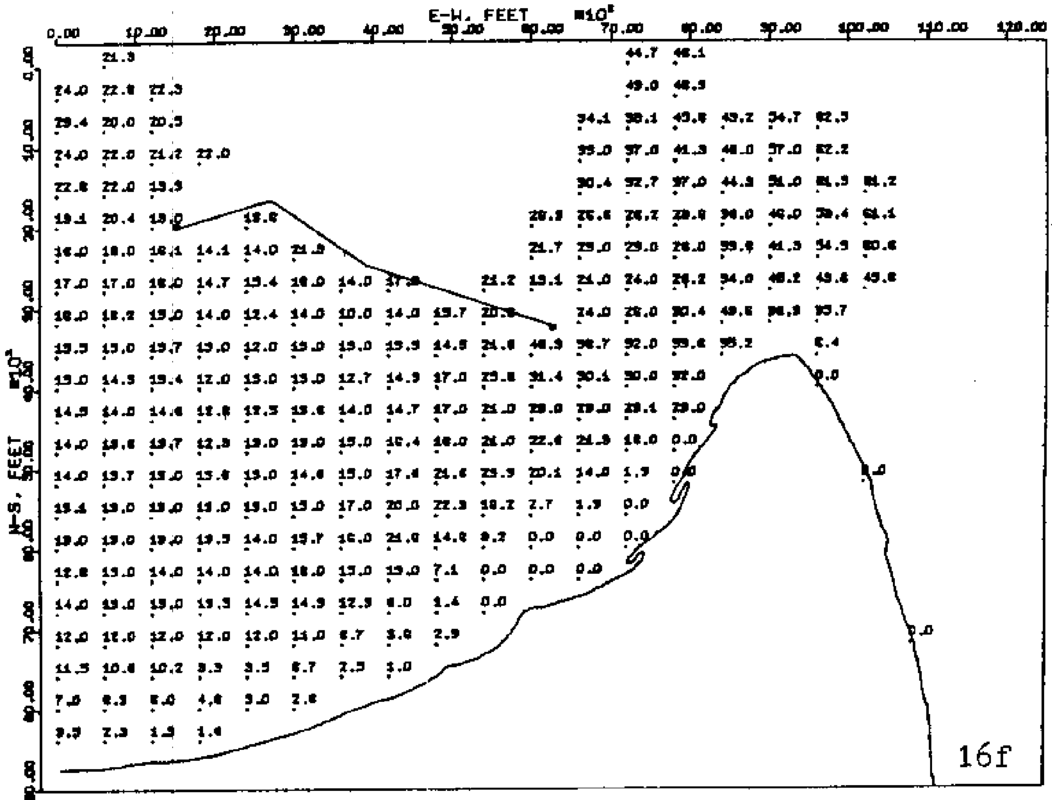
1945 DEPTHS IN FEET (ØRIGINAL DATUM)



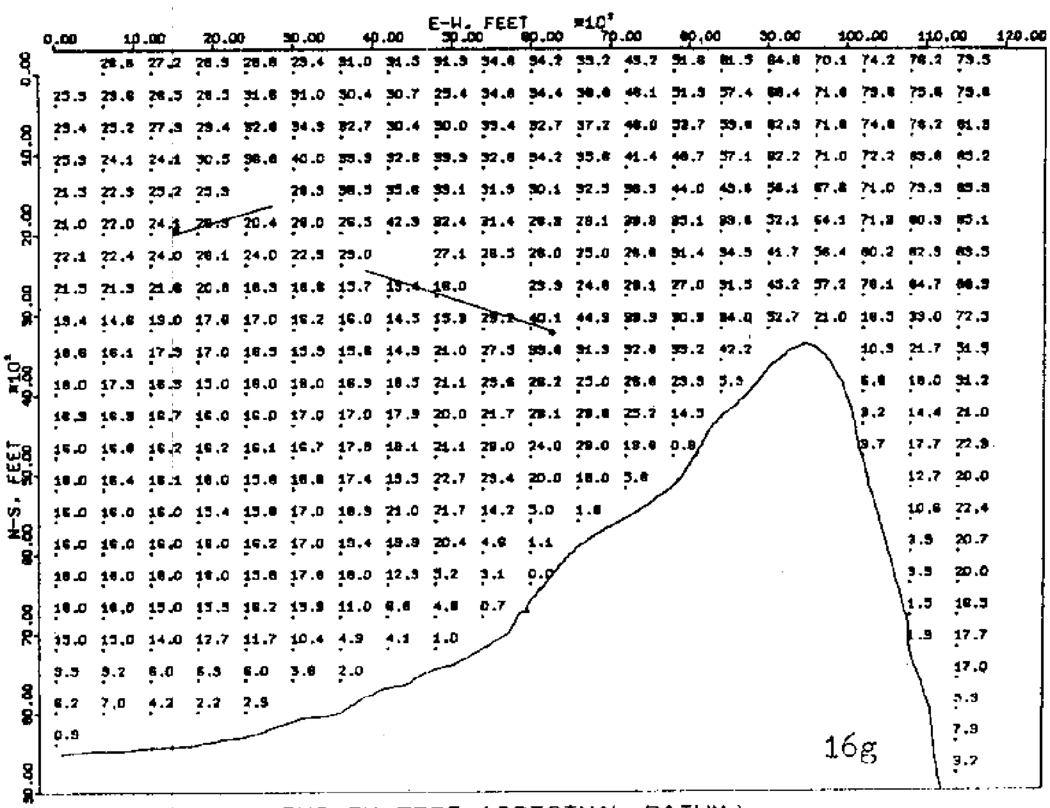
1929 DEPTHS IN FEET (ØRIGINAL DATUM)



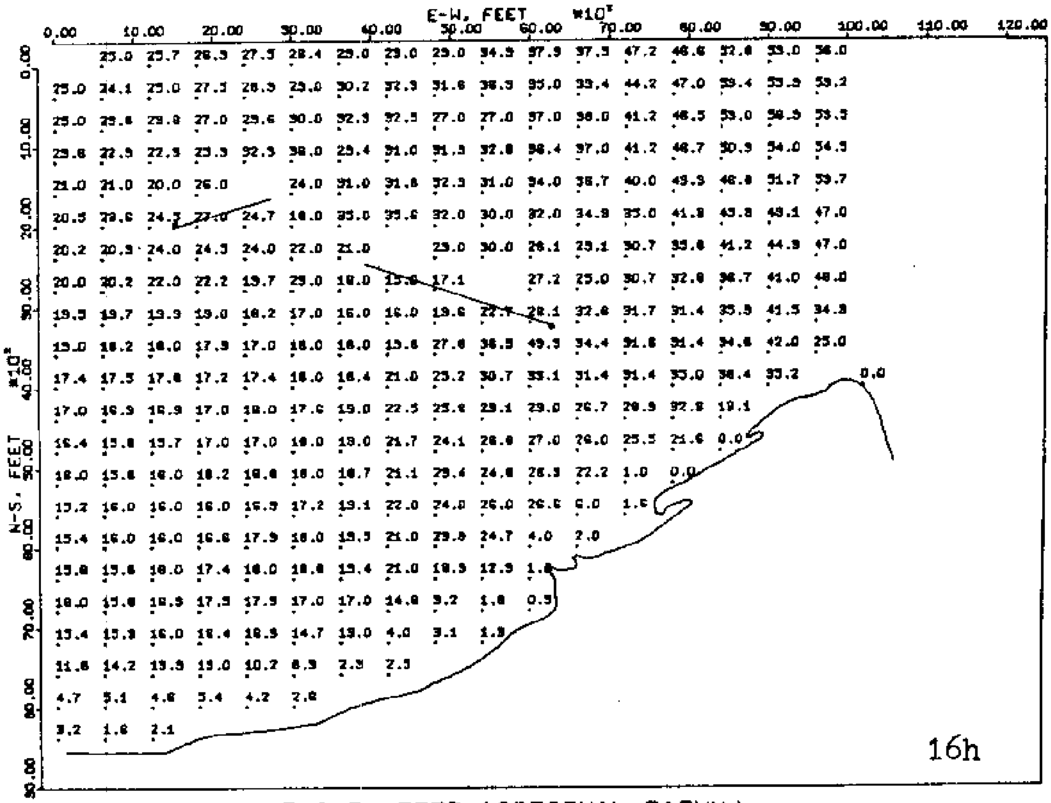
1913 DEPTHS IN FEET (ØRIGINAL DATUM)



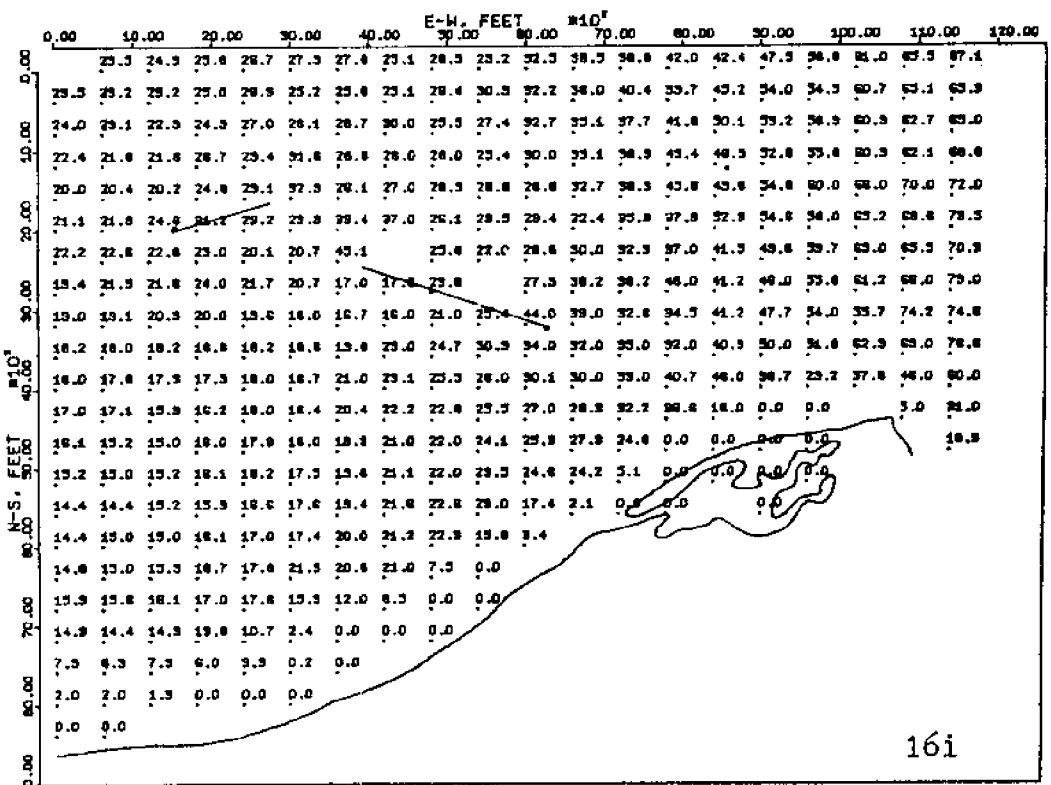
1894 DEPTHS IN FEET (ORIGINAL DATUM)



1883 DEPTHS IN FEET (ORIGINAL DATUM)



1863 DEPTHS IN FEET (ØRIGINAL DATUM)



1842 DEPTHS IN FEET (ØRIGINAL DATUM)

1842 to 1971 (Figure 17)

In the following set of maps (Figure 17 a, b, c, and d), the interpolated depths, depth changes, and shoaling rates for the entire study period are shown. These data show the net average change in bathymetry. The first available data were collected about ten years after the construction of the first two sections of the inner breakwater.

Depths in 1842 for the central portions of the harbor were 17 to 20 feet (5.2 to 6.1 m). They increased to around 30 feet (9.1 m) in the channel between the sections of the breakwater and in the channel east of the breakwater. Depths off the west end of the breakwater were about the same as those in the central portion of the harbor. To the north and east of Cape Henlopen, depths were 50 feet (15.2 m) or greater.

Between 1842 and 1971, the bathymetry of the harbor changed from one of gradual deepening toward the north and east (from depths of 8 feet [2.4 m] to depths of 20 or 30 feet [6.1 to 9.1 m]), to bathymetry showing a slight shallowing toward the north and deepening toward the east (comparison of Figure 17a and Figure 26).

Breakwater Harbor has, in general, filled in between 6.0 and 15.0 feet (1.8 and 4.6 m). In the region of spit growth, depths have changed from 40 feet (12.2 m) or greater to sea level or above. Offshore of Cape Henlopen, significant deposition (as much as 56 feet [17.1 m]) has occurred while to the north in the present channel between the cape and the outer breakwater as much as 27 feet (8.2 m) has eroded.

Slight erosion off the east end of the breakwater of less than 0.1 feet/year (3 cm/yr) average for 129 years has occurred. The highest average shoaling rate found was 0.45 feet/year (13.7 cm/yr), on the present location of Hen and Chickens Shoal. The shoaling rates diagrams show that on the average the area has filled in slowly, with the higher rates being in the eastern portions of the study area.

In the long term, the channel between the inner breakwater and the cape has filled in, except in the "hole" at the end of the breakwater. A similar "hole" exists off the west end of the inner breakwater and off the south end of the outer breakwater (not shown in Figure 17; see Figure 1).

Figure 17 (pages 74 and 75)

Page 74

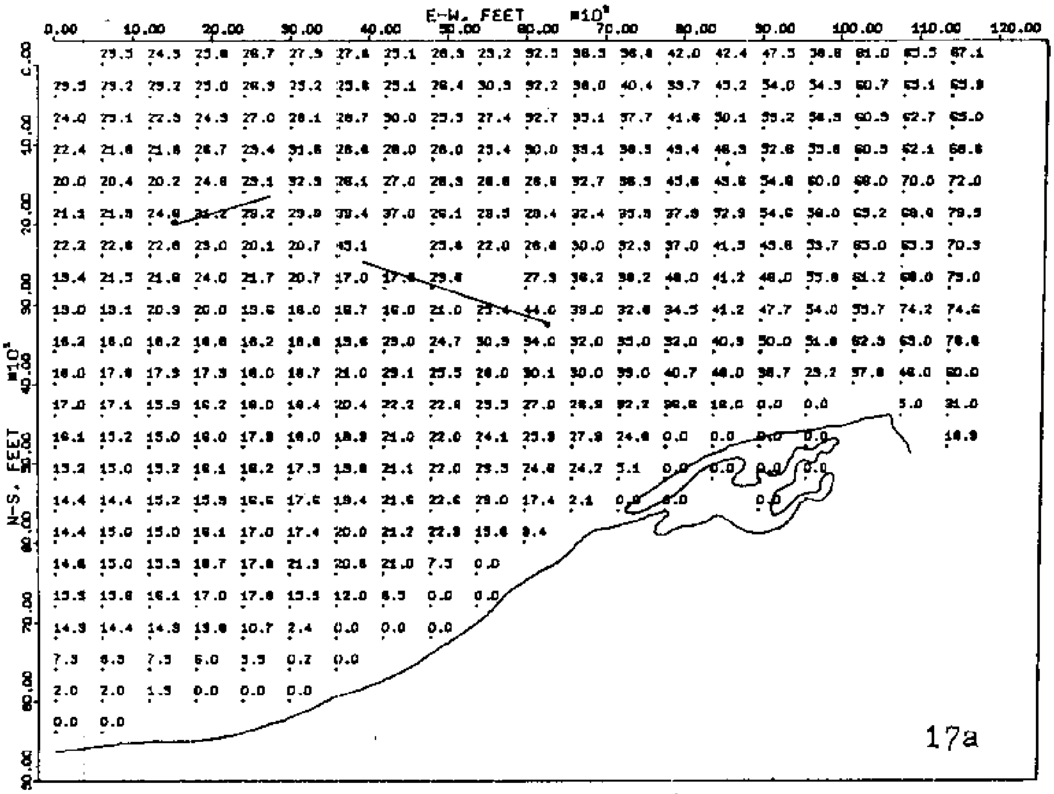
17a. 1842 Depths in Feet. Interpolated depths are from 1842 data. Depths are plotted every 400 feet (120 m) north-south and every 600 feet (180 m) east-west. Depth positions are located to the lower left of the numbers.

17b. 1842-1971 Depth Change. Depth change values are calculated from the interpolated data in Figure 16i and 16b. Negative values indicate erosion. The shorelines are labeled in Figure 17d.

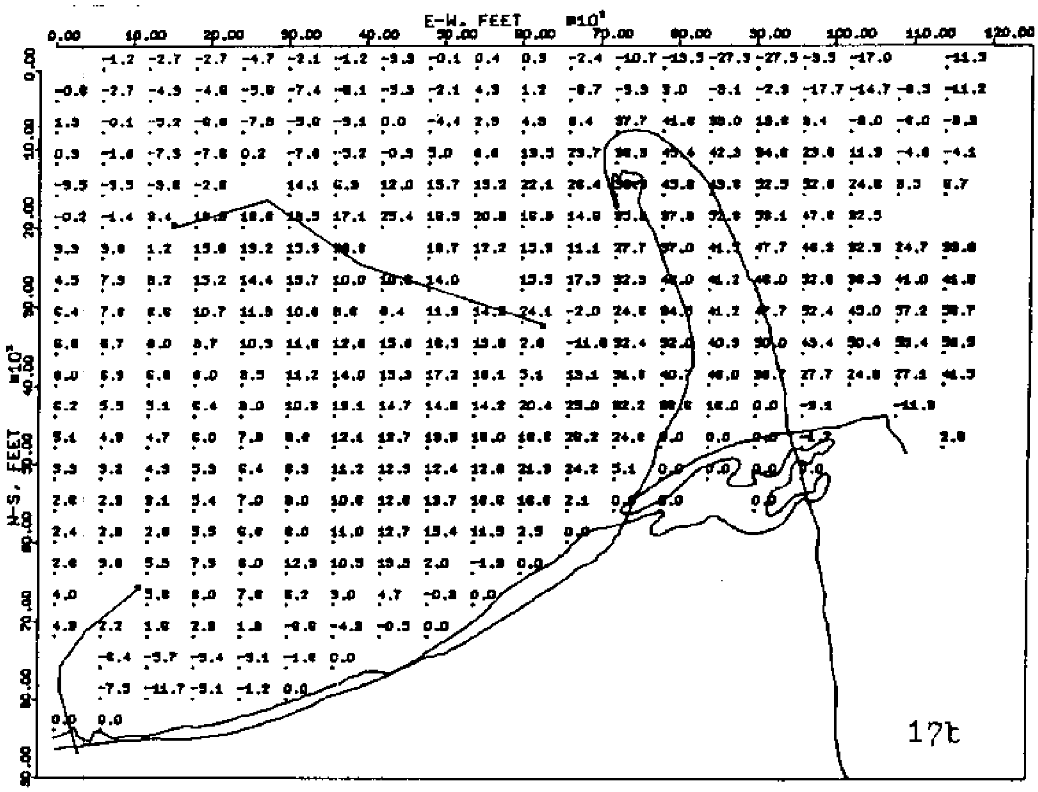
Page 75

17c. 1842-1971 Shoaling Rates (feet/year). Shoaling rates are calculated from Figure 17b, by dividing each value by 129.

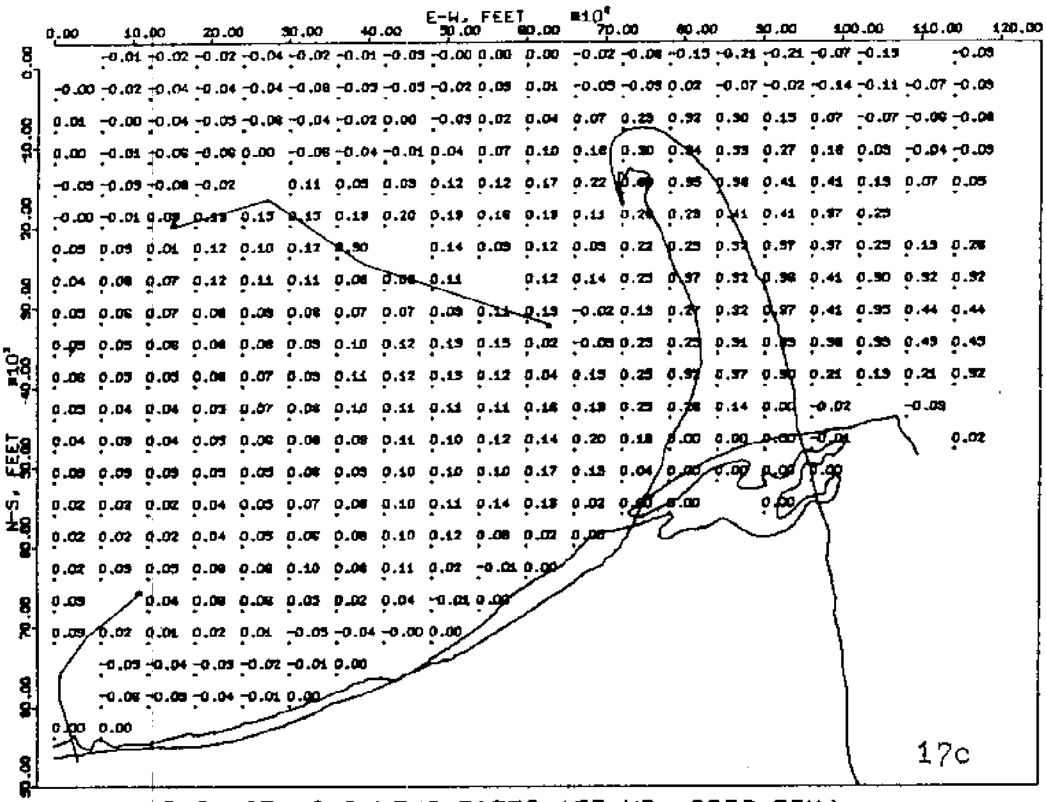
17d. 1842-1971 Shoaling Rates Contour Map. The data in Figure 17c were hand-contoured to produce this map. The "slashing" shows where the land remained above mean high water throughout the survery interval. The "slashing" does not follow one shoreline.



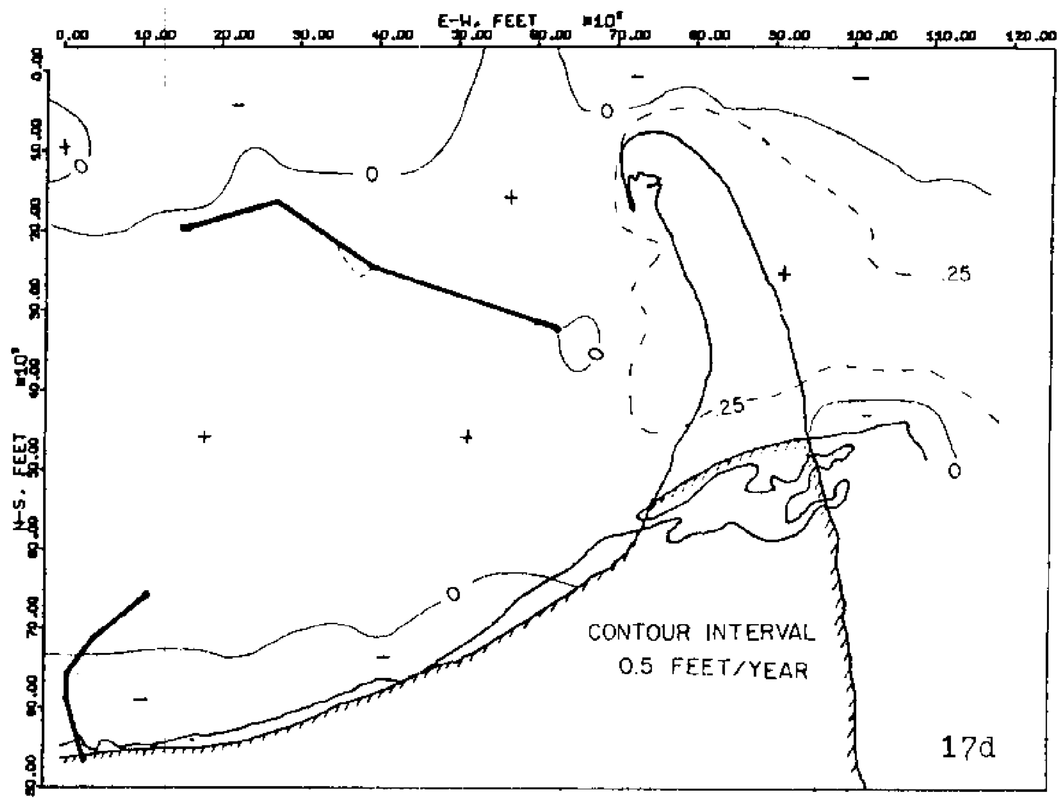
1842 DEPTHS IN FEET (ØRIGINAL DATUM)



1842-1971 DEPTH CHANGE (FT, ØRIG DTM)



1842-1971 SHOALING RATES (FT/YR, ORIG DTM)



1842-1971 SHOALING RATES CONTOUR MAP

1842 to 1863 (Figure 18)

The depths for 1842 were previously discussed. For the interval 1842-1863 depth changes in the harbor ranged from -12.0 to 3.0 feet (-3.7 to 0.9 m). North and northeast of the cape, depth changes ranged from near zero to greater than 60 feet. North of the inner breakwater, almost all depth changes were negative.

There were small depositional areas on the northeast side of the breakwaters, which was the "ebb-tide-lee" side. The rest of the study area, except the area to the north of the cape, was erosional or nearly nondepositional. The maximum erosion occurred off the harbor shoreline and to the north of the breakwaters. A small depositional area was present in the center of the harbor. Shoaling rates ranged from -1.0 to just over 1.0 feet/year (-0.3 to 0.3 cm/yr) averaged over the 21-year period and averaged -0.02 feet/year (0.6 cm/yr) in the harbor.

Figure 18 (pages 78 and 79)

Page 78

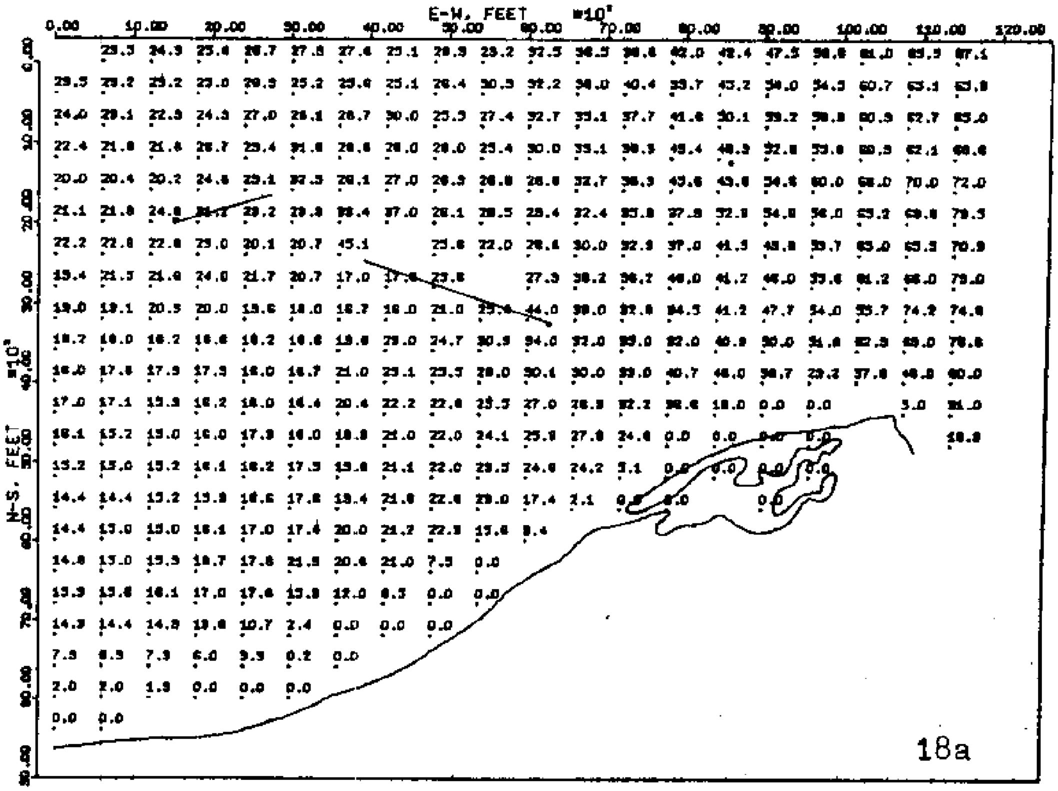
18a. 1842 Depths in Feet. Interpolated depths are from 1842 data. Depths are plotted every 400 feet (120 m) north-south and every 600 feet (180 m) east-west. Depth positions are located to the lower left of the numbers.

18b. 1842-1863 Depth Change. Depth change values are calculated from the interpolated data in Figure 16h and 16i. Negative values indicate erosion. The shorelines are labeled in Figure 18d.

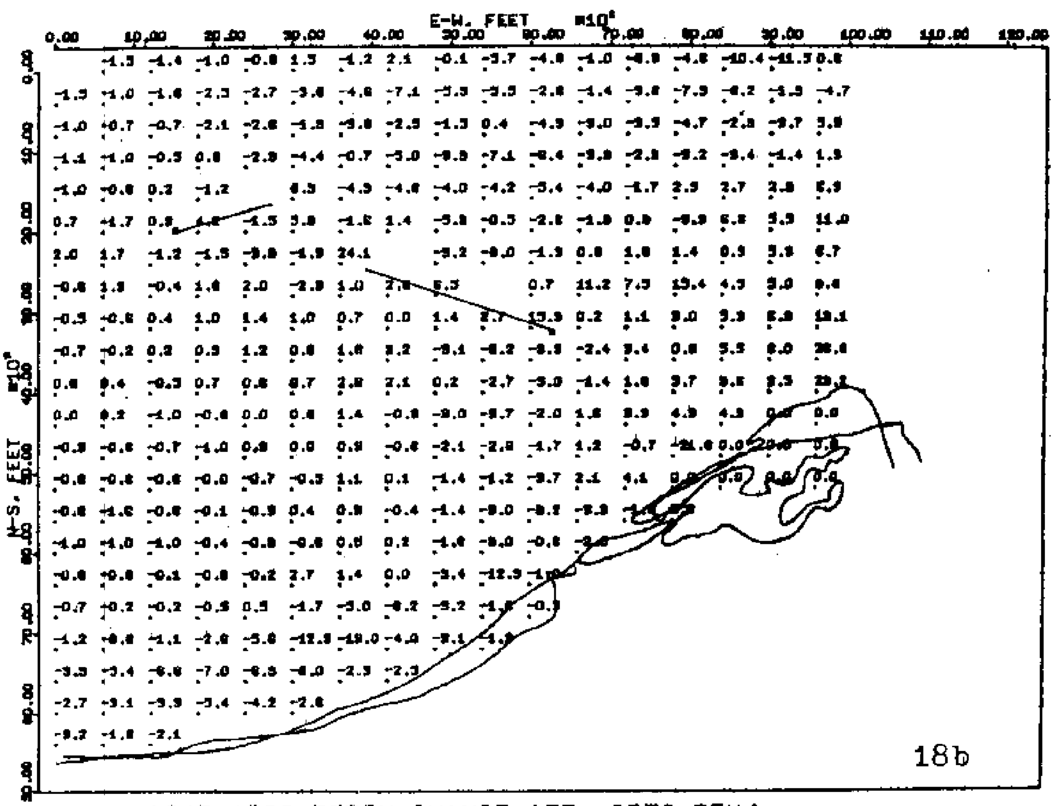
Page 79

18c. 1842-1863 Shoaling Rates (feet/year). Shoaling rates are calculated from Figure 18b, by dividing each value by 21 years.

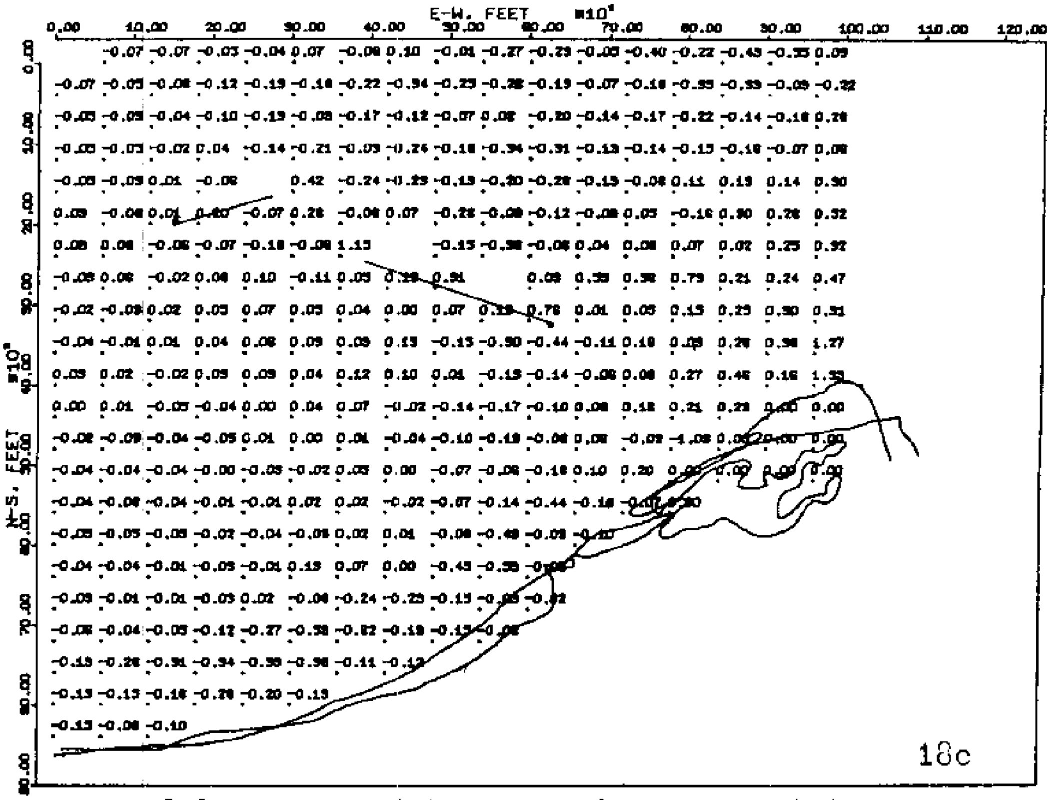
18d. 1842-1863 Shoaling Rates Contour Map. The data in Figure 18c were hand-contoured to produce this map. The "slashing" shows where the land remained above mean high water throughout the survey interval. The "slashing" <u>does not</u> follow one shoreline.



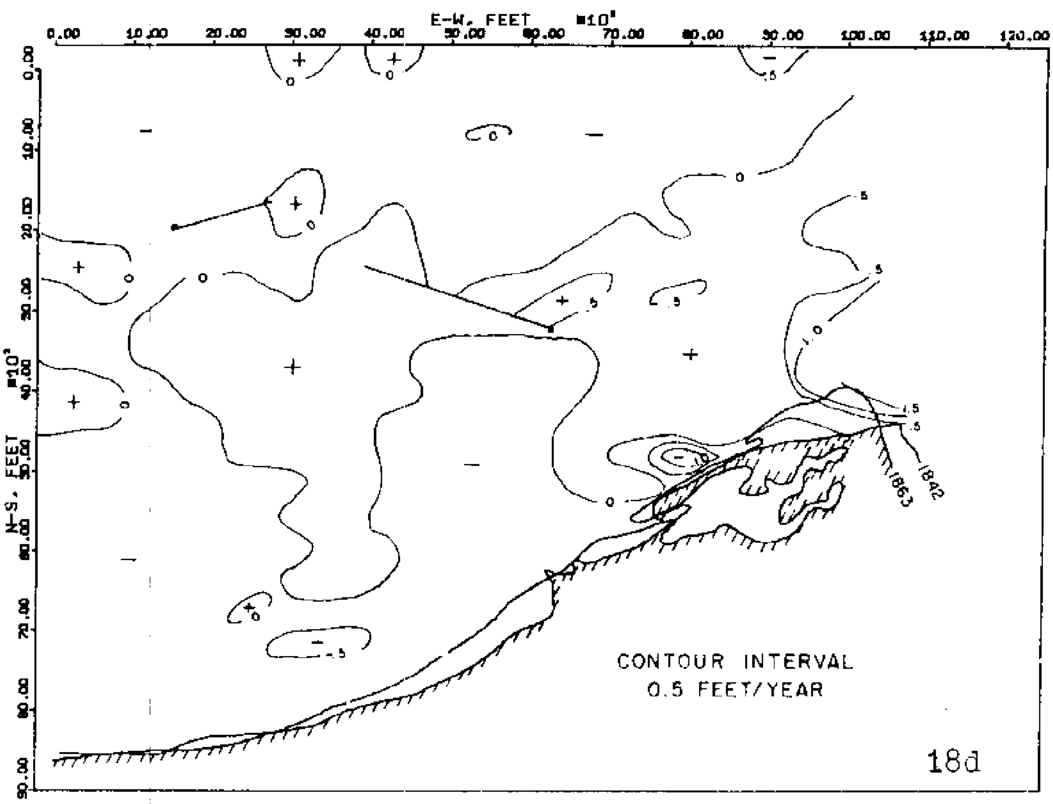
1842 DEPTHS IN FEET (ORIGINAL DATUM)



1842-1863 DEPTH CHANGE (FT, ORIG DTM)



1842-1863 SHØALING RATES (FT/YR, ØRIG DTM)



1842-1863 SHØALING RATES CØNTØUR MAP

1863-1883 (Figure 19)

Depths for 1863 were around 17 feet (5.2 m) in the central portions of the harbor, increasing to around 30 to 40 feet (9.1 to 12.2 m) in channels between the sections of the breakwater and to the east of the breakwater. The offshore profile along the harbor shoreline was much steeper than the present profile, indicating a less well-developed tidal flat. Depths off the cape ranged from 30 to 50 feet (9.1 to 15.2 m), but this was not necessarily representative of the full range, as no data were available to the north and east of the cape.

Depth changes for the central area of the harbor ranged from near zero to about 3.0 feet (0.9 m). As much as 10 feet (3 m) eroded in the channels around the breakwater.

From 1863 to 1883, the area immediately north of the cape was depositional; however, the northward extent of the depositional area was relatively more restrictive. A significant channel of erosion was present to the north of the cape just offshore of the 1883 shoreline. The depositional area in the "ebb-tide-lee" of the breakwater was again present for the eastern section, but had shifted to a "flood-tide-lee" position for the western section.

Two large depositional centers were present along the shore of the harbor, indicating more extensive development of the tidal flat during this interval. In addition to these depositional centers, the shoreline on the bay side of the cape did not erode as in other intervals.

The average shoaling rate for the harbor was 0.18 feet/year (5.5 cm/yr), while the rates ranged from near zero to 0.5 feet/year (15 cm/yr). In channels, the erosion rates were as high as -0.5 feet/year (-15 cm/yr). And in the area of new cape development, the depositional rates were greater than 2.0 feet/year (60 cm/yr).

Figure 19 (pages 83 and 84)

Page 83

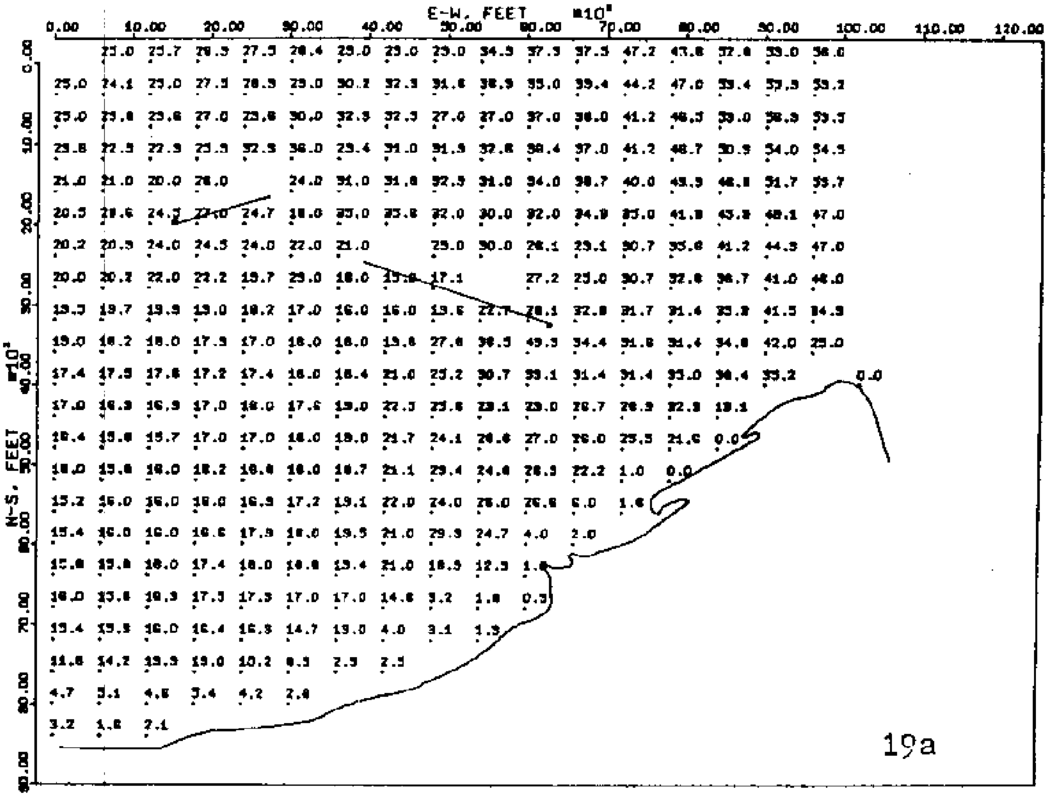
19a. 1863 Depths in Feet. Interpolated depths are from 1863 data. Depths are plotted every 400 feet (120 m) north-south and every 600 feet (180 m) east-west. Depth positions are located to the lower left of the numbers.

19b. 1863-1883 Depth Change. Depth change values are calculated from the interpolated data in Figure 16g and 16h. Negative values indicate erosion. The shorelines are located in Figure 19d.

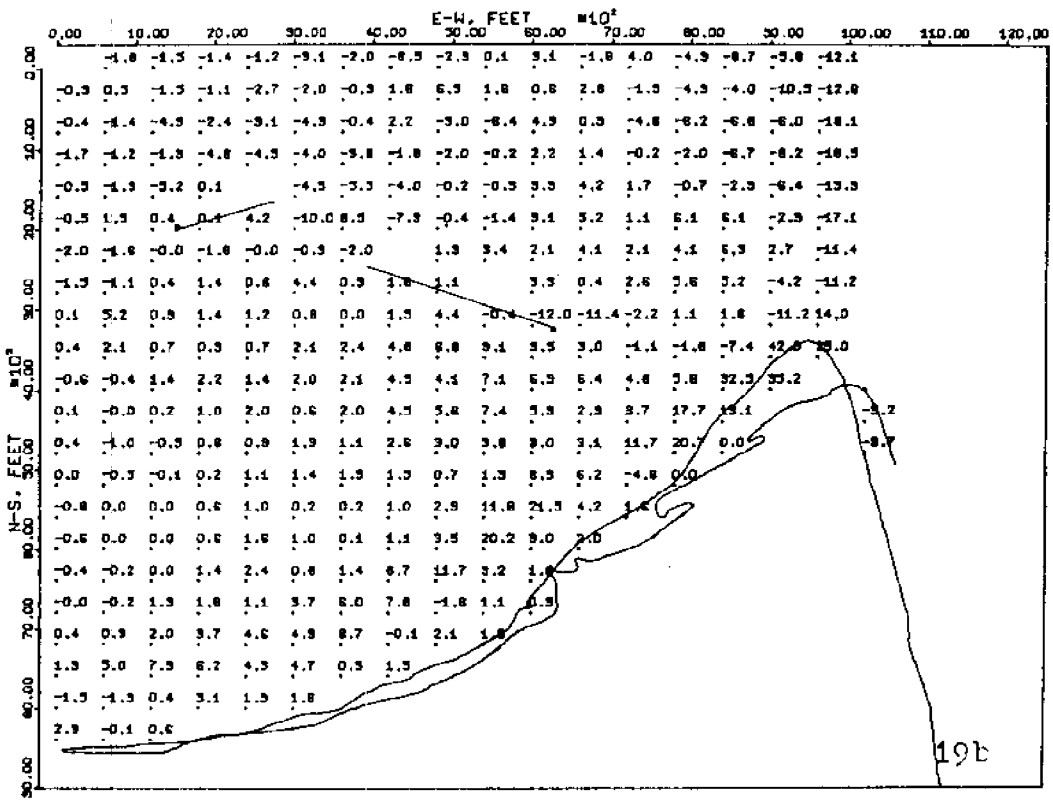
Page 84

19c. 1863-1883 Shoaling Rates (feet/year). Shoaling rates are calculated from Figure 19b, by dividing each value by 20 years.

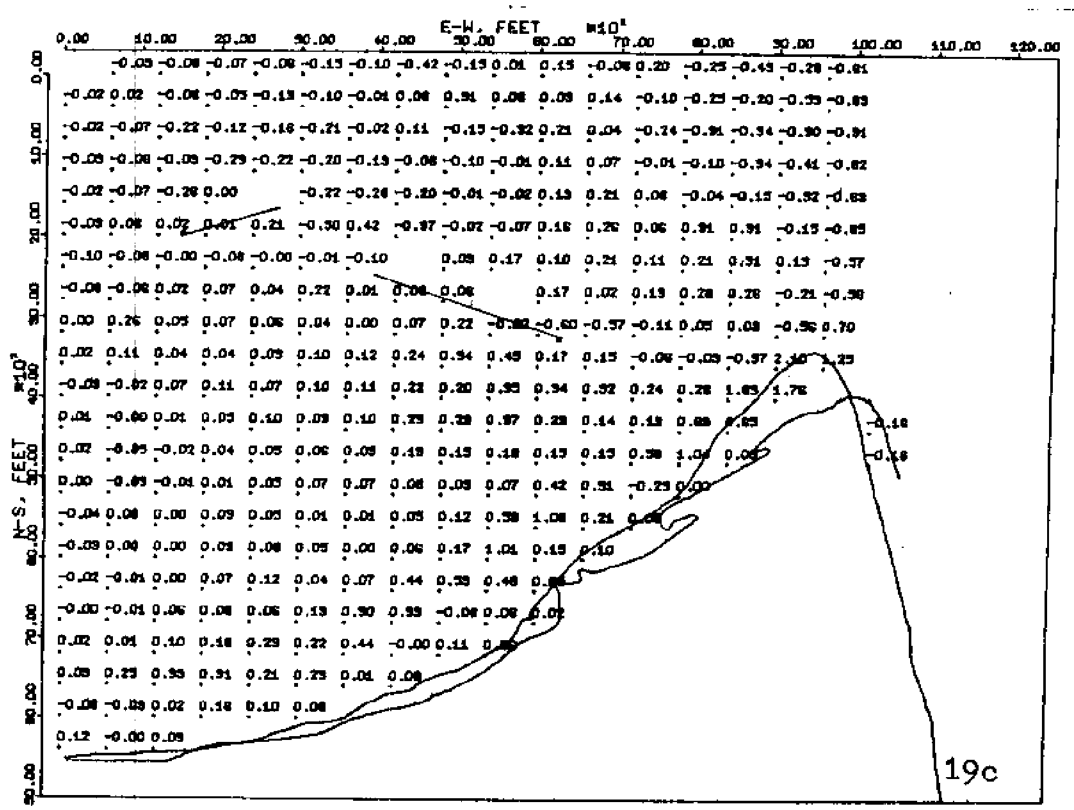
19d. 1863-1883 Shoaling Rates Contour Map. The data in Figure 19c were hand-contoured to produce this map. The "slashing" shows where the land remained above mean high water throughout the survey interval. The "slashing" <u>does not</u> follow one shoreline.



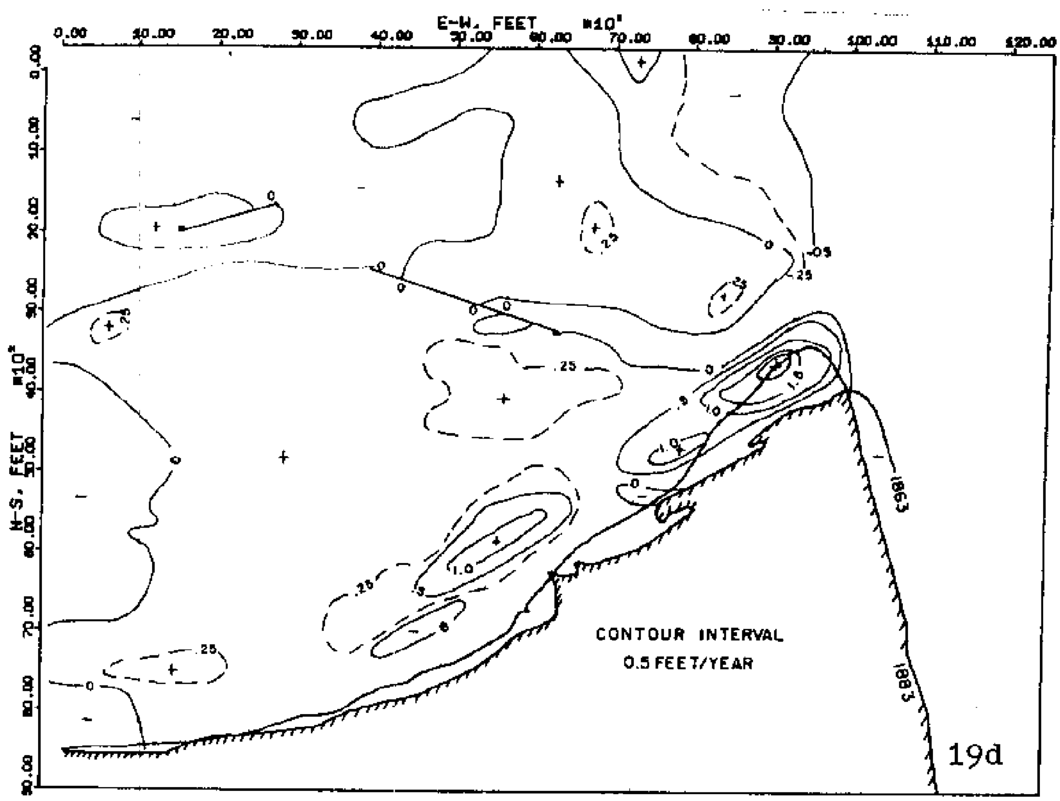
1863 DEPTHS IN FEET (ØRIGINAL DATUM)



1863-1883 DEPTH CHANGE (FT, ØRIG DTM)



1863-1883 SHØALING RATES (FT/YR, ØRIG DTM)



1863-1883 SHØALING RATES CØNTØUR MAP

The interval 1883-1929 was analyzed in two ways. First, the entire interval was analyzed, using the 1883 and 1929 data. Then, the interval was subdivided, using the 1894 and 1913 data. Averaging over longer periods showed the more general trends, while the shorter intervals pick up much of the local and short-lived complexities. The gap in the inner breakwater was filled in the late 1880s and the outer breakwater was constructed in 1900.

1883 to 1929 (Figure 20)

The 1883 depths ranged from 16 to 17 feet (4.9 to 5.2 m) in the central area of the harbor and deepened to 20 to 30 feet (6.1 to 9.1 m) in the channels around the breakwater. Depths off the tip of Cape Henlopen were around 50 feet (15.2), deepening to over 75 feet (22.9) farther offshore.

Depth changes ranged from 3 to 7 feet (0.9 to 2.1 m) in the central area of the harbor increasing to 20 feet (6.1 m) in two locations on the south side of the breakwater. Depth changes off the tip of the cape were as high as 50 feet (15.2 m). Again, as much as 10 feet (3 m) eroded in the channel offshore of the 1929 shoreline. To the east of the tip of the cape as much as 67 feet (20.4 m) deposited in one place. To the south of this region as much as 12 feet (3.7 m) eroded in some places.

The shoaling rates contour map indicates deposition over most of the area with some small areas of erosion present (Figure 20d). The average shoaling rate for Breakwater Harbor was 0.16 feet/year (4.9 cm/yr). The major deposition associated with the growth of Cape Henlopen was to the east of the cape tip with rates greater than 1.0 feet/year (30 cm/yr) in places. The tip of the cape grew almost 1000 feet (300 m) to the northwest, while the Atlantic coast retreated about 600 feet (180 m).

The next three sections divide the 46 year-interval from 1883-1929 into 11, 19 and 15-year intervals. Note the greater complexities of the patterns of deposition and erosion, and the greater magnitudes of shoaling.

Figure 20 (pages 88 and 89)

Page 88

20a. 1883 Depths in Feet. Interpolated depths are from 1883 data. Depths are plotted every 400 feet (120 m) north-south and every 600 feet (180 m) east-west. Depth positions are located to the lower left of the numbers.

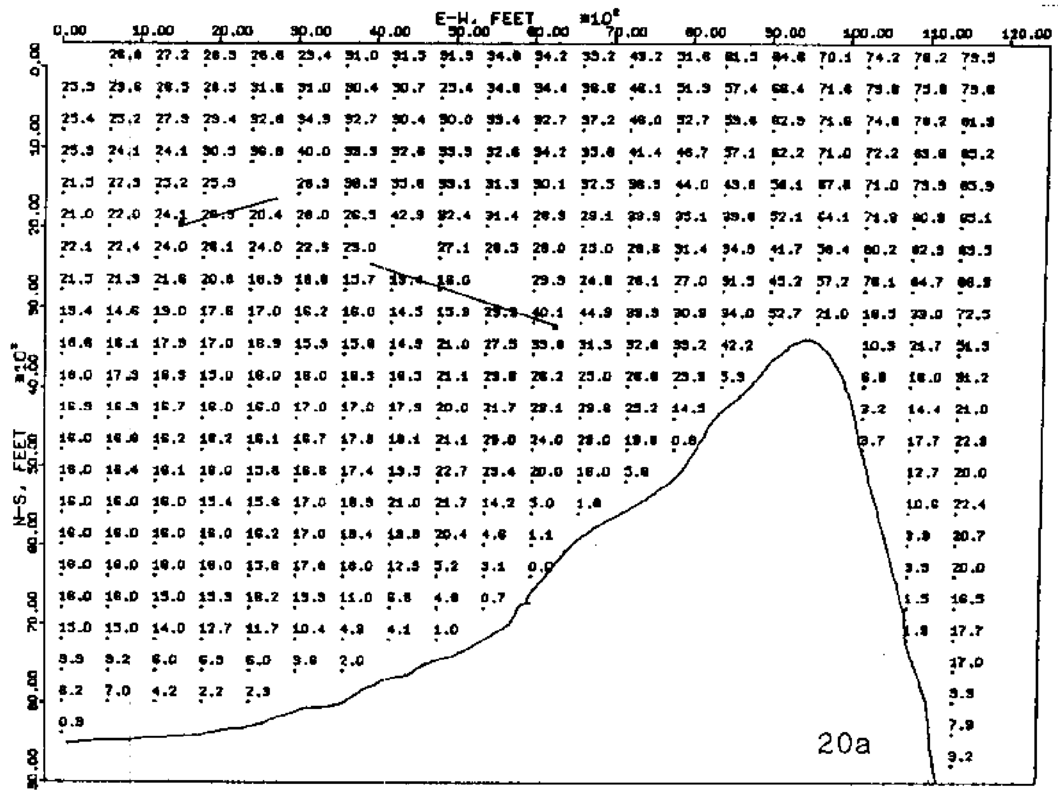
20b. 1883-1929 Depth Change. Depth change values are calculated from the interpolated data in Figure 16d and 16g. Negative values indicate erosion. The shorelines are labeled in Figure 20d.

Page 89

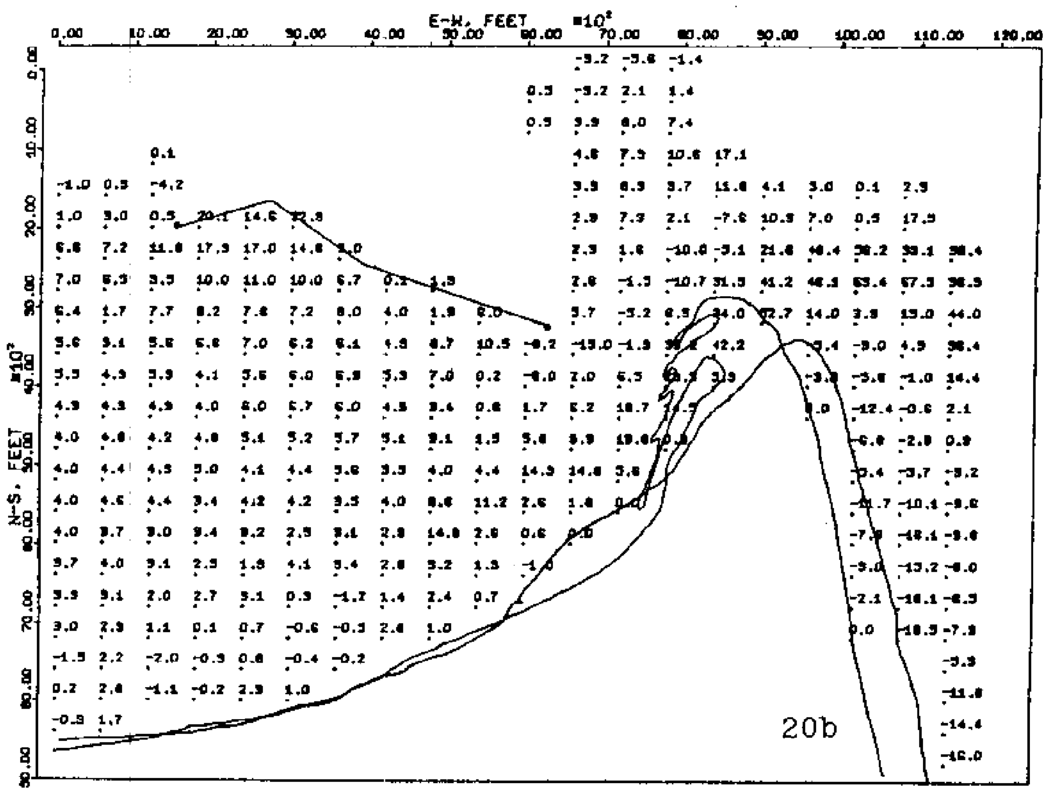
20c. 1883-1929 Shoaling Rates (feet/year). Shoaling rates are calculated from Figure 20b, by dividing each value by 46 years.

20d. 1883-1929 Shoaling Rates Contour Map. The data in Figure 20c were hand-contoured to produce this map. The "slashing" shows where the land remained above mean high water throughout the survey interval. The "slashing" does not follow one shoreline.

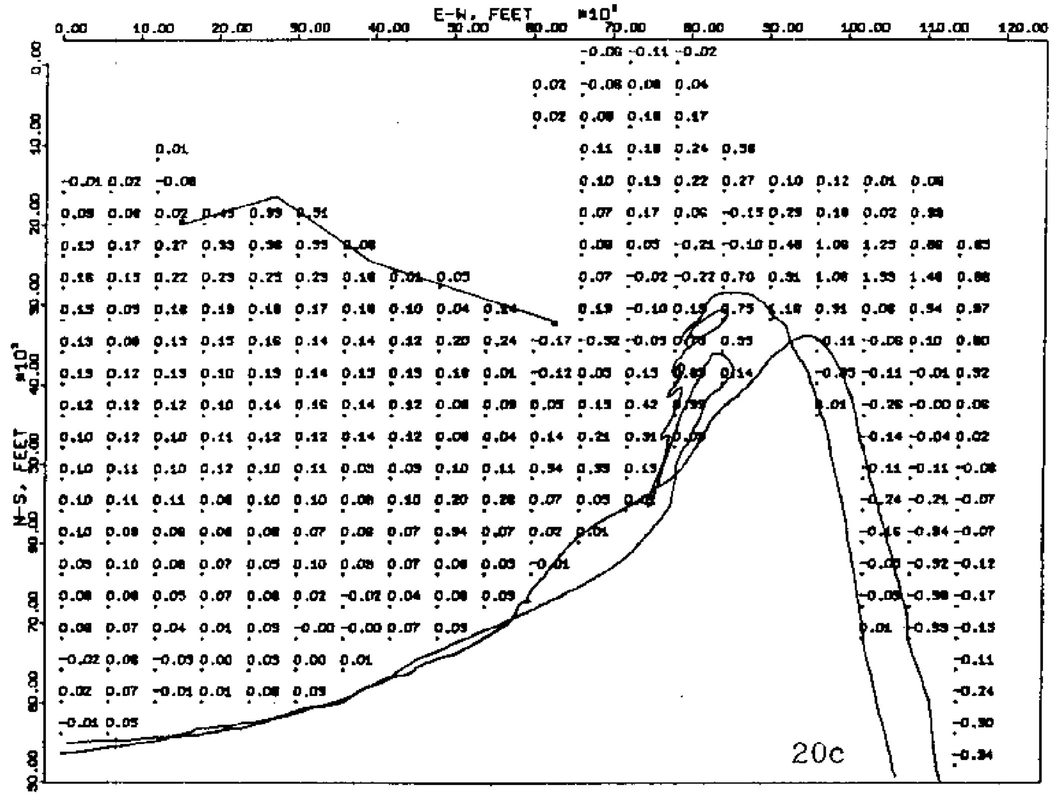
Note that this survey interval is subdivided further in the following three sections.



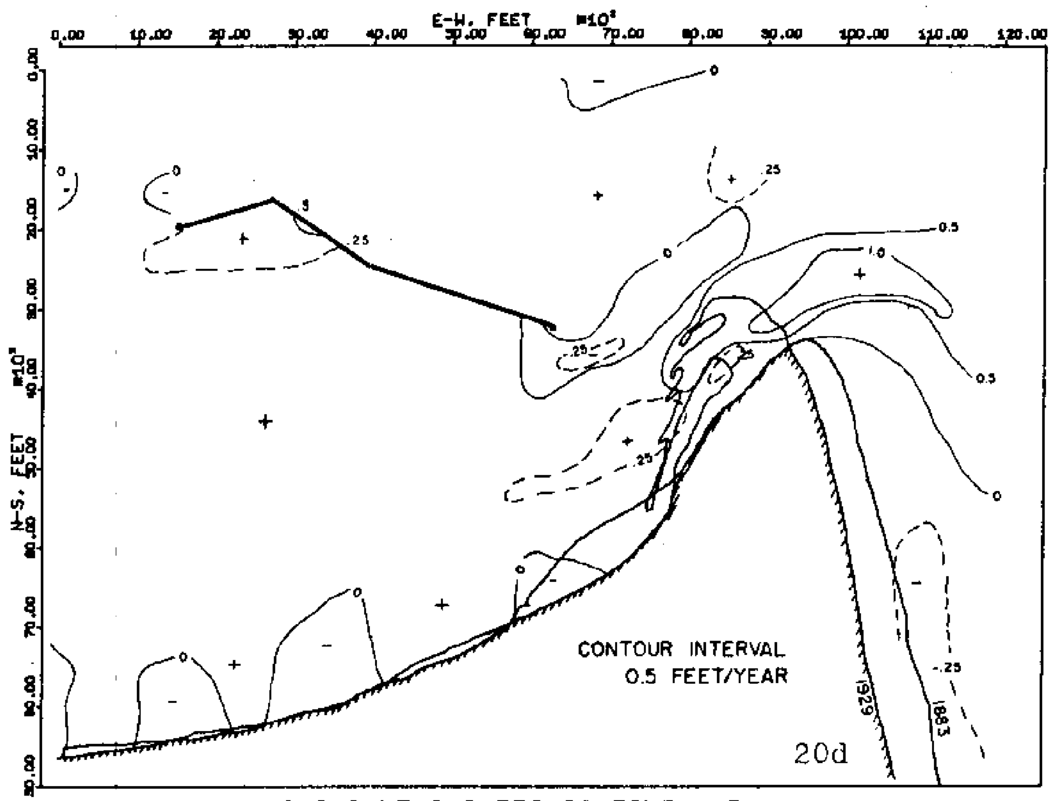
1883 DEPTHS IN FEET (ØRIGINAL DATUM)



1883-1929 DEPTH CHANGE (FT, ØRIG DTM)



1883-1929 SHOALING RATES (FT/YR, COR DTM)



1883-1929 SHOALING RATES CONTOUR MAP

1883 to 1894 (Figure 21)

The 1883 depths were previously described. Depth changes for the area immediately south of the breakwater were as much as 10 feet (3 m), while for the central areas of the harbor they were from 1.0 to 3.0 feet (0.3 to 0.9 m). Note that about half of the total depth change for 1893-1929 in the area south of the breakwater was attained in the first five years after the construction of the center section of the breakwater. Deposition again occurred to the north of the 1883 position of Cape Henlopen in the area of new spit growth, with an erosional channel to the north of this depositional area. Up to 40 feet (12.2 m) of sediment deposited in the area offshore of the 1894 cape, representing an average shoaling rate of as high as 3.5 feet/year (1.1 cm/yr). This major deposition was centered to the northeast of the cape.

The shoaling rates contour map shows the greater complexity of the erosional and depositional patterns during this interval. As discussed earlier errors have a relatively greater significance because of the shorter time interval. Therefore, it is quite likely that some of the complexities are not real. However, magnitudes of change were sufficiently large in some areas to indicate that some of the complexity is real. The average shoaling rate for the center portion of the harbor was 0.14 feet/year (4.3 cm/yr), with a maximum as high as 0.64 feet/year (19.5 cm/yr).

The tip of the cape migrated toward the southwest, contrary to the long-term trends of the cape. Significant coastal erosion occurred in the southwestern area of the harbor, with associated erosion of the bottom offshore of this area.

Figure 21 (pages 93 and 94)

Page 93

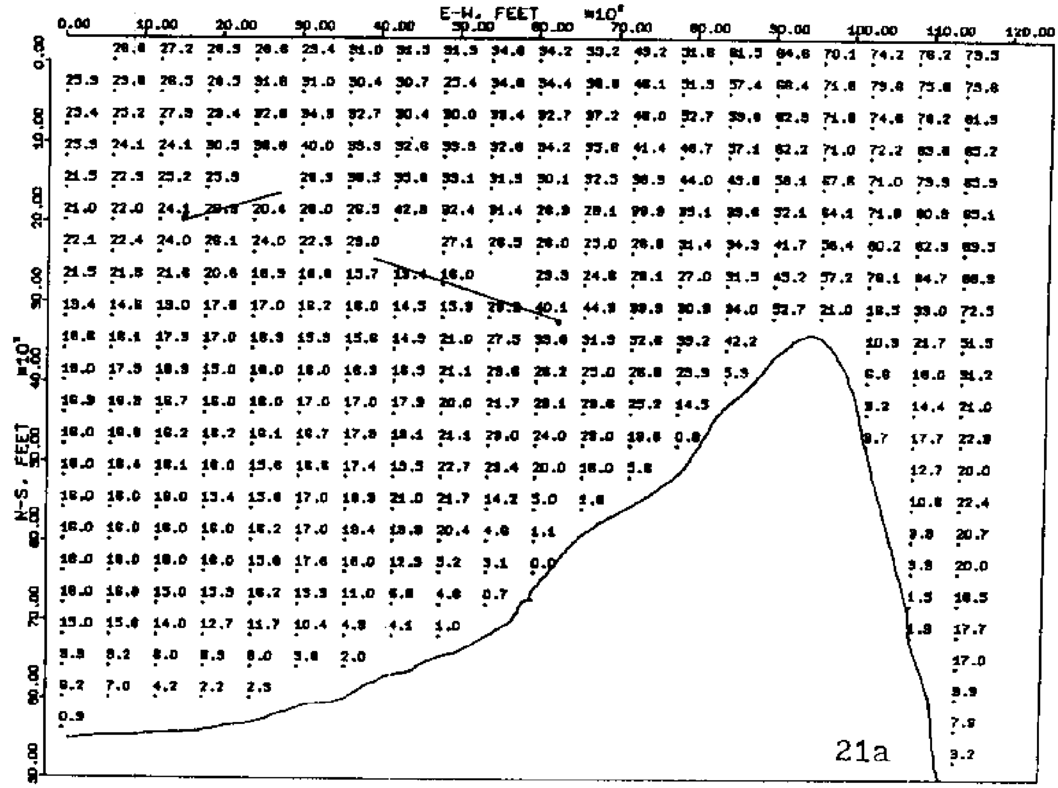
21a. 1883 Depths in Feet. Interpolated depths are from 1883 data. Depths are plotted every 400 feet (120 m) north-south and 600 feet (180 m) east-west. Depth positions are located to the lower left of the numbers.

21b. 1883-1894 Depth Change. Depth change values are calculated from the interpolated data in Figure 16f and 16g. Negative values indicate erosion. The shorelines are labeled in Figure 21d.

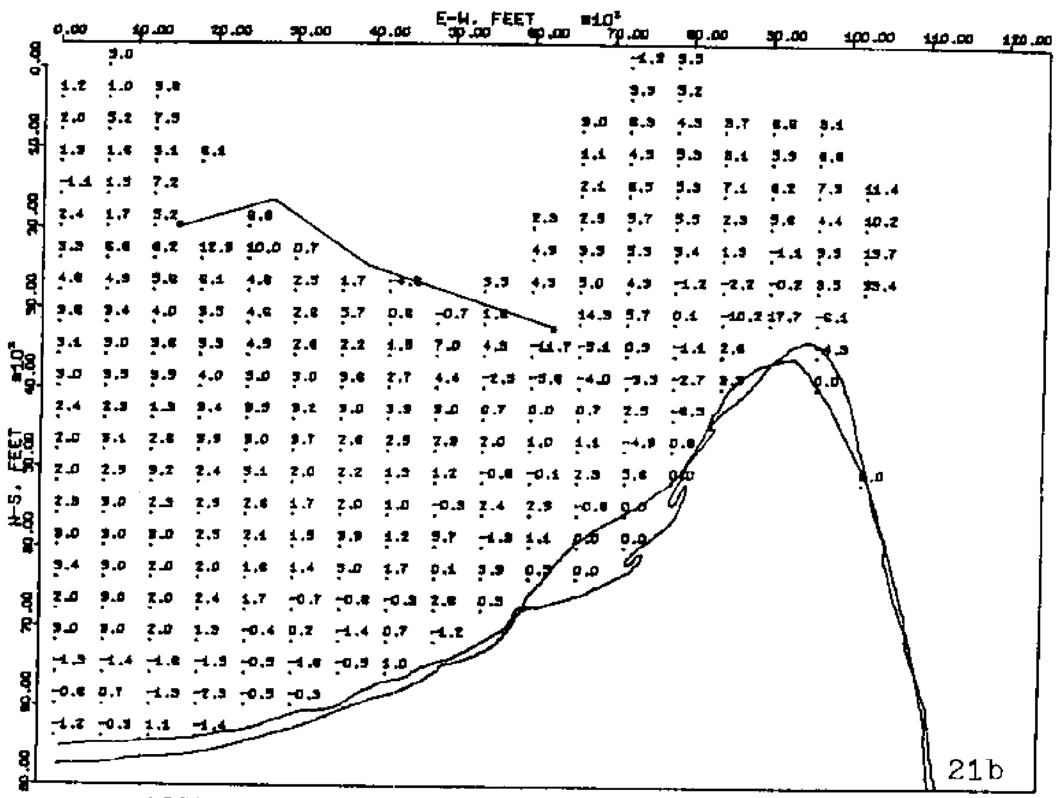
Page 94

21c. 1883-1894 Shoaling Rates (feet/year). Shoaling rates are calculated from Figure 21b, by dividing each value by 11 years.

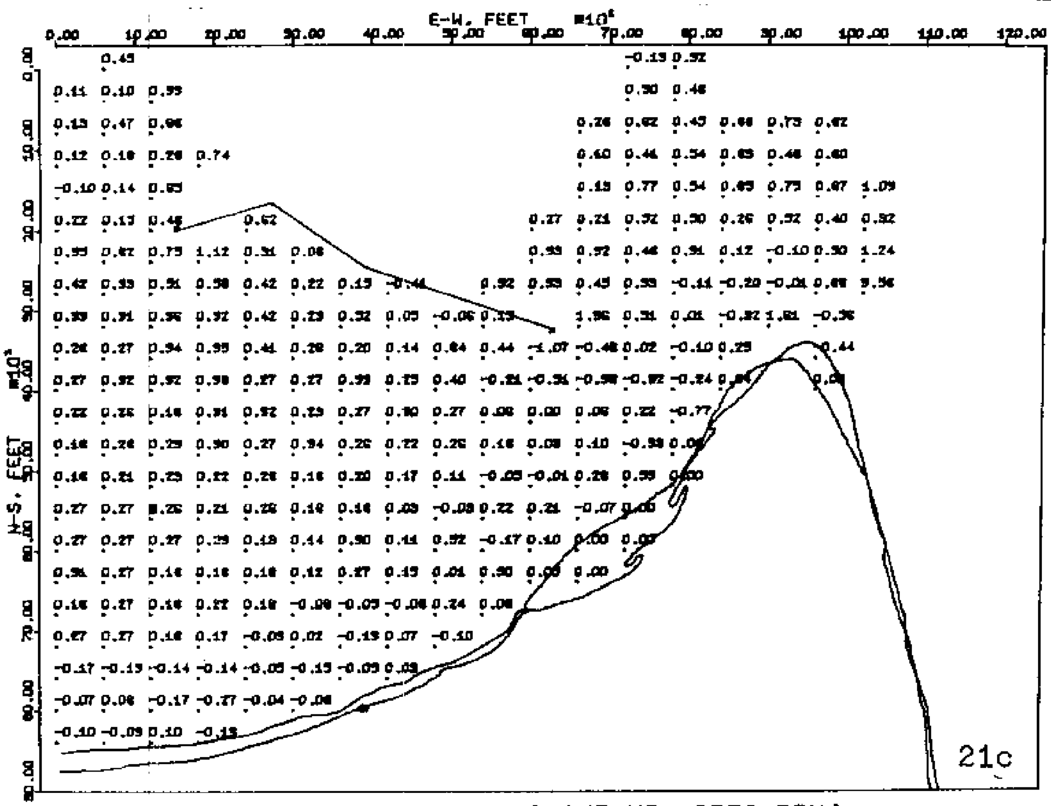
21d. 1883-1894 Shoaling Rates Contour Map. The data in Figure 21c were hand-contoured to produce this map. The "slashing" shows where the land remained above mean high water throughout the survey interval. The "slashing" <u>does not</u> follow one shoreline.



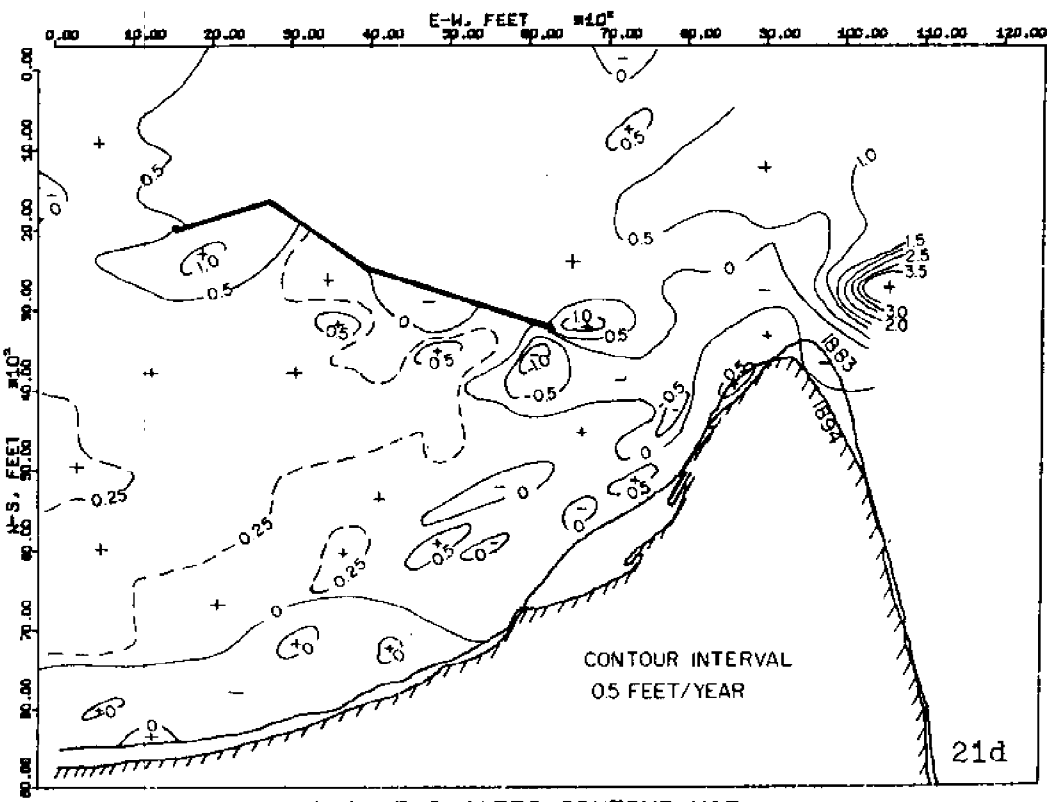
1883 DEPTHS IN FEET (ORIGINAL DATUM)



1883-1894 DEPTH CHANGE (FT, ORIG DTM)



1883-1894 SHØALING RATES (FT/YR, ØRIG DTM)



1883-1894 SHØALING RATES CØNTØUR MAP

1894 to 1913 (Figure 22)

Depths for 1894 were significantly shallower in the area immediately south of the breakwater. Depths for the central portions of the harbor ranged from 12 to 20 feet (3.7 to 6.1 m), while areas offshore of the tip of the cape were around 30 to 40 feet (9.1 to 12.9 m).

Depth change values for the harbor were from -2.0 to 11 feet (-0.6 to 3.4 m), with most of the harbor showing slightly positive depth change. Major deposition occurred in the sheltered areas of the harbor, while significant erosion occurred in the channel between the breakwater and the cape. The deepening of the channel was as much as 13 feet (4.0 m), becoming less as it entered the harbor. The average shoaling rate for the harbor was 0.08 feet/year (2.4 cm/yr).

The erosion rates for the inner breakwater-Cape Henlopen channel were on the order of -0.2 feet/year (6.1 cm/yr) but were as high as -0.7 (21.3 cm/yr) in places. Deposition rates off the tip of Cape Henlopen reached as high as 2.1 feet/year (64.0 cm/yr) with the deposition of as much as 40 feet (12.2 m) of sediment. In the channel between the cape and the outer breakwater considerable erosion occurred, except in the center of the channel, where as much as 9 feet (2.7 m) of sediment were deposited.

It should be remembered that the outer breakwater was built in 1900.

The tip of Cape Henlopen grew almost directly north by about 600 feet (180 m). Slight accretion of the harbor shoreline over most of its length occurred, coupled with some deposition offshore.

Figure 22 (pages 98 and 99)

Page 98

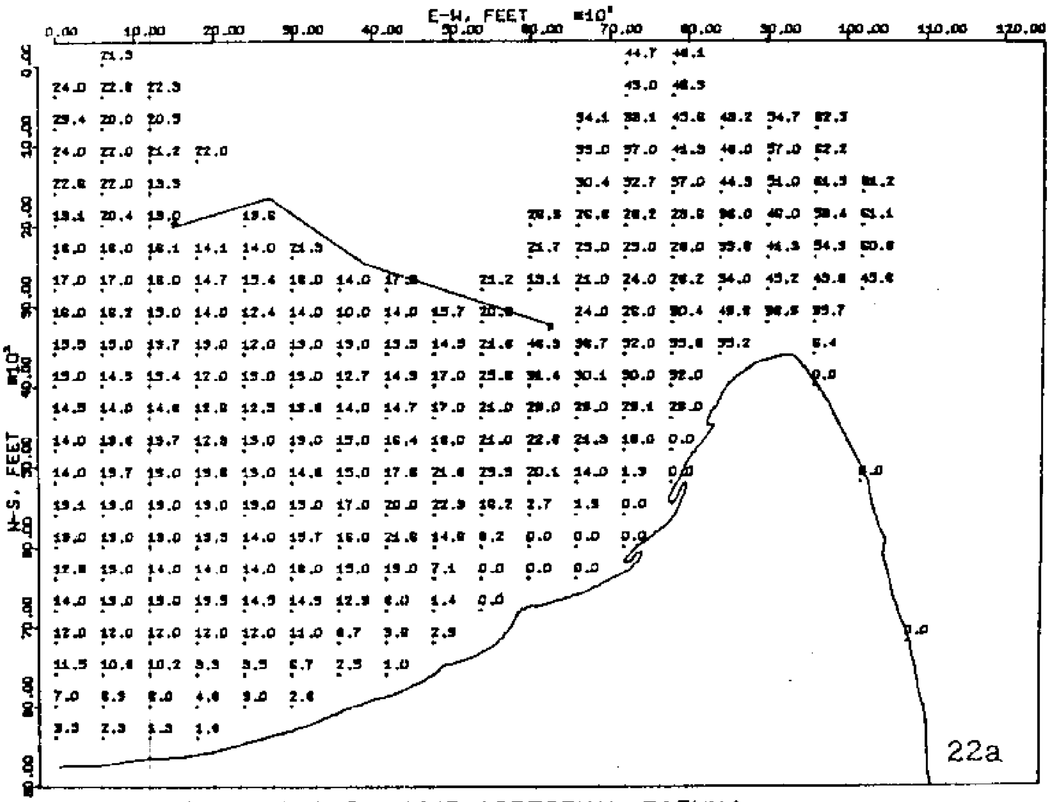
22a. 1894 Depths in Feet. Interpolated depths are from 1894 data. Depths are plotted every 400 feet (120 m) north-south and every 600 feet (180 m) east-west. Depth positions are located to the lower left of the numbers.

22b. 1894-1913 Depth Change. Depth change values are calculated from the interpolated data in Figure 16f and 16e. Negative values indicate erosion. The shorelines are labeled in Figure 22d.

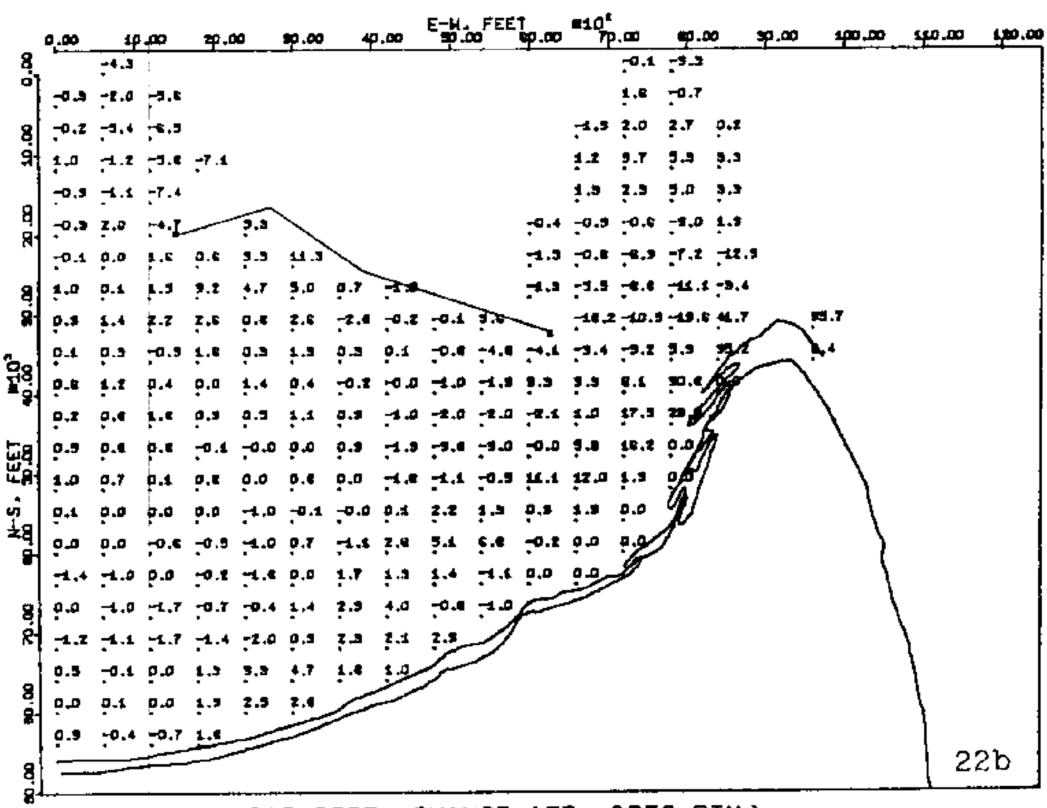
Page 99

22c. 1894-1913 Shoaling Rates (feet/year). Shoaling rates are calculated from Figure 22b, by dividing each value by 19 years.

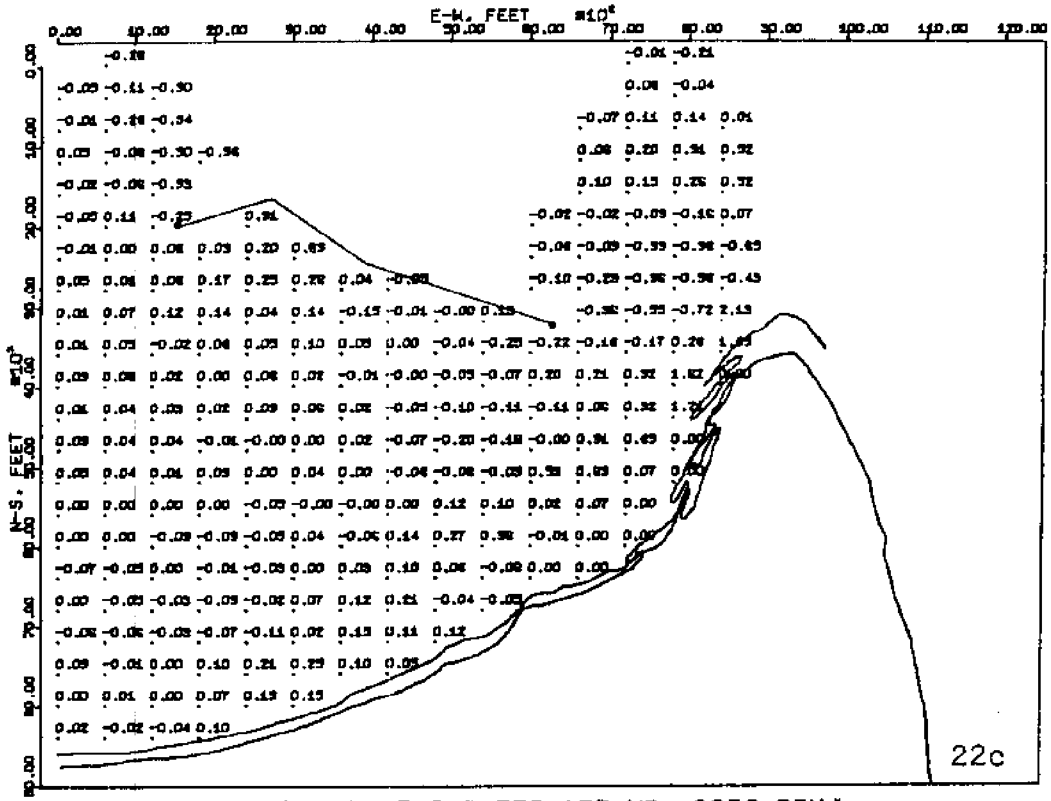
22d. 1894-1913 Shoaling Rates Contour Map. The data in Figure 22c were hand-contoured to produce this map. The "slashing" shows where the land remained above mean high water throughout the survey interval. The "slashing" does not follow one shoreline.



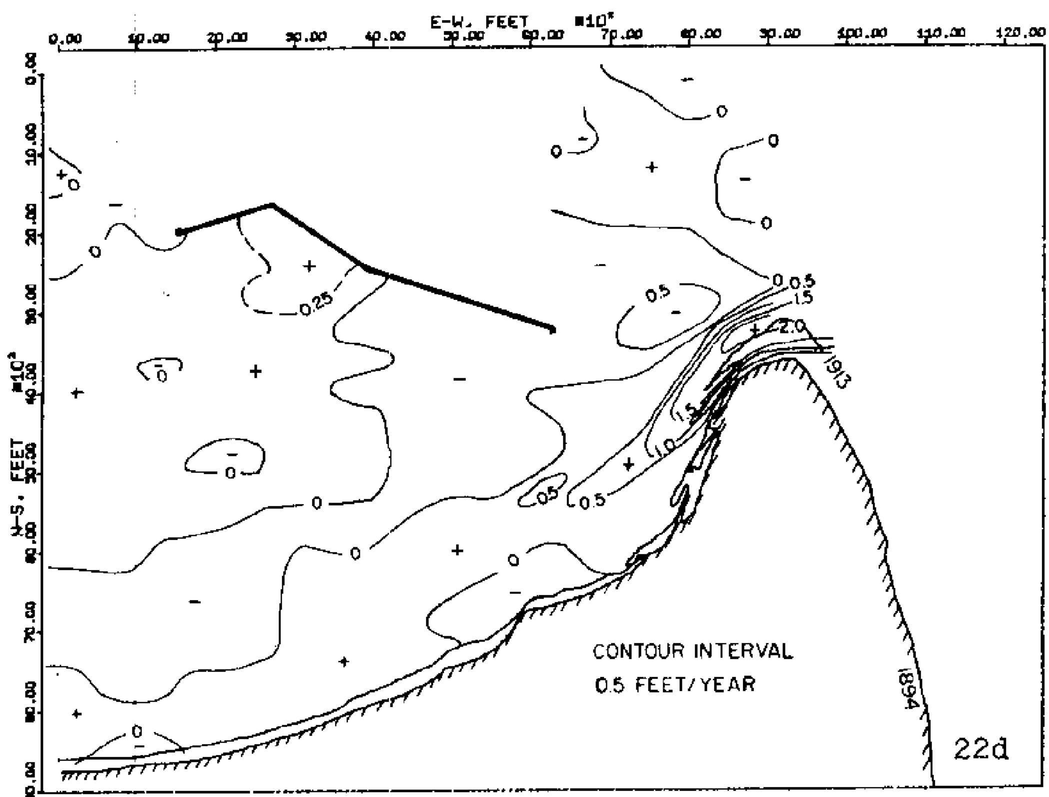
1894 DEPTHS IN FEET (ØRIGINAL DATUM)



1894-1913 DEPTH CHANGE (FT, ØRIG DTM)



1894-1913 SHOALING RATES (FT/YR, ORIG DTM)



1894-1913 SHOALING RATES CONTOUR MAP

1913 to 1929 (Figure 23)

The depth map for 1913 shows depths of 12 to 15 feet (3.7 to 4.6 m) for the central portions of the harbor and depths of 30 feet (9.1 m) or greater off the tip of Cape Henlopen.

Depth changes for 1913-1929 were around 2 to 3 feet (0.6 to 0.9 m) in the harbor and from -1.0 to 40 feet (-0.3 to 12.2 m) off the tip of the cape. Along the harbor shoreline, some erosion and some deposition occurred.

Shoaling rates ranged from 1.0 to 3.0 feet/year (30 to 91 cm/yr) in the harbor to as high as 2.6 feet/year (82 cm/yr) off the tip of the cape. Erosion farther north off the tip of the cape was as high as -1.7 feet/year (-52 cm/yr). The average shoaling rate for the harbor was 0.11 feet/year (3.4 cm/yr). The tip of the cape grew to the northwest about 700 feet (210 m).

Figure 23 (pages 102 and 103)

Page 102

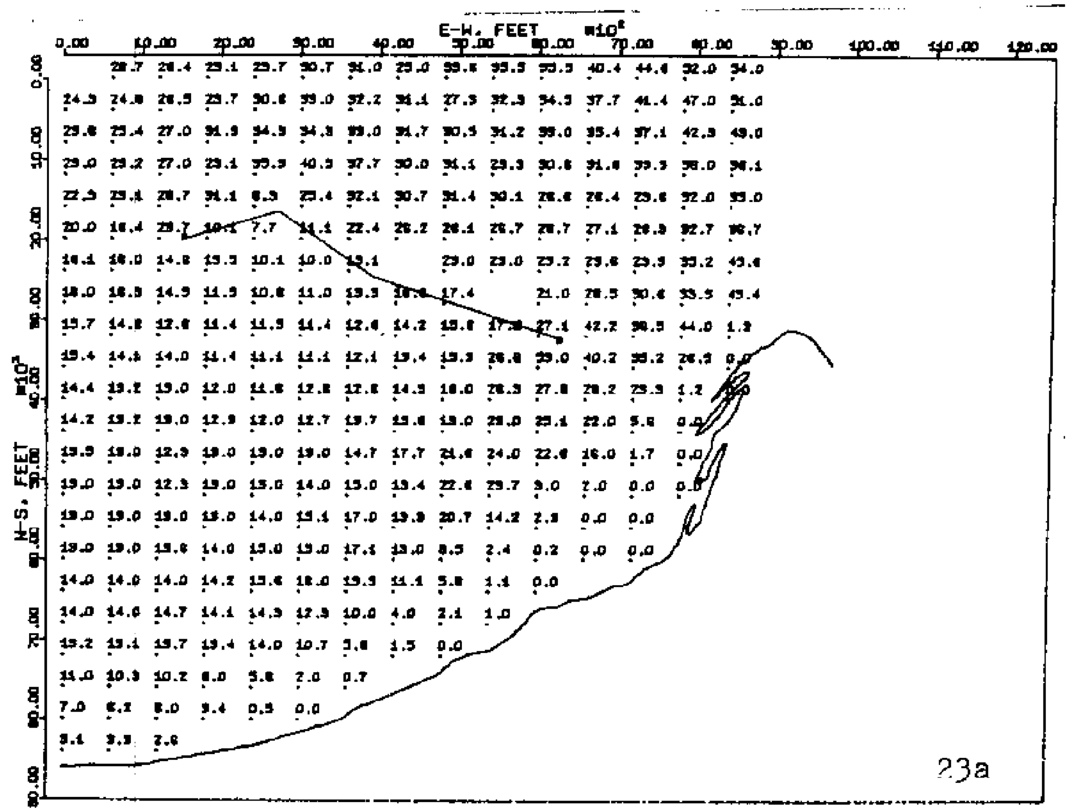
23a. 1913 Depths in Feet. Interpolated depths are from 1913 data. Depths are plotted every 400 feet (120 m) north-south and every 600 feet (180 m) east-west. Depth positions are located to the lower left of the numbers.

23b. 1913-1929 Depth Change. Depth change values were calculated from the interpolated data in Figure 16e and 16d. Negative values indicate erosion. The shorelines are labeled in Figure 23d.

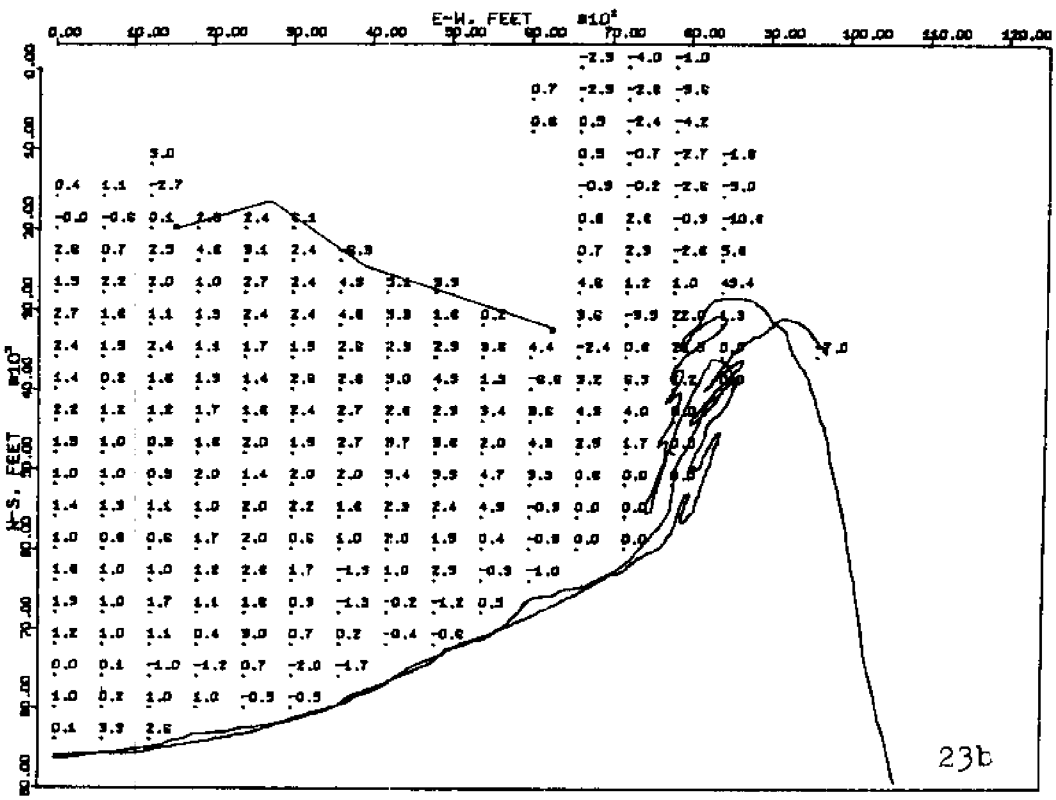
Page 103

23c. 1913-1929 Shoaling Rates (feet/year). Shoaling rates are calculated from Figure 23b, by dividing each value by 16 years.

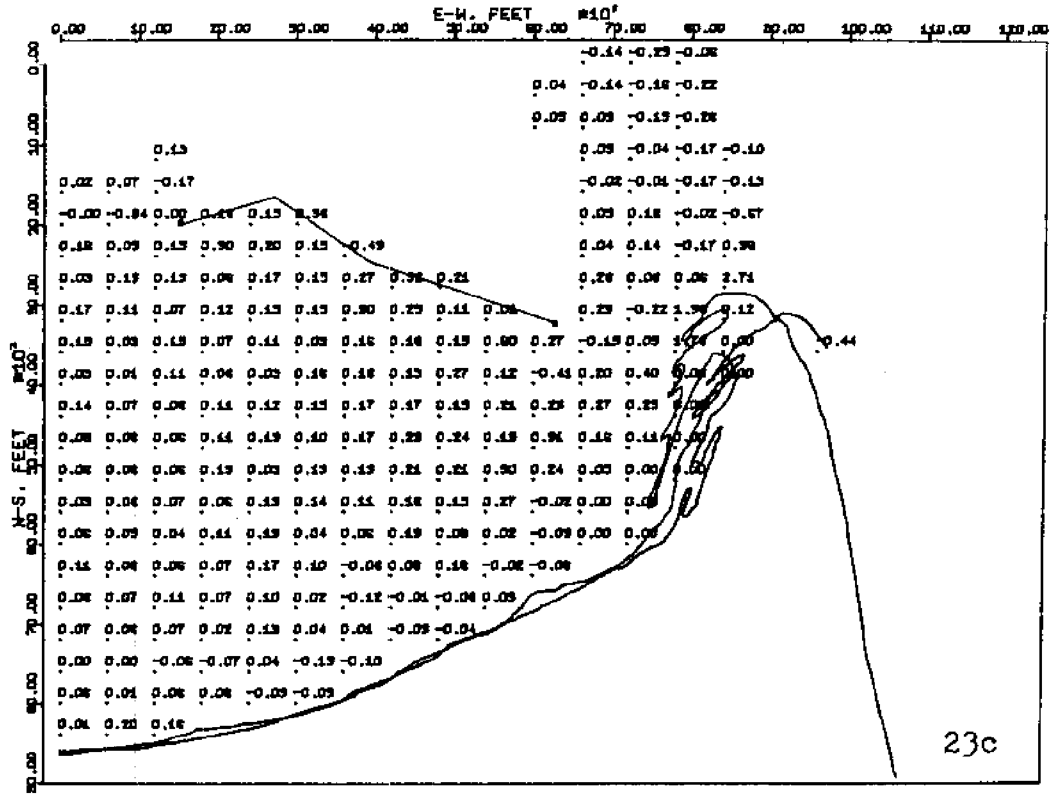
23d. 1913-1929 Shoaling Rates Contour Map. The data in Figure 23c were hand-contoured to produce this map. The "slashing" shows where the land remained above mean high water throughout the survey interval. The "slashing" does not follow one shoreline.



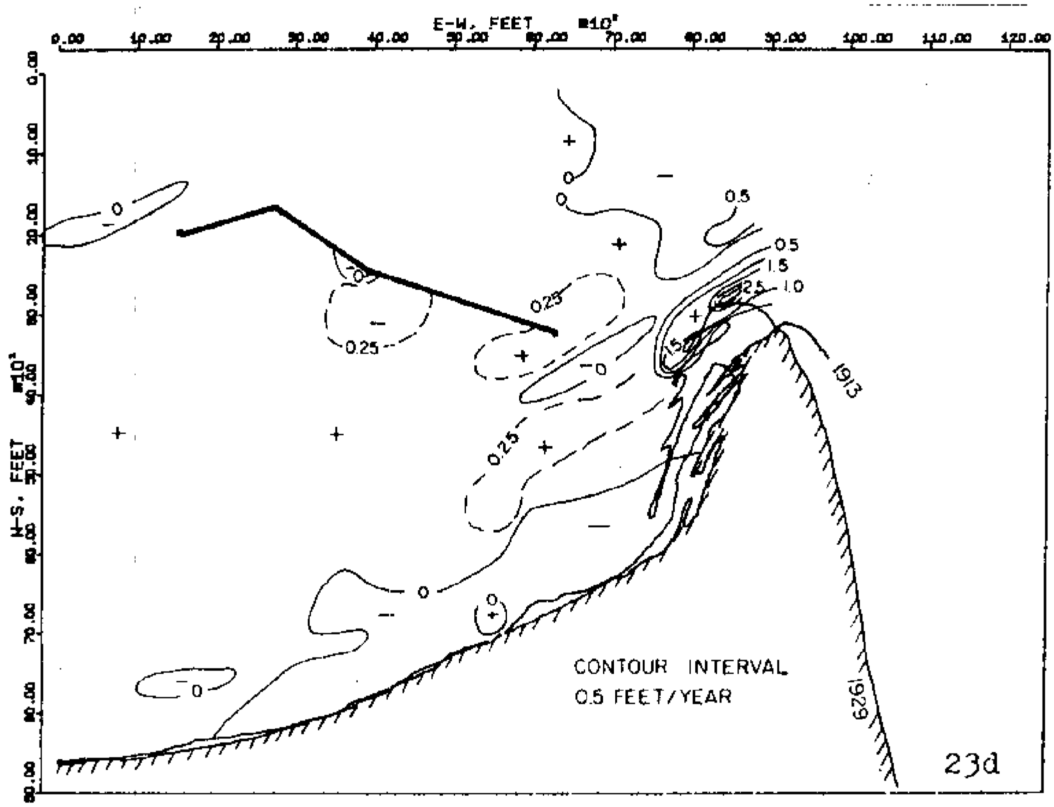
1913 DEPTHS IN FEET (ORIGINAL DATUM)



1913-1929 DEPTH CHANGE (FT, ORIG DTM)



1913-1929 SHOALING RATES (FT/YR, ORIG DTM)



1913-1929 SHOALING RATES CONTOUR MAP

Summary for 1883 to 1929

During the interval 1883 to 1929 marine processes produced net deposition in most areas and erosion in the channel between the inner breakwater and the cape (Figure 20). Although from 1883 to 1929 significant deposition in the central areas of the harbor occurred, one can see that actually there was major deposition from 1883 to 1894, followed by erosion from 1894 to 1913, followed by deposition from 1913 to 1929 (Figures 21-23). It is suggested that the actual initiation of the deposition took place in the late 1880s with the construction of the center section of the inner breakwater and that the initiation of the period of erosion was around the turn of the century with the construction of the outer breakwater.

Deposition of sediments associated with spit growth occurred in localized areas immediately to the north of the cape, with very high sedimentation rates. Commonly, just north of this depositional center, an erosional channel was present. The center of deposition associated with the tip of the cape migrated considerably from survey interval to survey interval, with the net depositional center being seaward of the spit tip (Figure 20d).

The tip of Cape Henlopen showed net growth toward the northwest, while actually it migrated to the west, then migrated to the north, then migrated to the northwest (Figures 21d, 22d, and 23d).

It appears that the net result of changes in bathymetry and shorelines from 1883 to 1929 was simple. However, the short-term changes were quite complex, as a result of storms and construction projects. This analysis should caution workers in coastal areas who would predict long-term trends (50 years) on the basis of short-term studies (as long as 10 years), without fully evaluating man's effects and the effects of abnormal or unusual climatic conditions.

1929 to 1945 (Figure 24)

Depths for the central area of the harbor were around 11 to 14 feet (3.4 to 4.3 m), with depths off the tip of the cape around 30 to 40 feet. To the east of the cape the depths were 10 to 20 feet (3 to 6 m).

Depth changes were on the order of 2 to 4 feet (0.6 to 1.2 m) in the central areas of the harbor and less than one foot (0.3 m) near the southern side of the breakwater. Depth changes in the vicinity of the spit tip were around 40 feet (12.2 m), with erosion of 10 feet (3 m) or more north of the depositional area. Offshore, to the east, the depth changes were mostly negative.

The shoaling rates maps show general deposition in the harbor, except along the south shore where some local erosion occurred. Off the tip of the cape, most of the area was depositional, and very little eroded similar to that seen before, in the channel between the inner breakwater and the cape. General deposition occurred during this interval, except in a small area of the channel between the outer breakwater and the cape.

Shoaling rates ranged from 0.1 to 0.25 feet/year (3 to 9 cm/yr) in the harbor and increased to as high as 2.5 feet/year (80 cm/yr) off the spit tip. The average shoaling rate for the harbor was 0.19 feet/year (5.8 cm/yr).

The depositional area associated with the cape had two centers. One was located just off the spit tip, while the other was about 1700 feet (500 m) to the east of the spit tip. Very little coastal erosion occurred on the Atlantic side of the cape, and the cape grew northward about 800 feet (240 m). The bay shoreline changed little in position during this interval.

Figure 24 (pages 109 and 110)

Page 109

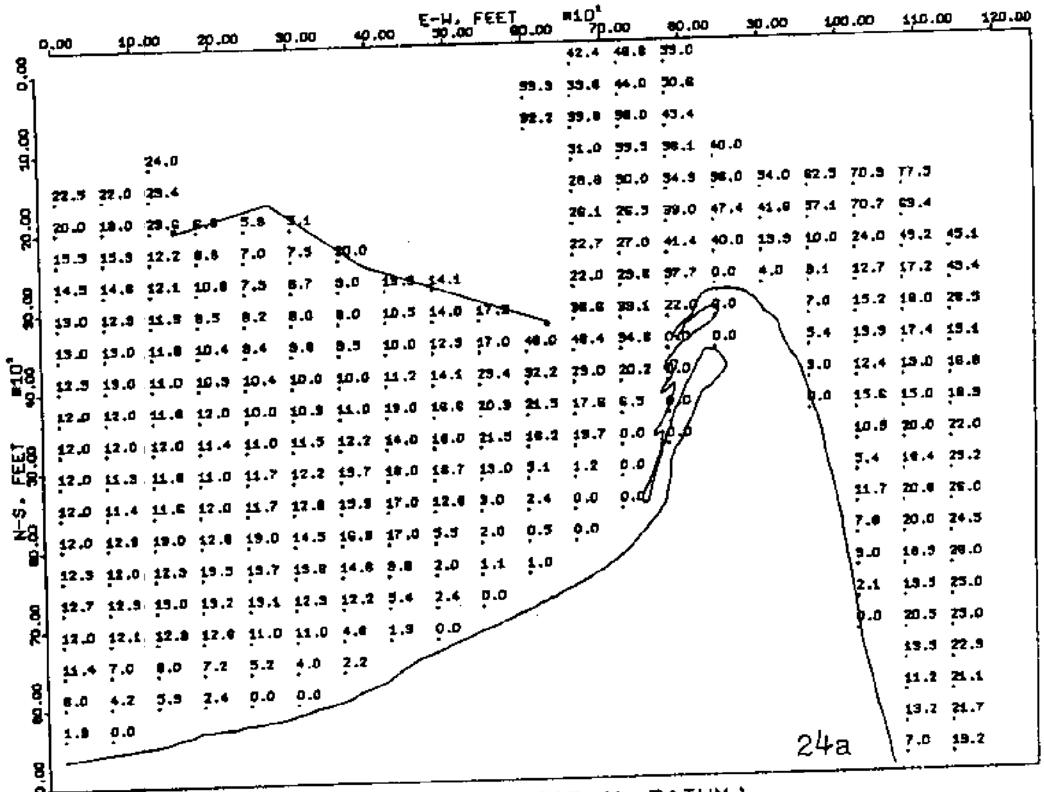
24a. 1929 Depths in Feet. Interpolated depths are from 1929 data. Depths are plotted every 400 feet (120 m) north-south and every 600 feet (180 m) east-west. Depth positions are located to the lower left of the numbers.

24b. 1929-1945 Depth Change. Depth change values are calculated from the interpolated data in Figure 16d and 16c. Negative values indicate erosion. The shorelines are labeled in Figure 24d.

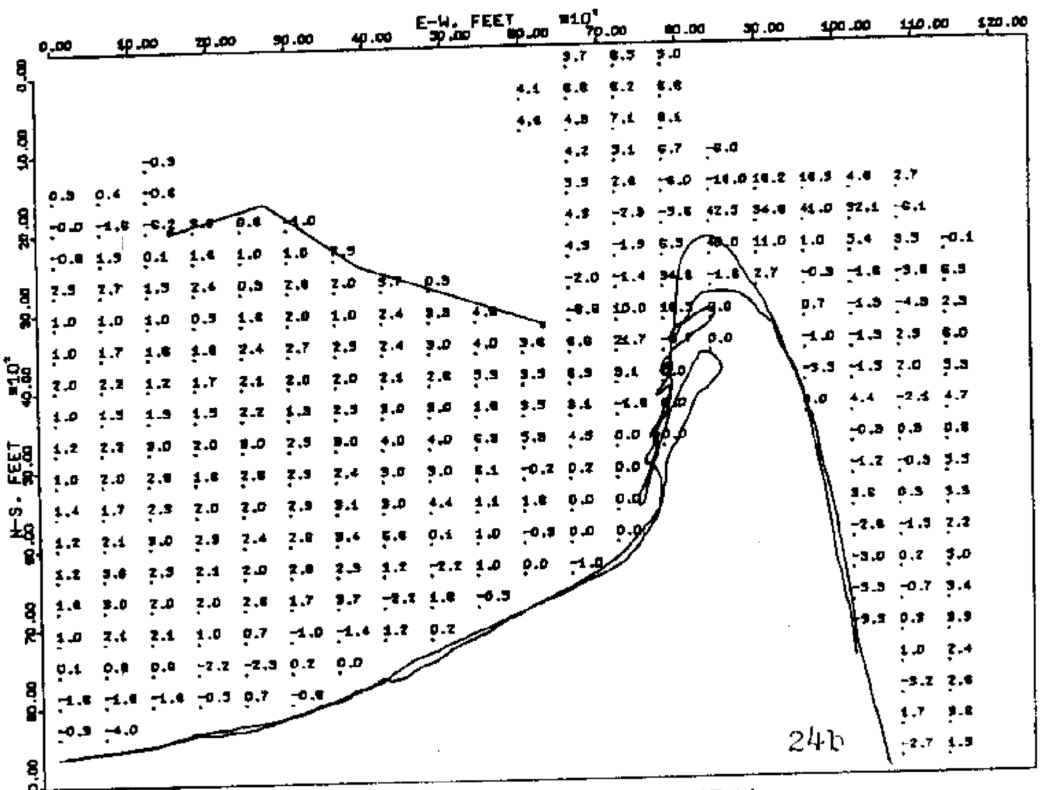
Page 110

24c. 1929-1945 Shoaling Rates (feet/year). Shoaling rates are calculated from Figure 24b, by dividing each value by 16 years.

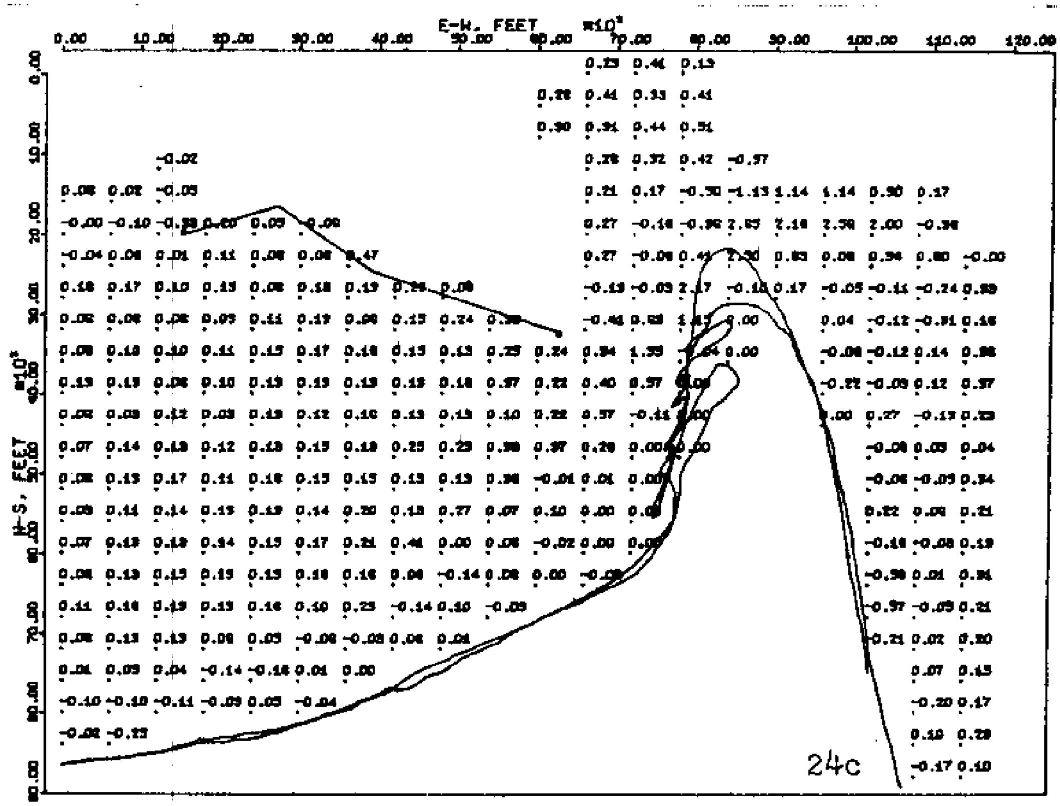
24d. 1929-1945 Shoaling Rates Contour Map. The data in Figure 24c were hand-contoured to produce the map. The "slashing" shows where the land remained above mean high water throughout the survey interval. The "slashing" does not follow one shoreline.



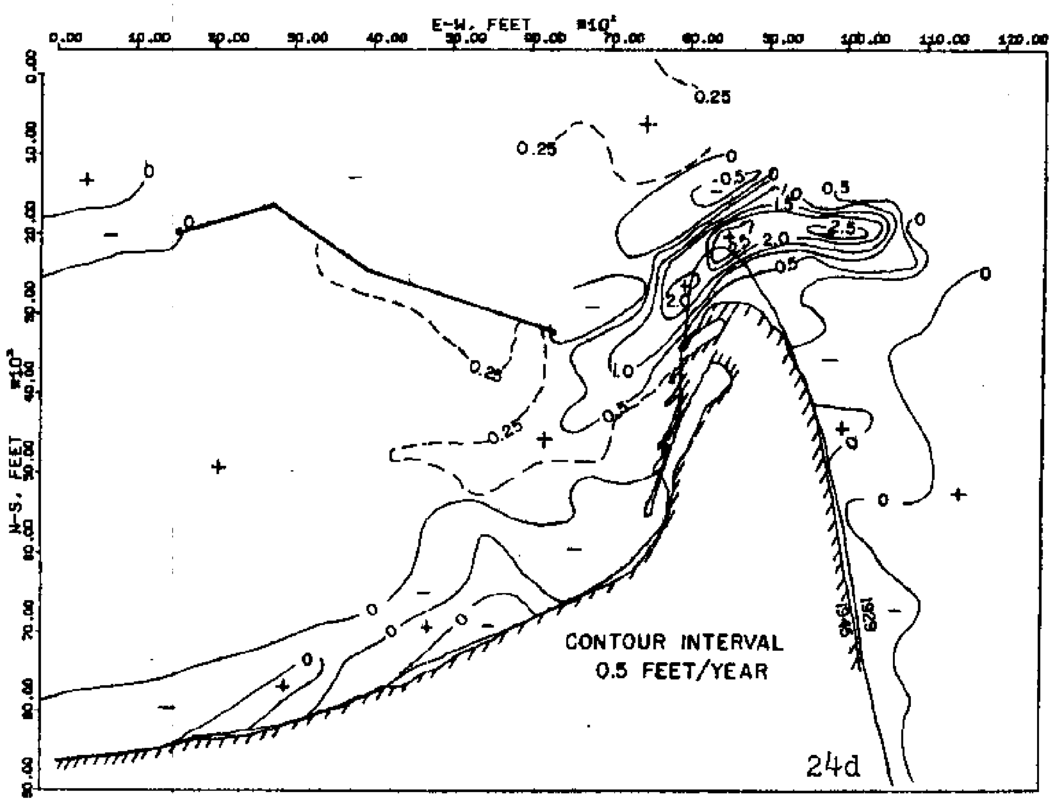
1929 DEPTHS IN FEET (ØRIGINAL DATUM)



1929-1945 DEPTH CHANGE (FT, ØRIG DTM)



1929-1945 SHOALING RATES (FT/YR, ORIG DTM)



1929-1945 SHOALING RATES CONTOUR MAP

1945 to 1971 (Figure 25)

In 1964, the ferry terminal jetty was built on the harbor shoreline. The most recent shoreline plotted on these maps is the 1977 shoreline, while the most recent bathymetric data are valid for 1971.

The depths for 1945 were 7 to 11 feet (2.1 to 3.4 m) in the central areas of the harbor and as much as 45 feet (13.7 m) in the channel between the inner breakwater and the cape. Depths to the north of the spit tip were 30 to 40 feet (9.1 to 12.2 m), and depths offshore were greater than 70 feet (21.3 m) to the northeast of the cape and 15 to 20 feet (4.6 to 6.1 m) to the southeast of the cape.

Depth changes were around -1.0 feet (-0.3 m) between the ferry jetty and the west end of the breakwater and 1 to 6 feet (0.3 to 1.8 m) in the more easterly parts of the central harbor. Depth changes in the channel between the inner breakwater and the cape show erosion of -9.6 feet (-2.9 m) to deposition of over 20 feet (6 m). Depth changes in the area of new cape growth were on the order of 30-40 feet (9-12 m). This depositional center extended east of the spit tip about 3000 feet (900 m).

The shoaling rates contour map shows considerable deposition over much of the area with some erosion in the western harbor and to the north of the 1977 position of the cape. Alternating zones of deposition and erosion occurred on the Atlantic side of the cape. Shoaling rates as high as 2.1 feet/year (64 cm/yr) were present in the vicinity of the cape and erosion rates as high as -0.4 feet/year (12 cm/yr) were found to the north of the present position of the cape. The average shoaling rate between 1945 and 1971 for the harbor was 0.04 feet/year (1.2 cm/yr).

Cape Henlopen grew to the north-northwest by 1800 feet (550 m). The Atlantic coast eroded by about 200 feet (60 m), and the harbor shoreline east of the inner breakwater showed about the same amount of erosion. The southern shoreline of the harbor eroded in the eastern section and accreted in the western section less than 10 feet (30 m).

Figure 25 (pages 114 and 115)

Page 114

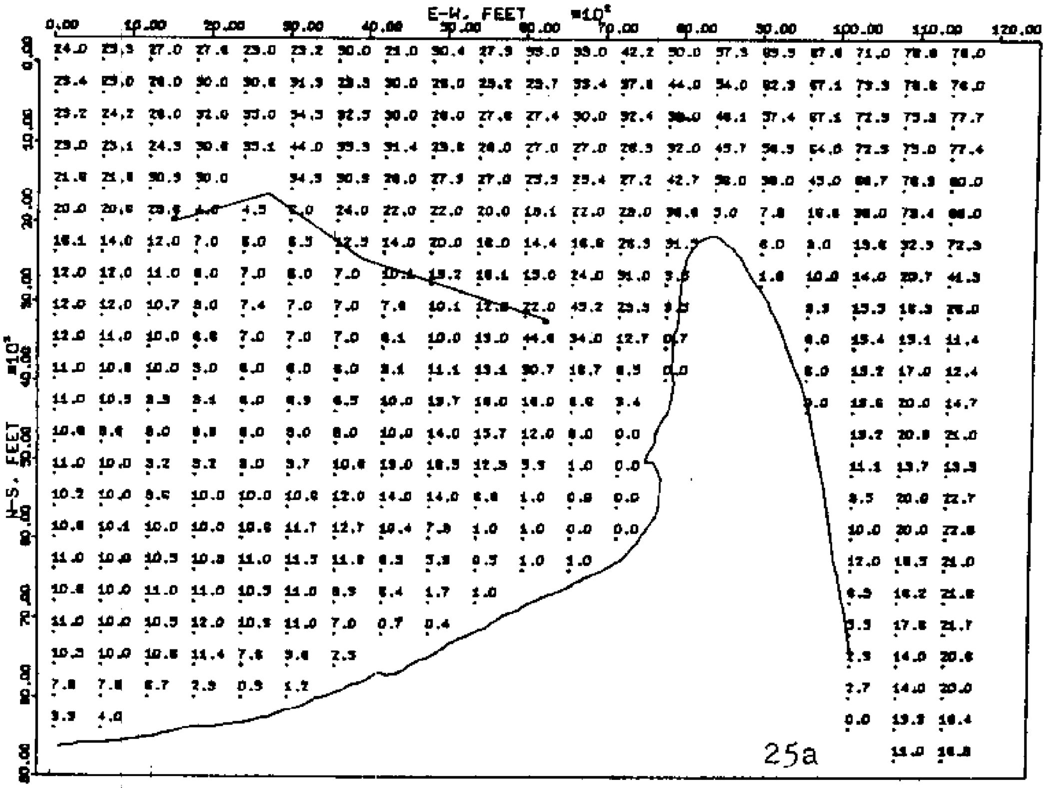
25a. 1945 Depths in Feet. Interpolated depths are from 1945 data. Depths are plotted every 400 feet (120 m) north-south and every 600 feet (180 m) east-west. Depth positions are located to the lower left of the numbers.

25b. 1945-1971 Depth Change. Depth change values are calculated from the interpolated data in Figure 16c and 16b. Negative values indicate erosion. The shorelines are labeled in Figure 25d.

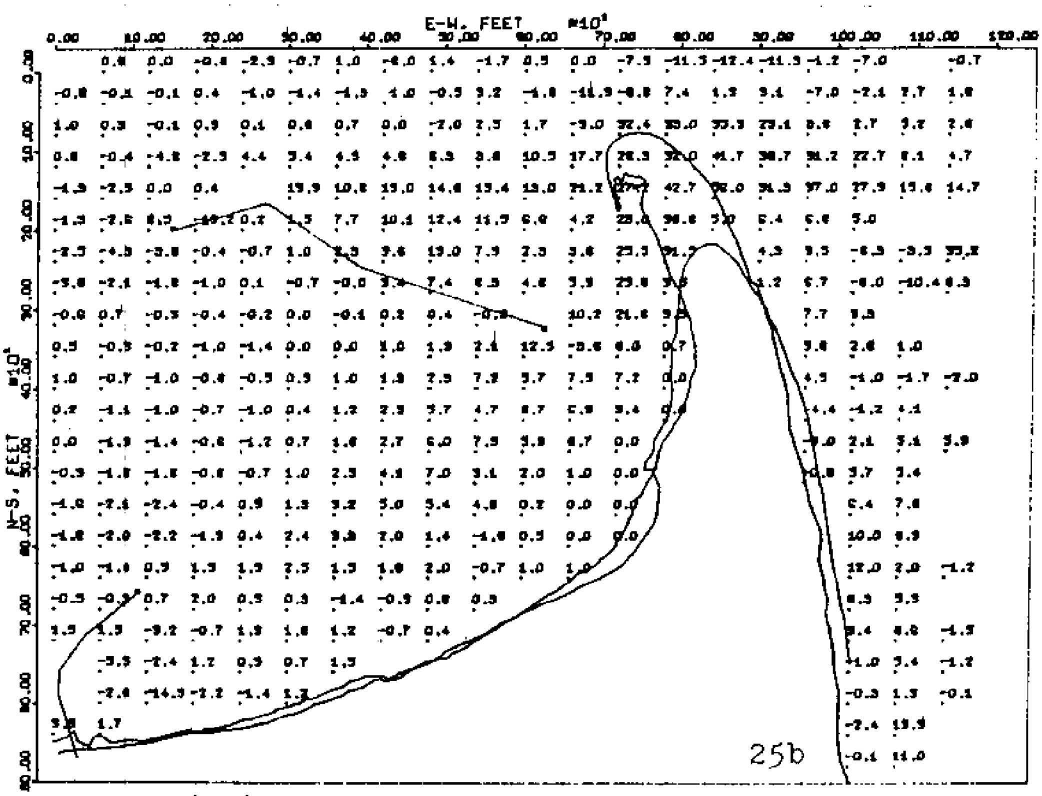
Page 115

25c. 1945-1971 Shoaling Rates (feet/year). Shoaling rates are calculated from Figure 25b, by dividing each value by 26 years.

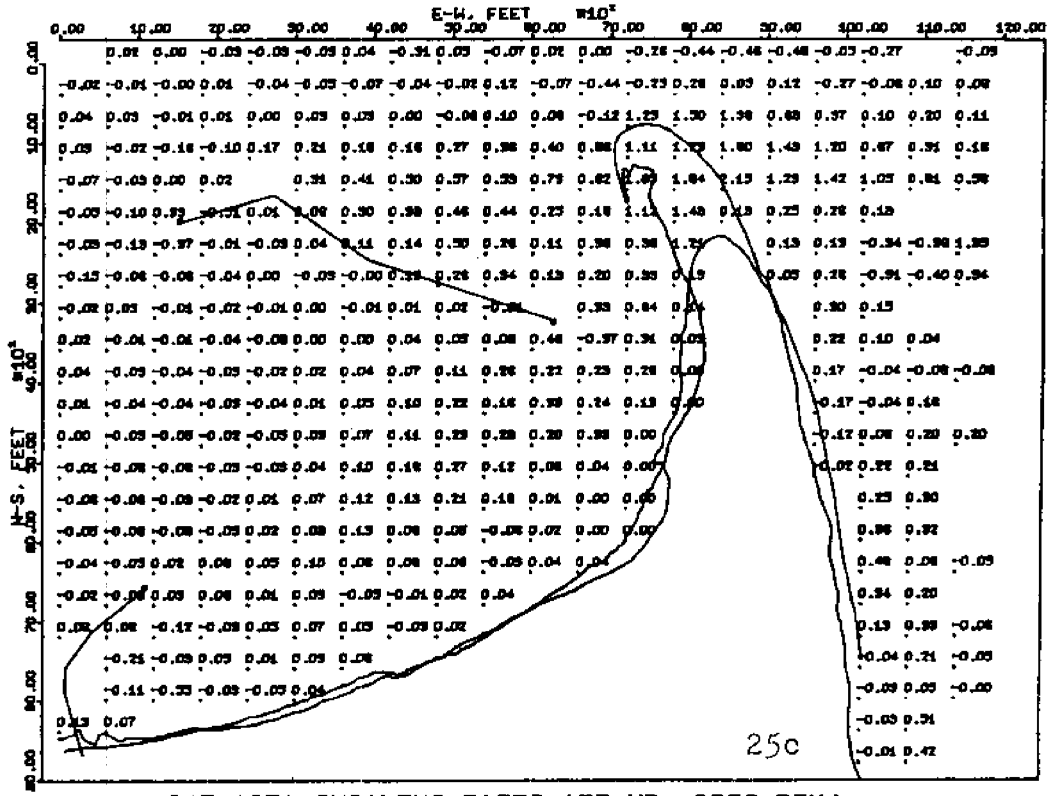
25d. 1945-1971 Shoaling Rates Contour Map. The data in Figure 25c were hand-contoured to produce this map. The "slashing" shows where the land remained above mean high water throughout the survey interval. The "slashing" <u>does not</u> follow one shoreline.



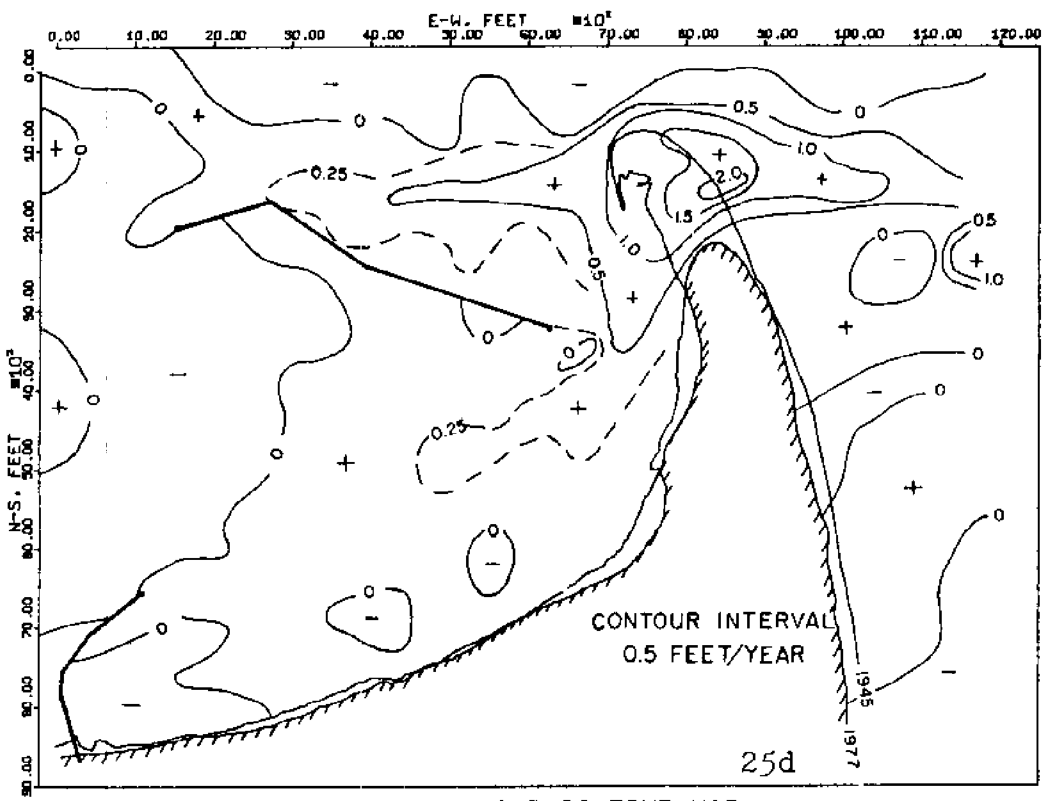
1945 DEPTHS IN FEET (ORIGINAL DATUM)



1945-1971 DEPTH CHANGE (FT, ORIG DTM)



1945-1971 SHOALING RATES (FT/YR, ORIG DTM)



1945-1971 SHOALING RATES CONTOUR MAP

1971 Depths (Figure 26)

The latest bathymetric survey was done in 1971. The first published chart to show all the 1971 data is the 1977 NOS chart 12216. The depths in Breakwater Harbor ranged from 4 to 10 feet (1.2 to 3.0 m). The scour hole off the east end of the inner breakwater was about 50 feet (15 m) deep. Depths in the central harbor were progressively shallower from south to north. Depths in the channel north of the cape ranged from 30 feet (9 m) to the northwest to over 70 feet (21 m) to the northeast of the cape.

A shoal was present on the west side of the spit tip, between the inner breakwater and the cape. Other survey charts show shoaling on the ebb-tidal-lee side of the inner breakwater. In addition, it is separated from the cape by a 30-foot deep channel (Figure 4), that has become deeper according to a comparison of the 1975 published chart with that of 1977. As discussed earlier the exact date for which the 1975 depths were valid is unknown, except that it is earlier than that on the 1977 edition.

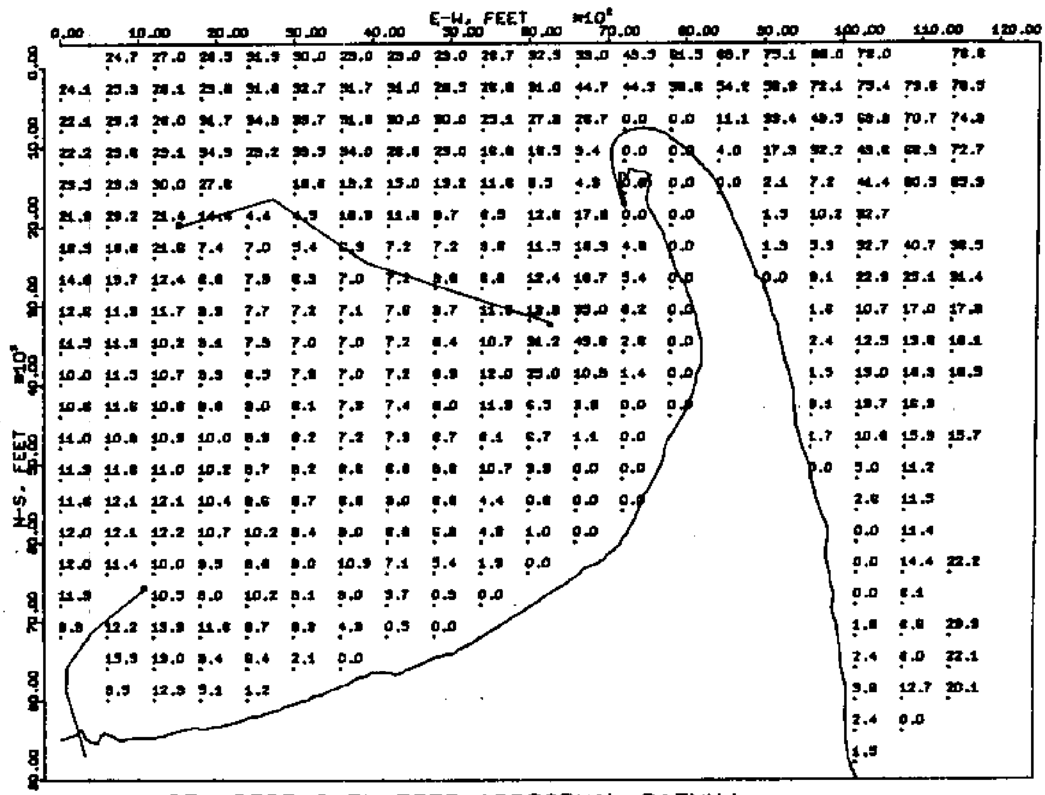


Figure 26 - 1971 Depths in Feet. Interpolated depths are from 1971 data. Depths are plotted every 400 feet (120 m) north-south and every 600 feet (180 m) east-west. Depth positions are located to the lower left of the numbers.

Summary 1842 to 1971

Figure 27 plots calculated parameters against time to summarize the area changes. From 1842-1971, Breakwater Harbor filled in by 6 to 40 feet (1.8 to 12.2 m). This represents an average shoaling rate of 0.05 to 0.31 feet/year (1.5 to 9.4 cm/yr), or corrected for sea level rise (as outline earlier) 7.3 to 41.3 feet (2.3 to 12.6 m) of infill, and shoaling rates of 0.06 to 0.32 feet/year (1.8 to 9.8 cm/yr). The average rate of infill was 0.11 ft/yr (3.4 cm/yr). The maximum average shoaling rate for Breakwater Harbor occurred from 1929 to 1945 with a rate of 0.19 feet/year (5.8 cm/yr), this was a total change in depth of about 4.0 feet for the 20 years from 1863 to 1883, averaged over the area of the harbor. The slowest shoaling rate was from 1842 to 1863, when slight erosion actually occurred when rates were averaged of the area of the harbor.

Shoaling rates increased from 1842 to 1883, and decreased from 1883 to 1894. From 1894 to 1913, slow sedimentation again occurred with a gradual increase in the rate in the following two survey intervals. The slowest shoaling rates correlate well with the times of construction of breakwaters. The latest survey interval agains shows a slowing in the rate of shoaling.

Cape Henlopen grew toward the northwest from 1842 to 1971, at an average rate of about 30 feet/year (9 m/yr). In addition, the tip of Cape Henlopen migrated westward almost 3000 feet (900 m). The northward component of growth varied from -20 to 50 feet/year (-6 to 15 m/yr), while the westward migration rate of the tip of the cape ranged from 0 to 50 feet/year (0 to 15 m/yr). The maximum westward migration rate occurred from 1913 to 1929, while the minimum rate occurred from 1894 to 1913. The minimum northward migration rate was from 1883 to 1914, and the maximum was from 1929 to 1971 (it was constant for two survey intervals).

All the rates and depth changes just described were averages over a survey interval, and in the case of Breakwater Harbor rates, they were also averaged over the area of the harbor. Rates at any instant could have been greater or less than the average for the interval. These short-term potential variations are unknown.

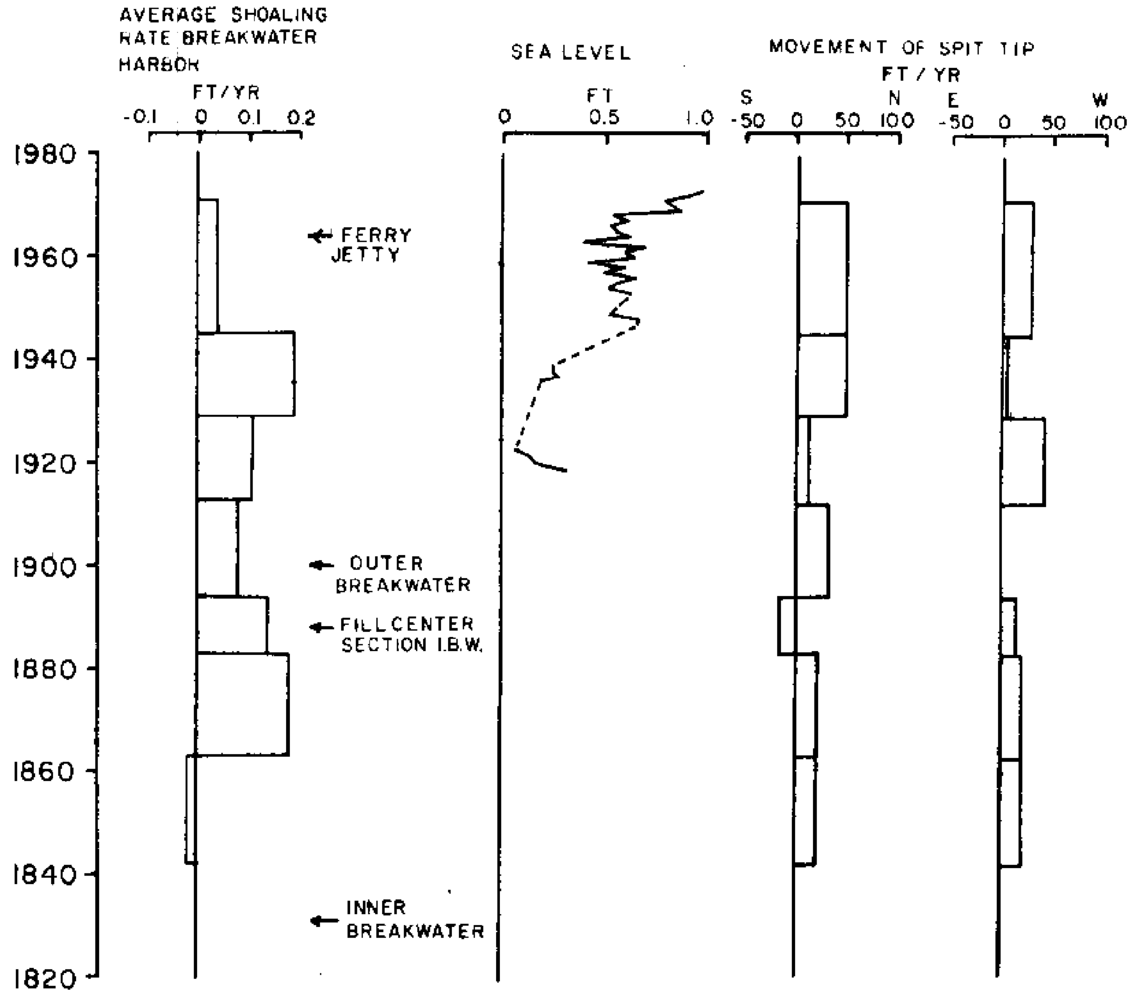


Figure 27 - Time vs. Breakwater Harbor average shoaling rate, sea level from tide measurements, movement of spit tip. The average shoaling rate for Breakwater Harbor is calculated by averaging all the shoaling rates south of the inner breakwater and between the cape and the western edge of the study area. The area of the harbor changes as a result of spit growth. The tip of the cape is defined as the most northerly point of the shoreline at any time. The dates of construction of the breakwaters and ferry jetty are also shown.

Discussion

The growth of Cape Henlopen toward the northwest over the last 129 years has caused general deposition in much of the area of study. This has been a general response to decreased tidal flow because of narrowed channels and growth of Cape Henlopen. Breakwater construction in 1831 and 1900 also caused decreased tidal flow, in a catastrophic manner. As a result, in the survey intervals following the construction of a breakwater, a temporary halt in deposition occurred reversing the normal trend toward deposition. The actual duration of this erosional period was not determined for lack of more frequent data. The construction of the center section of the inner breakwater showed a similar reversal of the depositional trend, but it was not nearly as widespread as those caused by the breakwater construction projects. The western part of Breakwater Harbor has undergone similar erosion, seen on the 1945-1971 maps, as a result of the construction of the ferry jetty in 1964.

Two sources of sediment for the study area are littoral transport along the Atlantic coast of Delaware and Delaware Bay sediment settling from suspension. The littoral transport system along the shore of Delaware Bay supplies some sediment but not nearly as much as the other sources.

The Atlantic coast littoral transport system was the largest sediment source and supplied all the material which makes up Cape Henlopen, as well as much of the sediment in other parts of the study area. Hen and Chickens Shoal was supplied by the tidal redistribution of some of these littoral sediments. Littoral transport is presently supplying material for further spit growth and for tidal flat progradation southward along the harbor shoreline.

Delaware Bay suspended sediment was responsible for the filling of Breakwater Harbor but added little to other parts of the study area. The actual location in which a particle of sediment was "permanently" deposited was determined to a large extent by the tidal currents of the area.

One of the important aspects of this study is the determination of whether or not a "spit platform," as described by Meistrell (1972), was developed at any time during the study period. Meistrell (1972) stated: (1) a spit platform is a "prerequisite to spit growth"; (2) it is a depositional feature; and (3) it is morphologically an embankment. When looking for a spit platform, one must use the bathymetric charts, not shoaling rates or depth change diagrams. Figure 28 is a plot of north-south profiles off the tip of Cape Henlopen for each of the surveys indicated. These profiles show little evidence of an accretional spit platform. Instead, the cape has prograded with a steep leading edge extending from about the low tide line to the floor of the channel being filled. Occasionally, a "platform-like" feature appears off the spit tip, just below the low tide, but this feature is ephemeral only present after storms and commonly in winter (E. Maurmeyer and J. C. Kraft, personal communications, 1977). This feature is, therefore, an erosional "bench" caused by wave attack at the spit tip during northeast storms.

Cape Henlopen is evidence that a spit platform is not a prerequisite for spit growth. Spits can grow into a deep channel in spite of strong tidal currents without the development of an accretional spit platform. Thus, spit platforms may in fact be a common feature of spits, but they are not essential for spit growth.

Figure 29 shows the relationship between 1842 depths and the average shoaling rates calculated for all points between 1842 and 1971. The line labeled "Maximum Possible Shoaling Rates" is a mathematical construction, produced by dividing any depth by the 129 years of the survey interval. This line represents the maximum shoaling rate that can occur, assuming any depth fills to sea level during the 129

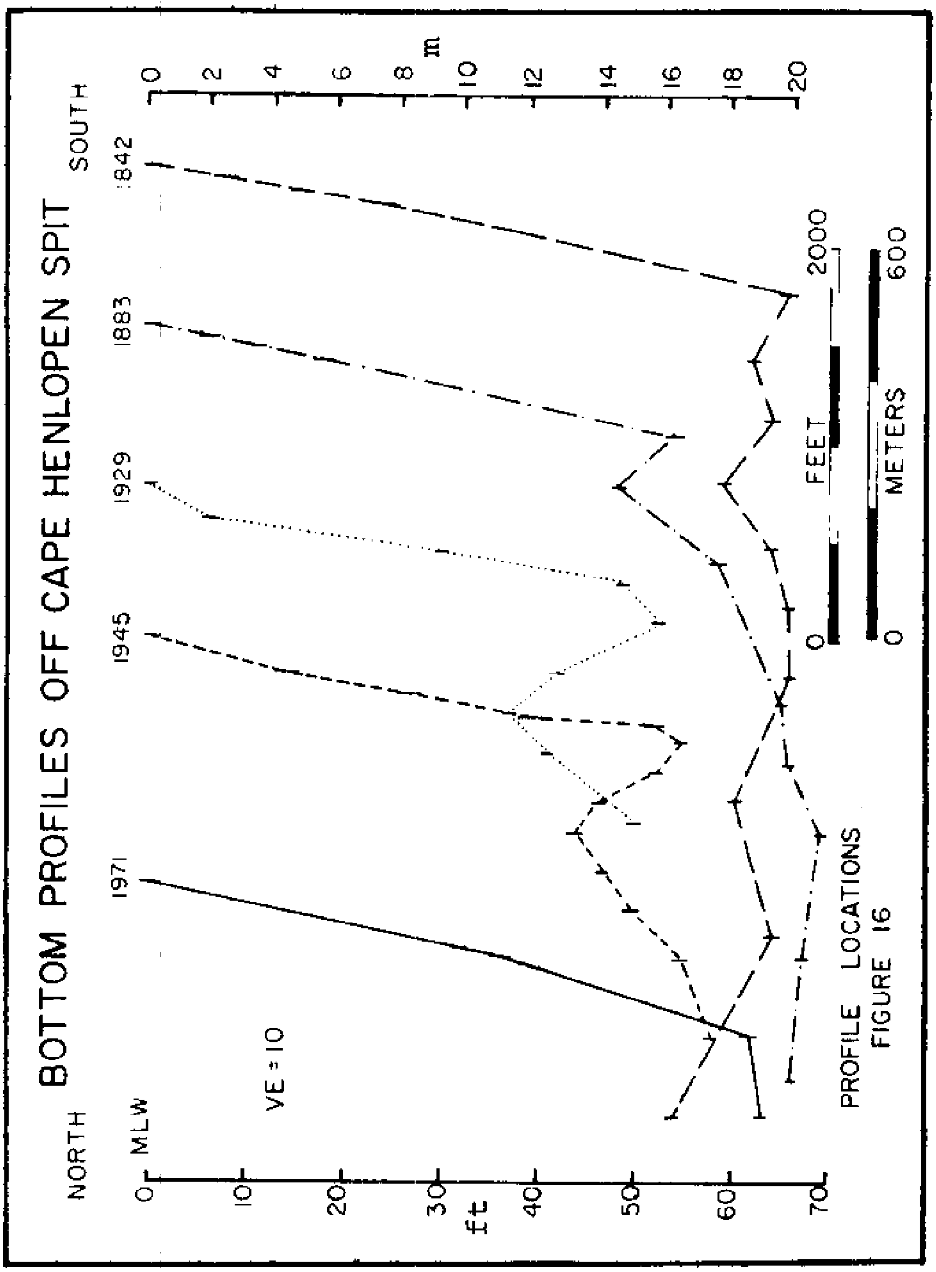


Figure 28 - North-south profiles off the tip of Cape Henlopen for the indicated years. Profiles are plotted from the original survey data and migrate with the position of the spit tip. Profile locations are plotted in Figure 16a. None of the profiles show evidence of Spit-platform development.

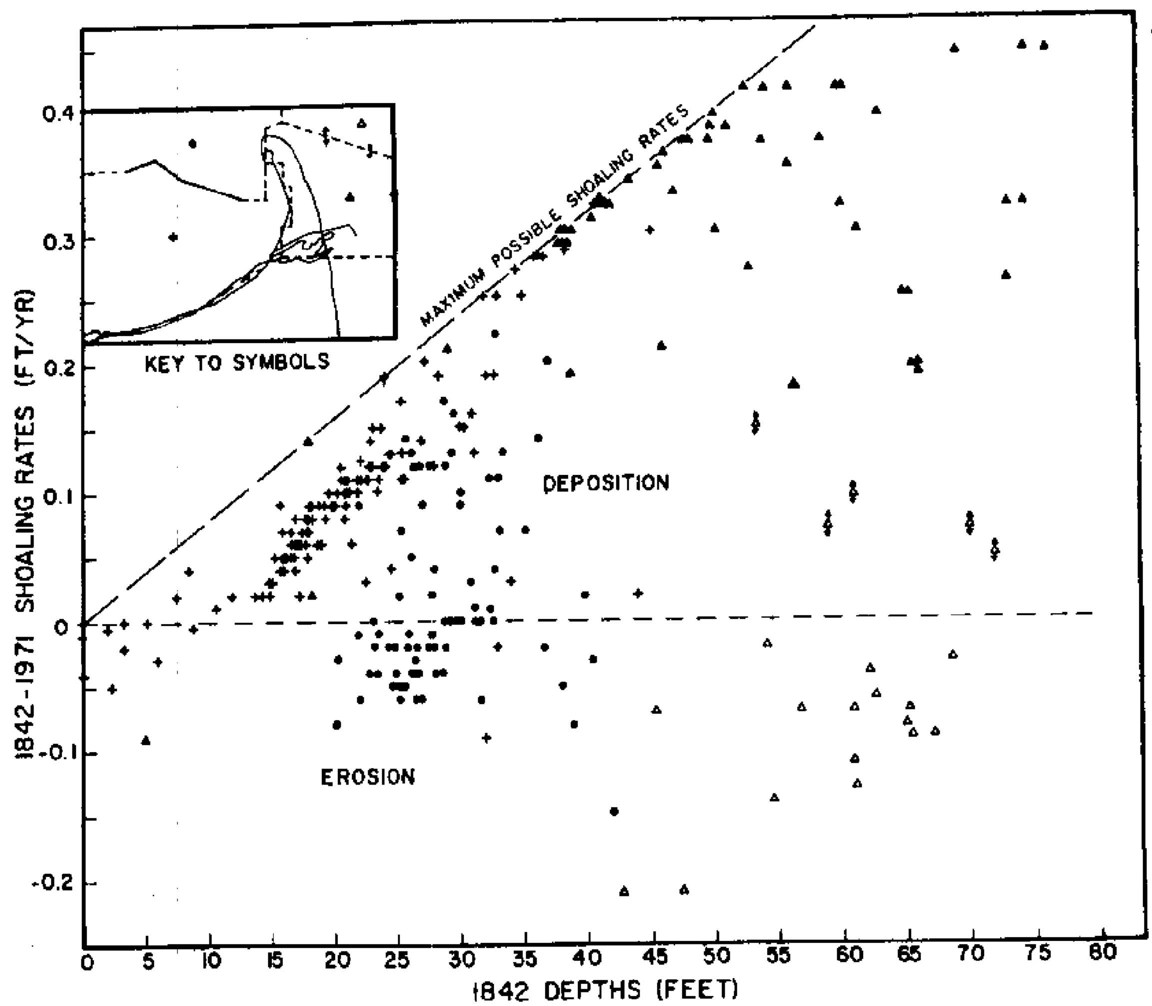


Figure 29 - 1842-1971 Shoaling Rates vs. 1842 Depths. The four sections of the study area indicated in the upper left of the diagram are plotted using different symbols. The only area which shows a consistent relationship between shoaling rate and depth is Breakwater Harbor. The significance of this relationship is discussed in the text. The "Maximum Possible Shoaling Rates" line is a mathematical construction produced by dividing any depth by the 129 years of the survey interval.

years of the study.

No relationship between original depth and average shoaling rate is present, except in Breakwater Harbor. All areas except Breakwater Harbor are strongly affected by storm conditions and, therefore, would be considerably more complex in patterns of deposition and erosion than the protected area of the harbor. The trend of the plus signs (Breakwater Harbor data) is subparallel to the maximum possible shoaling rates line and 'therefore' shows a consistent trend toward higher shoaling rates with increased original depths. Similar plots for other shorter survey intervals showed much less correlation indicating the complex nature of this general trend when details of the process are examined.

These data, coupled with the fine grained nature of the sediment, suggest that over the long term the harbor area has filled as a result of sediment settling from suspension to an equilibrium depth determined by the amount of tidal flow. This equilibrium depth has continually decreased with the growth of the cape toward the northwest and therefore, there has been deposition of substantial amounts of sediment.

A large depositional center associated with the tip of the cape has consistently been present on the shoaling rates contour maps. The position of this depositional center is attributed to the redistribution of littoral sediments by tidal currents and the progradation of the spit as described earlier. Due to the dominants of ebb tides, on the average, the center has been shifted toward the east of the spit tip. However, since it is likely that the sedimentation in the area of the spit tip has been strongly dominated by storm transport of sediment, it is also likely that the short-term position of this center during a particular survey interval has been determined by the timing of storms with respect to tidal currents.

If, during a survey interval, the major amount of sediment was transport in the littoral system during storm conditions on a flooding tide, it is likely that the depositional center was shifted toward the west for that interval. In addition, wind stress could have caused significant variation from the norm for tidal currents. (The fastest current recorded for current meter Station 2, between the inner breakwater and the cape, was during a flood tide.) As a result of these factors, the position of the depositional center at any time is dependent on complex factors, including the timing between tidal cycles and storm conditions, and is, therefore, variable. Over the long term (120 years) the position of the major deposition associated with cape growth was to the east of the growth axis, showing a long-term dominance of ebb tidal transport of littorally supplied sediments.

The depositional feature called Hen and Chickens Shoal is similar to an ebb-tidal delta commonly associated with tidal inlets (Hayes and Kana, 1976). This feature again attests to the strong ebb dominance of the tidal currents of the area. The ebb dominance that was measured in the harbor is probably exaggerated as a result of the geometry of the cape and inner breakwater. The funnel-shape of the harbor and the sharp bend that is made at its eastern end cause a concentration of ebb tides and a diminishment of flood tides through the harbor. Since this affect will have increased with time as a result of cape growth, it is likely that some of the sediments that are now carried around the spit tip onto Hen and Chickens Shoal may have been carried into the harbor in the past. This possibility can be tested stratigraphically, and would also be a good basis from which to calculate volumes of sediment deposited, since sediment deposited by different mechanisms could be handled separately.

It is important to determine the relationship between bathymetric change and sediment type. It is inferred that areas which showed rapid shoaling rates during a survey interval received coarser sediments from the littoral drift system along the Atlantic coast, while areas which showed slower rates received sediment from either littoral transport systems or suspension. Sediment deposition in rapidly filling areas (greater than about 0.5 feet/year [15 cm/yr]) is probably not caused by a response toward equilibrium between the bottom and tidal flow, but rather the result of insufficient tidal or wave energy to continue transporting the sediment. This is the case in Cape Henlopen and explains how the spit tip can continue to grow despite the strong tidal currents. Although energy conditions off the spit tip seem quite high, the energy is not sufficient to transport all the sediment, supplied by littoral transport around the spit tip into the tidal flat. A large amount of sediment but not all the sediment supplied to the cape area is transported onto the tidal flat and onto Hen and Chickens Shoal. Cape growth causes a change in the equilibrium conditions of the rest of the area and, therefore, is the cause of significant deposition both from suspension and from littoral transport.

Sediment settling from suspension is deposited during low-flow conditions of the tidal cycle, and on the average only the material required to maintain equilibrium as a result of decreased tidal flow remains behind. It is difficult to evaluate the exact timing of this process because of the complex variables involved 1) in tidal fluctuations and currents; 2) in storm conditions, and

3) in the complexities of resuspension of sediments, especially fine grained sediments and the relative importance of flocculation.

These results indicate that the prediction of future trends or the determination of past trends on the basis of short-term studies of conditions and processes will determine only the short-term tendencies for change. The actual change which will occur in the coastal area is dependent on long-term tendencies and short-term random processes of storms. Detailed bathymetric analysis shows many trends of a general nature that can be explained on the basis of "uniformitarian" arguments, but the details of many of these changes are catastrophic in nature due to random processes of climate and morphologic change. Man's influences can be evaluated and predicted only in a general way with emphasis on the long-term tendencies.

Volume Calculations

The volume of material deposited during any given survey interval is important for the calculation of sediment budgets and for the determination of dredging costs. However, since the volume calculated is inevitably dependent on the area over which it is calculated, and since the area for which data were available changed from survey interval to survey interval, volumes were not used in this analysis.

In addition, the volumes for any given area will not give any more information about the shoaling history than the shoaling rates diagram. If one prefers to think in terms of volumes, Table 1 gives the conversion of shoaling rates to volumes. This is possible because the units of shoaling rates in addition to feet/year could be $feet^3/year/feet^2$, by assuming that each of the shoaling rates values are representative of the 200-by-300-foot "box" which contains the value at its center. This area can be multiplied by the shoaling rates value to produce a volume. These volumes can be summed for any area of interest to calculate the total volume/year deposited during any survey interval.

When one is dealing with the volumes of sediment deposited during a survey interval, the material deposited by eolian processes and wave swash must be considered. No topographical data are presented here because they are available only at 10-foot-contour intervals for just a few surveys. At present, detailed topographic data are available for the cape (Belknap, and others, unpublished data), but the use of these data to calculate past volumes deposited above sea level would require assumptions about the topography in the past based on present morphology, coupled with land area changes calculated from the diagrams presented in this report.

SHOALING RATE TO VOLUME CONVERSION TABLE

ft/yr	ft^3/yr	yd^3/yr	m^3/yr
3.5	2.1×10^5	7.7×10^3	5.9×10^3
3.0	1.8×10^5	6.7×10^3	5.1×10^3
2.5	1.5×10^5	5.5×10^3	4.2×10^3
2.0	1.2×10^5	4.4×10^3	3.3×10^3
1.5	0.9×10^5	3.3×10^3	2.5×10^3
1.0	0.6×10^5	2.2×10^3	1.6×10^3
0.5	0.3×10^5	1.1×10^3	0.8×10^3
0.4	2.4×10^4	8.9×10^2	6.8×10^2
0.3	1.8×10^4	6.7×10^2	5.1×10^2
0.2	1.2×10^4	4.4×10^2	3.4×10^2
0.1	0.6×10^4	2.2×10^2	1.6×10^2
0.05	0.3×10^4	1.1×10^2	0.8×10^2
0.03	1.8×10^4	6.7×10^2	5.1×10^2
0.01	0.6×10^3	2.2×10^1	1.6×10^1

Table 1 - These numbers are based on the assumption that the shoaling rates as presented on the maps are representative of the shoaling rates in a 200-by-300 foot rectangle. Each volumetric number is the volume of sediment deposited or eroded (negative the value) in the rectangle containing the shoaling rate. To estimate the volume of sediment deposited in any given area, multiple the number of points in the area by the number of years in the survey interval and by the appropriate number in this table. These are only estimates.

CHAPTER IV

CONCLUSIONS

Tidal Flat Processes

1. The source of sediment on the tidal flat is from the tip of Cape Henlopen, as evidenced by the decrease in elevation and relief, the decrease in mean grain size, and increase in sorting, from north to south. Halsey (1971) suggested the same source based on movement of sand ridges.

2. Sediment size analysis along three profiles on the tidal flat show that the size of the largest particles deposited on the tidal flat is dependent on micro-environment, while the size of the finest particles deposited on the tidal flat is not dependent on micro-environment. The evidence for this conclusion is in the plot of mean grain size plus and minus one standard deviation across the tidal flat.

3. Fining-landward found in one profile on the tidal flat is caused by a decrease in wave energy in the landward direction. Tidal currents on this particular tidal flat

are not strong enough to resuspend the sand which predominates. A detailed understanding of wave refraction and diffraction patterns is necessary to thoroughly understand and quantify the tidal flat dynamics.

4. A theory to explain the movement of and morphology of the sand ridges on the tidal flat is developed from limited data and much observation. This theory can be field tested through extensive measurements.

The reorientation of the sand ridges from coast-parallel to coast-perpendicular is caused by a shift in the dominant transport mechanism in the central part of the tidal flat. In the north, overwash predominates, while in the south littoral transport along the sides of the ridges predominates. The spit-like ridge which first develops by littoral transport near the low tide line at the spit tip, is overwashed during high tides moving the ridge upward and landward on the tidal flat. These ridges are breached in the central area of the tidal flat because the sediment supply is insufficient to maintain them.

Littoral processes in the more southerly part of the tidal flat redistribute the stranded sediments in the central area moving them southeast until they connect to the high tide beach as a coast-perpendicular ridge. Wave diffraction through the inner breakwater-Cape Henlopen gap while the ridges are submerged perpetuates the coast-perpendicular orientation of the ridges in the southern part of the tidal flat. The relative importance of storms is unknown.

5. As a result of the very short duration of wave attack and very low energy of the waves along the high tide shoreline landward of the tidal flat, little sediment is transported during "normal" conditions at high tide. During storm conditions, the higher tides and higher wave energy combine to erode the high tide shoreline. Under normal conditions this sediment is not replaced. As a result, the high tide shoreline on the west side of the cape is undergoing erosion. Analysis of shorelines in the past shows that this erosion on the west side has been substantial, and continuous during the development of Cape Henlopen.

Breakwater Harbor Processes

1. The new technique for the presentation of tidal current data used in this report allows large volumes of data to be presented in a compact straight forward manner. In addition to showing the statistical relationship between the duration of velocities and directions of flow, it also shows the relationship between predicted and measured tidal duration, demonstrating the complexities of the flow patterns resulting from factors not considered in the prediction models.

The current data demonstrates that the duration of the ebb tide is much longer than the duration of flood tide (8 and 4 hours respectively). This is attributed to the normal ebb dominance of the tidal currents in southeastern Delaware Bay and the suppression of flood tides by the "funnel" configuration of the harbor. The current data also demonstrates that the central part of the harbor is affected by wave motions during northwest winds and low flow rates. The mode of the velocities at Station 1 was between 30 and 40 cm/sec at 80° to 100° magnetic, while for Station 2 the mode was 40 to 50 cm/sec at 20° to 40° magnetic. Very little flow through the harbor occurs on flood tide.

2. The source of fine grained material in Breakwater Harbor is from the west, as evidenced by

dominant ebb-tidal currents and the sediment type distributions. Strom (1972) suggests the same source.

3. Sand which is transported off the tidal flat is either 1) carried out of the harbor by the strong ebb tide or 2) deposited just off the edge of the tidal flat as the flood tides are usually too weak to transport tidal flat sediments. Since sediment normally moves off the tidal flat during falling (ebb) tides, very little sediment is transported into the central harbor from the tidal flat. Material which is not transported back around the tip of the cape during ebb tides, after it moves off the tidal flat contributes to the progradation of the tidal flat into the harbor, especially in the southern portions.

4. The trend of coarsening with increased depth found by Oostdam (1971) in Delaware Bay was also observed in Breakwater Harbor when going from the center of Breakwater Harbor into the channel off the east end of the breakwater. This trend suggests that the channels are maintained as a result of strong tidal flow, rather than a lack of sediment supply.

Bathymetric Change and Marine Processes

1. Deposition in Breakwater Harbor has been in response to decreased tidal flow, resulting from the growth of Cape Henlopen toward the northwest. The pattern of deposition has been quite simple in the long term (129 years) while very complex in the short term (a survey interval).

2. Some of the short term complexities of depositional and erosional patterns have been caused by the construction of the two breakwaters and the ferry jetty. In each case, the construction of one of these barriers caused a brief period of erosion in the resulting narrowed areas, and slowed or stopped deposition in some of the other less narrowed areas. This erosional period was followed by increased deposition rates as the sedimentation regime adapted to the new construction. Spit growth continued in a form adapted to the construction, and continued to decrease tidal flow through the area.

3. Average shoaling rates for Breakwater Harbor during survey intervals ranged from -0.02 feet/year (-0.6 cm/yr) to 0.19 feet/year (5.7 cm/yr). Rates of the spit tip were as high as 3.0 feet/year (90 cm/yr). All the shoaling rates shown on the shoaling rates diagrams are averages over the survey interval. Rates could have been higher or lower at any instant during the interval.

4. The deposition off the spit tip was characterized by extremely rapid deposition in a localized area associated with spit growth. This depositional area was probably much more restrictive than indicated on the shoaling rates diagrams because the shoaling rates are averaged over a decade or more. The actual rates were probably very much higher, on the order of 20 to 30 feet/year (600 to 900 cm/yr), immediately off the spit tip, but only lasting a year or two, before the area was filled to sea level and the depositional center was moved northward. When this amount of deposition is averaged over the survey interval the apparent shoaling rate is decreased and the apparent area of deposition is increased.

5. Sediment is supplied to the study area by littoral transport along the Atlantic Coast of Delaware, and by sediment in Delaware Bay waters settling from suspension. The net accumulation resulting from suspended sediment deposition is dependent upon many complex factors, including sediment load, flocculation, bottom time before resuspension, tidal flow, and the affect of storms on tidal flow and wave energy. This source has been the most important contributor to the sediment deposited in the harbor, keeping the harbor at an equilibrium depth with respect to tidal flow in the long term. The harbor has filled in more in the previously deeper areas and less in the previously

shallower areas. This has resulted in a flattening of the bathymetry of the harbor and a good correlation between original depths and the average shoaling rates for the last 129 years. This correlation is not found in other parts of the study area.

6. The long-term tendencies can be analyzed by historic and geologic studies, and understood by study of short-term processes. Man's influence can only be evaluated and predicted in a general way with emphasis on the long-term tendencies, determined by the identification and analysis of past long-term trends.

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APPENDIX A

SIZE ANALYSIS - TECHNIQUES AND DATA

Sediment samples were examined in the field for their approximate size characteristics. Samples which contained silt and clay were placed in plastic sample bags, while samples which appeared to be entirely sand were placed in cloth sample bags. All samples taken in plastic sample bags were analyzed by pipette and samples taken in cloth bags were analyzed using dry sieves at one phi intervals. The percent sand, percent silt and percent clay were calculated for the samples analyzed by pipette and mean grain size, sorting, skewness, and kurtosis were calculated for samples analyzed using dry sieving. The techniques for each type of analysis are described below.

Pipette Analysis

The pipette analysis followed the procedure described by Folk (1974). A portion of the sediment from each sample was placed in a 1000 ml. beaker. Enough sample was taken to provide between 5 and 15 grams dry weight of silt and clay. This required an estimate of the amount of sand and water in each sample. With some experience, this can be done with acceptable accuracy. Each of these samples was then dispersed in 300 ml. of 0.1% calgon solution for 24 hours after which the samples were placed in a mixer for 5 minutes to aid in the dispersion of the sediment.

Each sample was wet sieved using a 4 phi (.0635 mm., U. S. standard 230 mesh) sieve. Wash bottles containing 0.1% calgon were used to wash the silt and clay through the sieve. Care was taken not to use more water than was required to bring the total volume of the water-sediment suspension to 1000 ml. The sediment retained in the sieve was dried and weighed. This was the total amount of sand in the sample. The clay and silt was contained in the 1000 ml. suspension, which was placed in a 1000 ml. settling tube for pipette analysis.

The amount of silt and clay in the settling tube was calculated by allowing the suspension to settle long enough to allow and particles larger than .063 mm. to settle past a depth of 20 cm. This time was calculated by substituting the temperature, density of the particle (which was assumed to be that of quartz), and the diameter of the particle into Stokes Law as simplified by Folk (1974, p. 40). At this time an aliquot was taken from a depth of 20 cm. using a 25 ml. pipette. The material in the aliquot was one 40th of the material in suspension finer than 0.063 mm.

Since all the material coarser than 0.063 mm. was removed from the suspension by wet sieving, this represents one 40th of the total weight of the material in the settling tube, and therefore is a measure of the weight of silt plus clay in the original sample. This aliquot was placed in a 40 ml., pre-weighed beaker, and dried in an oven at 80-90° C.

In order to determine what portion of the suspension in the settling tube was silt and what portion was clay, another aliquot was removed from a depth of 10 mm. when enough time has passed to allow a 0.004 mm. (8 phi) sized particle to settle past a 10 mm. depth. The material in the 25 ml. aliquot was one 40th of the material in the settling tube finer than 0.004 mm. This was one 40th of the amount of clay that was in suspension. This aliquot was also put in a pre-weighed 40 ml. beaker and placed in the oven to dry.

In each of the 25 ml. aliquots, there were three components. First, there was the water, which was evaporated off. Second, there was the material in suspension, which was the quantity being determined. Third, there was material in solution in the water which is left behind during evaporation of the water, and therefore, added to the weight of each dried aliquot. In order to remove the weight of this material from the weight of the dried aliquot, about 60 ml. of the suspension was poured into a centrifuge tube and centrifuged for one hour at 20,000 rpm. This removed all the suspended material. A 25 ml. aliquot was then taken from the solution in the centrifuge tube, placed in a pre-weighed 40 ml. beaker, and placed in the oven to dry. The weight of the residue which was the material dissolved in the water was then subtracted from the weights of each of the other aliquots so that only the weight of the material in suspension in the settling tube used in the calculation. This procedure for the removal of the dissolved material was described by R. N. Strom (personal communication).

To calculate the percent of sand, silt and clay in the sample the weight of the sand in the sieve after wet sieving was added to the weight of the dried 25 ml. aliquot containing silt and clay multiplied by 40. This was the total dry weight of the original sample. The weight of each of the sand, silt and clay was divided by the total weight and multiplied by 100 to calculate the percent.

Dry Sieving

The samples taken in cloth bags were rinsed in fresh water, dried, and split. Fifty gram portions of each sample were placed in a stack of sieves at one phi intervals from -2 to 4 phi. The sediment retained in each sieve was weighed on a top loading Mettler balance. Cumulative percent curves were plotted and mean grain size and sorting calculating according to Folk (1974). The data for Breakwater Harbor samples are given in Table 2, and the data for tidal flat samples are given in Table 3.

TABLE 2
BREAKWATER HARBOR SAMPLE DATA

SAMPLE NO.	PERCENT SAND	PERCENT SILT	PERCENT CLAY	FOLK'S CLASSIFICATION
500	71	17	11	muddy sand
501	7	49	44	mud
502	4	32	63	mud
503	27	48	24	sandy mud
504	45	43	11	sandy silt
505	35	47	17	sandy silt
506	5	62	33	mud
507	6	61	34	clayey silt
508	1	77	22	silt
509	8	60	32	mud
511	100	0	0	sand
512	-	-	-	-
513	15	55	30	sandy mud
514	25	53	21	sandy silt
515	15	61	25	sandy silt
516	17	58	26	sandy mud
518	11	63	27	sandy silt
519	16	65	19	sandy silt
521	100	0	0	sand
522	100	0	0	sand
523	100	0	0	sand
524	3	91	7	silt
525	63	25	11	silty sand
526	86	9	6	muddy sand
527	77	14	9	muddy sand
531	100	0	0	sand
532	99	1	0	sand
533	77	15	8	muddy sand
534	83	11	6	muddy sand
535	28	52	20	sandy silt
536	85	10	6	muddy sand
541	100	0	0	sand
542	100	0	0	sand
544	97	2	1	sand
545	94	4	2	sand

TABLE 3
TIDAL FLAT SAMPLE DATA

SAMPLE NO.	GRAPHIC MEAN (Ø)	INCLUSIVE GRAPHIC STAND. DEVIATION (Ø)	INCLUSIVE GRAPHIC SKEWNESS	KURTOSIS
1	0.48	0.73	-0.18	1.22
2	0.49	0.75	0.01	1.07
3	1.04	0.50	0.00	1.16
4	0.38	0.86	-0.04	1.18
5	1.05	0.45	0.09	1.10
6	0.93	0.56	0.05	0.89
7	0.80	0.57	-0.07	1.04
8	0.42	0.73	-0.04	1.10
9A	0.71	0.64	-0.01	1.04
9B	0.82	0.65	-0.05	1.07
10	-0.75	2.54	-0.67	1.29
11	0.60	1.01	-0.28	1.34
12A	-	-	-	-
12B	0.57	1.23	-0.39	1.86
13	0.54	0.73	-0.01	0.90
14	1.24	0.41	0.06	1.07
15	1.33	0.37	0.08	1.02
16	0.91	0.68	0.08	0.75
17	1.32	0.49	-0.04	0.98
18	1.21	0.55	-0.09	1.00
19	1.14	0.49	-0.03	1.00
20	0.89	0.66	-0.01	0.89
21	0.85	1.67	-0.53	2.39
22	0.91	1.31	-0.40	1.88
23	-1.16	3.04	-0.66	0.46
24	1.14	0.63	-0.13	1.11
25	0.84	0.58	-0.12	1.18
50	-1.14	0.50	-0.03	0.97
51	1.13	0.48	-0.06	0.95
52	1.08	0.53	0.00	1.08
53	1.17	0.58	-0.05	0.90
54	1.23	0.63	-0.17	0.94
55	1.20	0.53	-0.03	1.04
56	1.13	0.55	-0.05	1.01
57	1.06	0.52	-0.04	1.14
59	1.04	0.45	0.24	0.94
60	0.99	0.52	-0.04	0.98
61	1.07	0.61	-0.06	1.00
62	1.27	0.56	-0.14	0.99
63	1.25	0.58	-0.10	0.97
64		destroyed		
65	1.28	0.59	-0.25	0.97
66	1.20	0.59	-0.17	0.98
67		destroyed		
68		destroyed		
69		destroyed		

TABLE 3
(cont.)

SAMPLE NO.	GRAPHIC MEAN (Ø)	INCLUSIVE GRAPHIC STAND. DEVIATION (Ø)	INCLUSIVE GRAPHIC SKEWNESS	KURTOSIS
70		destroyed		
71	0.97	0.59	-0.10	1.12
72	0.23	1.27	-0.34	1.01
600	0.79	0.45	-0.05	1.03
601		destroyed		
602	0.67	0.58	-0.19	0.92
604	1.01	0.47	-0.09	1.20
605	1.05	0.55	-0.08	1.02
606	0.92	0.54	-0.13	1.22
607	1.06	0.51	-0.05	1.06
608	0.96	0.54	-0.06	1.02
609	0.99	0.54	-0.07	0.99
610	0.96	0.54	-0.05	1.04
611	1.09	-0.48	-0.06	1.04
612	1.02	0.46	-0.04	1.00
613	1.13	0.46	-0.37	0.96
614	1.10	0.49	0.00	1.02
615	1.16	0.49	0.15	0.97
616	1.26	0.44	0.17	0.99
617	1.34	0.44	-0.01	1.02

APPENDIX B

FORTRAN PROGRAMS

MAPWORK (08/30/77)

```
 $SET AUTOBIND
 $BIND = FROM (0427)TESTRESET/=
C-   CREATE FILES
FILE  6(KIND=PRINTER,MAXRECSIZE=132,UNITS=1)
FILE  9(TITLE="FILEID", KIND=DISKPACK, FILETYPE=7)
FILE  10(TITLE="FILEID", KIND=DISKPACK, FILETYPE=7)
FILE  11(KIND=REMOTE,MYUSE=10,MAXRECSIZE=22)
C-  DIMENSION ARRAYS
      DIMENSION FILEID(3), VF(64)
      COMMON HEADER(12), MAP(100,120), FRAY(5), MG(64), VALUE(4),
     -   CLOSE(4)
      DATA FRAY/' (1H0 ' , ',I3,1X' , '  ,2X ' , '  ,I2 ' , ' )    '/
      DIMENSION RMAP(35,35), BMAP(35,35), AMAP(35,35), DMAP(35,35),
     -     XMAP(35,35), YMAP(35,35), ISV(4), JSV(4)
C-  BEGIN EXECUTION
      WRITE(11,/)"YOU ARE RUNING A PROGRAM TO CALCULATE"
      WRITE(11,/)"  SHOALING RATES   AND  VOLUMES - THEN PLOT"
   10 CONTINUE
C-  SET ARRAY SIZE
      MXE=120
      MXS=90
C-  SET INTERPOLATION FREQUENCE
  WRITE(11,/)"**********************************************"
      WRITE(11,/) "ENTER INCREMENT IN X FOR INTERPOLATION, THEN ','"
      WRITE(11,/) "THEN INCREMENT IN Y FOR INTERPOLATION"
      WRITE(11,/)  "EACH INCREMENT MUST BE FROM 3 TO 9"
      READ(11,1010) INKX, INKY
   WRITE(11,/)" DO YOU WANT TO PRINT BLANK MAPS 1=NO, 2=YES"
   READ(11,1020)  IPL
   IF(IPL.EQ.2)  CALL SHRPLT(MXE,MXS)
         WRITE(11,/)"DO YOU WANT TO QUIT HERE  1=NO, 2=YES"
         READ(11,1020) IGO
         IF(IGO.EQ.2) GOTO 40
C-  READ DATA FOR FIRST MAP
   20    WRITE(11,/) "ENTER MOST RECENT MAP"
         CALL  FILL(FILEID, 9, MXE, MXS)
         WRITE(11,/)"DO YOU WANT TO PRINT DATA 1=NO, 2=YES"
         READ(11,1020) IPL
         IF(IPL.EQ.2) CALL PRTDTA(FILEID,VF,MXE,MXS)
         WRITE(11,/)"DO YOU WANT TO QUIT HERE  1=NO, 2=YES"
         READ(11,1020) IGO
         IF(IGO.EQ.2) GOTO 40
         CALL  INTERP(XMAP, MXE, MXS, MXX, MXY, INKX, INKY)
         WRITE(11,/)"DO YOU WANT TO PLOT INTERP VALUES 1=NO, 2=YES"
         READ(11,1020) IPL
         IF(IPL.EQ.2) CALL PLTMAP(XMAP,MXE,MXS,MXX,MXY,INKX,INKY,YEARS)
         WRITE(11,/)"DO YOU WANT TO PRINT VALUES 1=NO,2=YES"
         READ(11,1020) IPL
         IF(IPL.EQ.2)  CALL PRTMAP(XMAP,MXE,MXS,MXX,MXY,INKX,INKY)
         WRITE(11,/)"DO YOU WANT TO QUIT HERE  1=NO, 2=YES"
         READ(11,1020) IGO
         IF(IGO.EQ.2) GOTO 40
         WRITE(11,/)  "ENTER OLDER MAP"
C-  BEGIN READING DATA FOR SECOND MAP
         CALL  FILL(FILEID, 10, MXE, MXS)
         WRITE(11,/)"DO YOU WANT TO PRINT DATA 1=NO, 2=YES"
         READ(11,1020) IPL
```

```
              IF(IPL.EQ.2) CALL PRTDTA(FILEID,VF,MXE,MXS)
              WRITE(11,/)"DO YOU WANT TO QUIT HERE  1=NO, 2=YES"
              READ(11,1020) IGO
              IF(IGO.EQ.2) GOTO 40
              CALL  INTERP(YMAP, MXE, MXS, MXX, MXY, INKX, INKY)
              WRITE(11,/)"DO YOU WANT TO PLOT INTERP VALUES 1=NO, 2=YES"
              READ(11,1020) IPL
              IF(IPL.EQ.2) CALL PLTMAP(YMAP,MXE,MXS,MXX,MXY,INKX,INKY,YEARS)
              WRITE(11,/)"DO YOU WANT TO PRINT VALUES 1=NO,2=YES"
              READ(11,1020) IPL
              IF(IPL.EQ.2)  CALL PRTMAP(YMAP,MXE,MXS,MXX,MXY,INKX,INKY)
              WRITE(11,/)"DO YOU WANT TO QUIT HERE  1=NO, 2=YES"
              READ(11,1020) IGO
              IF(IGO.EQ.2) GOTO 40
              CALL  MAPDIF(YMAP, XMAP, DMAP, MXX, MXY, INKX, INKY, YEARS)
              WRITE(11,/)"DO YOU WANT TO PLOT MAPDIF VALUES 1=NO, 2=YES"
              READ(11,1020) IPL
              IF(IPL.EQ.2) CALL PLTMAP(DMAP,MXE,MXS,MXX,MXY,INKX,INKY,YEARS)
              WRITE(11,/)"DO YOU WANT TO PRINT VALUES 1=NO,2=YES"
              READ(11,1020) IPL
              IF(IPL.EQ.2)  CALL PRTMAP(DMAP,MXE,MXS,MXX,MXY,INKX,INKY)
              WRITE(11,/)"DO YOU WANT TO QUIT HERE  1=NO, 2=YES"
              READ(11,1020) IGO
              IF(IGO.EQ.2) GOTO 40
              CALL SEDRTE(DMAP, RMAP,MXX, MXY,YEARS)
              WRITE(11,/)"DO YOU WANT TO PLOT SEDRATE VALUES 1=NO, 2=YES"
              READ(11,1020) IPL
              IF(IPL.EQ.2) CALL PLTMAP(RMAP,MXE,MXS,MXX,MXY,INKX,INKY,YEARS)
              WRITE(11,/)"DO YOU WANT TO PRINT VALUES 1=NO,2=YES"
              READ(11,1020) IPL
              IF(IPL.EQ.2)  CALL PRTMAP(RMAP,MXE,MXS,MXX,MXY,INKX,INKY)
         40 CONTINUE
            STOP
       1010 FORMAT(I1,1X,I1)
       1020 FORMAT(I1)
            END
```

SUBFILL (07/23/77)

```
$SET SEPARATE
C-  CREATE FILES
FILE  9(TITLE="FILEID", KIND=DISKPACK, FILETYPE=7)
FILE  10(TITLE="FILEID", KIND=DISKPACK, FILETYPE=7)
FILE  11(KIND=REMOTE,MYUSE=IO)
      SUBROUTINE FILL(FILEID, IN, MXE, MXS)
C-   DIMENSION ARRAYS
      DIMENSION FILEID(3)
      COMMON HEADER(12), MAP(100,120), FRAY(5), MG(64), VALUE(4),
     -   CLOSE(4)
C-  INITIALIZE MAP ARRAY VALUES TO -1
      DO 20 I=1,MXS
         DO 10 J=1,MXE
   10    MAP(I,J)=-1
   20 CONTINUE
C-  CHANGE TITLE OF INPUT FILE TO DATA FILE NAME
      WRITE(11,/) "ENTER INPUT FILE NAME . . .AND A PERIOD "
      READ(11, 1010) FILEID
      CHANGE(IN, TITLE=FILEID)
C-  READ AND WRITE FIRST 3 RECORDS OF DATA FILE
      DO 30  I=1,3
         READ(IN,1020) (HEADER(J), J=1,12)
         WRITE(11,1020) HEADER
   30 CONTINUE
C-  SKIP 4'TH RECORD OF DATA FILE
      READ (IN,1030)
C-  READ DATA RECORD
   40 READ (IN,1040,END=80) X, Y, Z, XX, YY, ZZ
      DO 70  I=1,2
C-                 CHECK FOR END OF DATA
   50    IF(Z.EQ.555) GOTO 80
C-  CORRECT DATA POSITION
         X=X-(0.0048*X)
         Y=Y+(0.0155*Y)
C-   ROUND OFF X AND Y AND MAKE INTEGER AND MOVE DECIMAL
         IROW=100*Y+.5
         JCOL=100*X+.5
C-                 CHECK FOR LEGAL X AND Y
         IF(IROW.GT.MXS) GOTO 60
         IF (IROW.LE.0) GOTO 60
         IF(JCOL.GT.MXE)  GOTO 60
         IF (JCOL.LE.0)  GOTO 60
C-                 PLACE Z IN MAP(JCOL,IROW) POSITION
         MAP(IROW,JCOL)=Z
C-  EXCHANGE X,Y,Z, WITH XX,YY,ZZ AND LOOP
   60    X=XX
         Y=YY
   70 Z=ZZ
C-  LOOP BACK TO READ NEXT RECORD OF DATA
      GOTO 40
   80 CONTINUE
C-   SAVE FILE AND RETURN TO MAIN PROGRAM
      LOCK IN
      RETURN
 1010 FORMAT (3A6)
 1020 FORMAT (' ',12A6)
 1030 FORMAT (1X)
 1040 FORMAT(8X,6(1X,F7.3))
      END
```

SUBINTERP (07/23/77)

```
      $SET SEPARATE
C- CREATE FILES
FILE  9(TITLE="FILEID", KIND=DISKPACK, FILETYPE=7)
FILE  10(TITLE="FILEID", KIND=DISKPACK, FILETYPE=7)
FILE  11(KIND=REMOTE,MYUSE=IO)
            SUBROUTINE INTERP(AMAP,MXE, MXS, MXX, MXY, INKX, INKY)
C- DIMENSION ARRAYS
            DIMENSION AMAP(35,35), YSV(4), XSV(4)
            COMMON HEADER(12), MAP(100,120), FRAY(5), MG(64), VALUE(4),
           -   CLOSE(4)
C-  CALCULATE SIZE OF INTERPOLATION ARRAY
            MXX=(MXE-1)/INKX +1
            MXY=(MXS-1)/INKY + 1
C-                WALK THROUGH MATRIX TO INTERPOLATE EVERY
C-                INKX POINT IN X AND EVERY INKY POINT IN Y
C-  STEP ACROSS ROWS OF MAP ARRAY
            K=1
            DO 170 IROW=1,MXS,INKY
              L=1
C-  STEP ACROSS COLUMNS OF MAP ARRAY
              DO 150 JCOL =1,MXE,INKX
C-  INITIALIZE VARIABLES
                AMAP(K,L) = 9999999
                DO 10 MM=1,4
                  CLOSE(MM)= 4000
                  YSV(MM)=-1
                  XSV(MM)=-1
   10           VALUE(MM)= -1
C-CHECK FOR  DATA AT THE POINT
                IF (MAP(IROW,JCOL).LT. 0) GOTO 20
                AMAP(K,L) = MAP(IROW,JCOL)
                GOTO  140
C-  GO TO FOUR QUADRANTS AROUND POINT TO BE INTERPOLATED
   20           DO 100 M=1,4
                  GO TO (30,40,50,60),M
C- SET LA & LB TO + OR - 1TO GO TO PROPER QUADRANTS
   30             LA=1
                  LB=1
                  GOTO 70
   40             LA=-1
                  GOTO 70
   50             LB=-1
                  GOTO 70
   60             LA=1
C-  ALTERNATE KA= -1 AND 0 TO PICK UP IROW AND JCOL DATA
   70             KA=(-1)**M
                  IF(KA.GT.0)  KA=0
C-  WALK THROUGH QUADRANT IN SEARCH OF CLOSEST POINT
                  DO 90 II=1,10
                    I = IROW + LA*(II+KA)
C- IF ROW NUMBER IS > CLOSEST POINT GOTO NEXT QUADRANT
                    IF(I.GT.CLOSE(M))  GOTO 100
                    DO 80 JJ= 1,10
                      J=JCOL + LB*(JJ+KA)
C- IF COLUMN NUMBER IS > CLOSEST POINT GOTO NEXT ROW
                      IF(J.GT.CLOSE(M))  GOTO 80
C-  CHECK FOR LEGAL ARRAY PARAMETERS
```

```
                              IF(I.LE.0.OR.I.GT.MXS) GOTO 100
                              IF(J.LE.0.OR.J.GT.MXE) GOTO 90
C-     CHECK FOR DATA
                              IF(MAP(I,J).LT.0)  GOTO 80
C- CHECK FOR BARRIER
                              IF(JJ.EQ.1.AND.MAP(I,J).GT.95.AND.II.GT.1)GOTO 100
                              IF(MAP(I,J).GT.95)  GOTO 90
C-      CALCULATE DISTANCE
                              DIST = SQRT ((IROW-I)**2 + (JCOL-J)**2)
C- SAVE DISTANCE VALUE, AND POSITION OF CLOSEST POINT
                              IF(DIST.GT.CLOSE(M))  GOTO 90
                              CLOSE(M) = DIST
                              VALUE(M) = MAP(I,J)
                              YSV(M) = ABS(I-IROW)
                              XSV(M) = ABS (J-JCOL)
C-  IF POSITION IS ZERO MAKE VERY SMALL (SHOULD NEVER OCCUR)
                              IF (YSV(M).EQ.0) YSV(M)=0.00001
                              IF (XSV(M).EQ.0) XSV(M)=0.00001
C- LOOP BACK
                              GOTO 90
   80                   CONTINUE
   90                CONTINUE
  100             CONTINUE
C-   CALCULATE INTERPOLATED VALUE FOR POINT MAP(IROW,JCOL)
C-  INITIALIZE VARIABLES
                  STORE =0.0
                  KPT=0
                  DENOM=0.0
C- CHECK FOR DATA FROM ALL FOUR QUADRANTS IF SO TEST
                  DO 110 MM=1,4
  110             IF (VALUE(M).LT.0) GOTO 120
                  CALL DATEST(YSV, XSV)
  120             CONTINUE
C-  CALCULATE GRID POINT VALUE
                  DO 130 M=1,4
C-  CHECK FOR DATA FROM THIS QUADRANT
                     IF (VALUE(M).LT.0) GOTO 130
C- COUNT THE NUMBER OF POINTS USED IN CALCULATION
                     KPT=KPT+1
                     STORE = VALUE(M)/CLOSE(M)+STORE
                     DENOM = 1 / CLOSE(M) + DENOM
  130             CONTINUE
C-  IF NOT ATLEAST 2 POINTS FOR INTERPOLATION THEN SKIP
                  IF(KPT.LT.2) GOTO 140
C- SET AMAP GRID POINT EQUAL TO INTERPOLATED VALUE
                  AMAP(K,L) = STORE/DENOM
C- INCREMENT TO NEXT GRID POINT AND GO AGAIN
  140             L = L+1
  150       CONTINUE
  160       K = K+1
  170 CONTINUE
      RETURN
      END
      SUBROUTINE DATEST(YSV, XSV)
C- SUBROUTINE TO TEST GEOMETRIC RELATIONSHIP OF POINTS
      DIMENSION YSV(4), XSV(4)
      COMMON HEADER(12), MAP(100,120), FRAY(5), MG(64), VALUE(4),
     -   CLOSE(4)
      LARGE=0
      DO 10 LP=1,4
```

```
C-  FIND QUADRANT CONTAINING FARTHEST AWAY POINT
        IF (LARGE.GT.CLOSE(LP)) GOTO 10
        LARGE=CLOSE(LP)
        LQ=LP
   10 CONTINUE
C- SET LT & LR TO ADJACENT QUADRANTS
      GO TO (20,30,40,50), LQ
   20 LT=2
      LR=4
      GOTO 60
   30 LT=3
      LR=1
      GOTO 60
   40 LT=4
      LR=2
      GOTO 60
   50 LT=1
      LR=3
C-CALCULATE ANGLE BETWEEN POINTS ON OPPOSITE SIDE FROM
C-         FARTHEST POINT
   60 ANGLE=ATAN(YSV(LT)/XSV(LT)) + ATAN(XSV(LR)/YSV(LR))
C- IF ANGLE IS GREATER THAN 90 DEGREES POINT IS SURROUNDED
C-   BY CLUSEST THREE POINTS SO USE ONLY THE THREE
      IF (ANGLE.GT.ARSIN(1.0)) VALUE(LQ)= -1
      RETURN
      END
```

SUBSEDRTE (08/05/77)

```
$SET SEPARATE
C-  CREATE FILES
FILE  9(TITLE="FILEID", KIND=DISKPACK, FILETYPE=7)
FILE  10(TITLE="FILEID", KIND=DISKPACK, FILETYPE=7)
FILE  11(KIND=REMOTE,MYUSE=IO)
      SUBROUTINE SEDRTE(DMAP, RMAP, MXX, MXY,YEARS)
C-  DIMENSION ARRAYS
      DIMENSION DMAP(35,35),  RMAP(35,35)
      COMMON HEADER(12), MAP(100,120), FRAY(5), MG(64), VALUE(4),
     -   CLOSE(4)
      WRITE(11,/)  "CALCULATING SED-RATE"
      DO 10 I=1,MXY
         DO 10 J=1,MXX
C- CALCULATE SHOALING RATES FOR DIFFERENCE MAP
            RMAP(I,J)= DMAP(I,J)/YEARS
   10 IF (DMAP(I,J).GT.95) RMAP(I,J)=DMAP(I,J)
      WRITE(11,/)   "SED-RATE  CALCULATED"
      RETURN
      END
```

SUBMAPDIF (08/05/77)

```
$SET SEPARATE
 C- CREATE FILES
FILE  9(TITLE="FILEID", KIND=DISKPACK, FILETYPE=7)
FILE  10(TITLE="FILEID", KIND=DISKPACK, FILETYPE=7)
FILE  11(KIND=REMOTE,MYUSE=IO)
      SUBROUTINE MAPDIF(AMAP, BMAP, DMAP, MXX, MXY, INKX, INKY, YEARS)
C-  DIMENSION ARRAYS
      DIMENSION AMAP(35,35), BMAP(35,35), DMAP(35,35)
      COMMON HEADER(12), MAP(100,120), FRAY(5), MG(64), VALUE(4),
     -   CLOSE(4)
      INTEGER OYEARS, RYEARS
C-  INITIALIZE VARIABLES
      WRITE(11,/) "ENTER DATE OF MOST RECENT MAP"
      READ(11,1010) RYEARS
      WRITE(11,/) "ENTER DATE OF OLDER MAP AND A PERIOD"
      READ(11,1010) OYEARS
      YEARS = RYEARS-OYEARS
      SUM=0.0
      NPTS=0
      AVG=0.0
      AREA=0.0
C- SUBTRACT NEW MAP FROM OLD ONE
      DO 10 I=1,MXY
         DO 10 J=1,MXX
            DMAP(I,J)=(AMAP(I,J)-BMAP(I,J))
C-  CHECK FOR BARRIERS
            IF (AMAP(I,J).GT.95) DMAP(I,J)=AMAP(I,J)
            IF (BMAP(I,J).GT.95)  DMAP(I,J)=BMAP(I,J)
            IF(DMAP(I,J).GT.95)  GOTO 10
C-  CHECK FOR DESIRED ARRAY PARRAMETERS
C- SKIP FIRST AND LAST ROW AND COLUMN
            IF(I.LE.1)  GOTO 10
            IF(J.LE.1)  GOTO 10
            IF(I.GT.(MXY-1))  GOTO 10
            IF (J.GT.(MXX-1))  GOTO 10
C-  COUNT NUMBER OF POINTS
            NPTS=NPTS+1
C- SUM DEPTH CHANGE
            SUM= SUM + DMAP(I,J)
   10 CONTINUE
C-  CALCULATE AREA, AVERAGE DEPTH CHANGE, VOLUME
      AREA=NPTS*INKX*INKY*10000.
      AVG=SUM/NPTS
      VOL=AVG*AREA
C-  OUTPUT CALCULATIONS
      WRITE(11,1060) OYEARS, RYEARS
      WRITE(11,1020) NPTS
      WRITE(11,1030) AVG, (AVG*.3048)
      WRITE(11,1040)  AREA, (AREA*.0929)
      WRITE(11,1050) VOL, (VOL*.0283)
      RETURN
 1010 FORMAT(I4)
 1020 FORMAT('-',5X,"NUMBER OF POINTS USED IN",
     -    " CALCULATION =",3X,I5)
 1030 FORMAT(' ',22X,"AVERGE DEPTH CHANGE =",3X,
     -       F5.2,"  FEET",/,43X,"=",3X,F6.3,"  METERS")
 1040 FORMAT(' ',5X,"AREA FOR WHICH VOLUME WAS ",
     -      "CALCULATED =",3X,E12.3,"  SQ FEET",/,43X,"=",
     -           3X,E12.3,"  SQ METERS")
 1050 FORMAT(' ',13X,"VOLUME OF SEDIMENT DEPOSITED ="
     +    ,3X,E12.3,"  CUBIC FEET",/,43X,"=",3X,E12.3,
     -            "  CUBIC METERS")
 1060 FORMAT('-',5X,"CALCULATIONS FOR ",I4,
     -      " TO ",I4)
      END
```

SUBPRTDTA (07/23/77)

```
        $SET SEPARATE
        C- CREATE FILES
        FILE  9(TITLE="FILEID", KIND=DISKPACK, FILETYPE=7)
        FILE  10(TITLE="FILEID", KIND=DISKPACK, FILETYPE=7)
        FILE  11(KIND=REMOTE,MYUSE=IO)
              SUBROUTINE PRTDTA(FILEID, VF, MXE, MXS)
        C- DIMENSION ARRAYS
              DIMENSION FILEID(3), VF(64)
              COMMON HEADER(12), MAP(100,120), FRAY(5), MG(64), VALUE(4),
             *   CLOSE(4)
        C- WRITE DAME OF FILE AT TOP OF PAGE
              WRITE(6,1010) FILEID
        C-                DIVIDE X DIRECTION INTO 2 PARTS SO IT FITS ON PAGE
        C- INITIALIZE VARIABLES
              NB=0
              DO 70  I=1,2
                 NA= NB + 1
                 NB = NB+ 60
                 IF (NB.GT.MXE) NB=MXE
        C-                PRINT HEADING TO ID MAP SECTION
                 IF (I.EQ.1) WRITE(6,1020)
                 IF (I.EQ.2) WRITE(6,1030)
                 WRITE(6,1040) (II, II=NA,NB,2)
        C-                CALCULATE FORMAT FOR EACH ROW TO BE PRINTED
           10    DO 70 IROW = 1,MXS
        C- INITIALIZE VARIABLES
                    DO 20 KK=1,64
           20       VF(KK)="      "
                    JJ=3
                    JZ=0
                    VF(1)=FRAY(1)
                    VF(64)=FRAY(5)
                    VF(2)=FRAY(2)
                    DO 40  JCOL= NA,NB
        C- SET FORMAT TO 2X
                       VF(JJ)=FRAY(3)
        C- CHECK FOR DATA
                       IF (MAP(IROW,JCOL).LT.0) GOTO 30
        C- IF DATA -  COUNT NUMBER OF POINTS, PUT VALUE IN NEXT
        C- POSITION OF ARRAY MG, SET FORMAT TO I2
                       JZ=JZ+1
                       MG(JZ)=MAP(IROW,JCOL)
                       VF(JJ)=FRAY(4)
        C-  GO TO NEXT POINT
           30          JJ=JJ+1
           40       CONTINUE
                    IF(JZ) 70, 60, 50
        C- IF DATA ON LINE PRINT LINE NUMBER AND LINE
           50       WRITE(6,VF) IROW, (MG(J),J=1,JZ)
                    GOTO 70
        C- IF NO DATA ON LINE JUST PRINT LINE NUMBER
           60       WRITE(6,1050) IROW
           70 CONTINUE
              RETURN
         1010 FORMAT ('1',50X,"DATE=", 3A6)
         1020 FORMAT ('0',50X, "SECTION ONE"/)
         1030 FORMAT ('1',50X, "SECTION TWO"/)
         1040 FORMAT ('0',2X, 60(1X,I3))
         1050 FORMAT('0',I3)
              END
```

SUBPRTMAP (08/05/77)

```
      $SET SEPARATE
      C- CREATE FILES
      FILE  9(TITLE="FILEID", KIND=DISKPACK, FILETYPE=7)
      FILE  10(TITLE="FILEID", KIND=DISKPACK, FILETYPE=7)
      FILE  11(KIND=REMOTE,MYUSE=IO)
            SUBROUTINE PRTMAP(AMAP, MXE, MXS, MXX, MXY, INKX, INKY)
      C- DIMENSION ARRAYS
            COMMON HEADER(12), MAP(100,120), FRAY(5), MG(64), VALUE(4),
           -   CLOSE(4)
            DIMENSION AMAP(35,35)
            WRITE(11,/) "PRINTING CALCULATED MAP"
      C-  READ MAP HEADING FOR LINE PRINTER
            WRITE(11,/)  "ENTER MAP HEADING"
            READ(11,1010) HEADER
            WRITE(6,1020) HEADER
      C- INITIALIZE VARIABLES
            ISPACE=INKX*2-6
            NB=0
            AA=120./INKX/2
            NOP=AA
      C- SPLIT ARRAY INTO TWO SECTIONS BY COLUMNS
            DO 60 L=1,2
               GO TO (10,20), L
         10    WRITE(6,1030)
               WRITE (6,1050)  (II, II=1,60,2)
               LEFT=0
               GOTO 30
         20    WRITE(6,1040)
               WRITE(6,1050)  (II, II=61,MXE,2)
               LEFT=(AA-NOP)*INKX*2
      C- PRINT TWO  HALVES
      C- INITIALIZE VARIABLES
         30    NA=NB+1
               NB=NB+NOP
               IF (NB.GT.MXX) NB=MXX
               DO 50 I=1,MXY
                  K=I*INKY-INKY+1
      C- PRINT LINE WITH PROPER SPACING BETWEEN POINTS
                  WRITE(6,1060) K, LEFT, ((AMAP(I,J),ISPACE), J=NA,NB)
      C- PRINT LINE NUMBERS OF EMPTY LINES
                  DO 40 MI=1,INKY-1
                     MJK=K+MI
         40       WRITE(6,1070)  MJK
         50    CONTINUE
         60 CONTINUE
            WRITE(11,/)  "MAP PRINTING COMPLETED"
            RETURN
       1010 FORMAT(12A6)
       1020 FORMAT('1',40X,12A6,/)
       1030 FORMAT('0',50X, "SECTION ONE")
       1040 FORMAT('1',50X, "SECTION TWO")
       1050 FORMAT('0',4X,32(1X,I3))
       1060 FORMAT('0',I3,1X,*X,20(F6.2,*X))
       1070 FORMAT('0',I3)
            END
```

SUBPLTMAP (09/01/77)

```
$SET SEPARATE
C-  CREATE FILES
FILE  9(TITLE="FILEID", KIND=DISKPACK, FILETYPE=7)
FILE  10(TITLE="FILEID", KIND=DISKPACK, FILETYPE=7)
FILE  11(KIND=REMOTE,MYUSE=IO)
FILE  8=FILE8,UNIT=REMOTE
      SUBROUTINE PLTMAP(AMAP,MXE,MXS,MXX,MXY,INKX,INKY,YEARS)
C- DIMENSION ARRAYS
      DIMENSION AMAP(35,35), NAME(2), FILEID(9), FILE(1), S(120)
      DATA NAME/'DEMARE 00115'/
      COMMON HEADER(12), MAP(100,120), FRAY(5), MG(64), VALUE(4),
     -   CLOSE(4)
      LOGICAL  VA
C-  INITIALIZE VARIABLES
   10 IFT=10
      DO 20 J=1,120
   20 S(J)=0.0
C-  DEFINE UNITS FOR OUTPUT NUMBERS
      WRITE(11,/)"DO YOU WANT DEPTHS/RATES PLOTTED IN"
      WRITE(11,/)"   1=FT,FT/YEAR; 2=M,M/YEAR; 3=CM,CM/YEAR"
      READ(11,1010) IUNTS
      CONV=1.0
      IF(IUNTS.EQ.2) CONV=.3048
      IF(IUNTS.EQ.3) CONV=30.48
C- ESTABLISH SHORELINES TO BE PLOTT?ED
      WRITE(11,/)"ENTER NUMBER OF SHORELINES TO BE PLOTTED"
      READ(11,1010) NS
      DO 40  I=1,NS
   30    WRITE(11,/)"ENTER SHORELINE DATAFILE * * * AND PERIOD, OR NO"
         READ(11,1020)  FILEID(I)
         FILE(1)=FILEID(I)
         IF(FILE(1).EQ."NO")  GOTO 40
         CHANGE(9,TITLE=FILE)
         INQUIRE(9,RESIDENT=VA)
          CLOSE 9
         IF(VA)  GOTO 40
C- SHORELINE DATA FILE DOESN'T EXIST
         WRITE(11,/)"DATA FILE DOESN'T EXIST  -- RE-ENTER !!"
         GOTO 30
   40 CONTINUE
C-  DEFINE CORRECTION FACTORS FOR DATUM OF MAPS
      WRITE(11,/)"DO YOU WANT DATUM CORRECTED  ",
     -         "1=NO, 2=DEPTHS, 3=DIFFS, 4=RATES"
      READ(11,1010) ICOR
C- IF DEPTHS ENTER DATE OF MAP TO CORRECT
      IF(ICOR.EQ.2) WRITE(11,/)"ENTER DATE OF MAP"
      IF(ICOR.EQ.2) READ(11,1030) IDATE
C-  SET HEADER EQUAL TO BLANKS
      DO 50 I=1,12
   50 HEADER(I)="      "
C-  ENTER MAP HEADING FOR PLOTTER
      WRITE(11,/) "    ENTER MAP HEADING FOR PLOTTER"
      READ(11,1040) HEADER
C-  DEFINE SIZE OF OUTPUT MAP
      WRITE(11,/) "    ENTER SCALE FACTOR - "
      READ(11,1050) SIZE
C-  DEFINE PRECISION OF OUTPUT NUMBERS
```

```
      WRITE(11,/)" ENTER NUMBER OF DIGITS TO BE PLOTTED "
      WRITE(11,/)"TO THE RIGHT OF THE DECIMAL POINT ON PLOTTER"
      READ(11,1010) NRGT
C- DEFINE OUTPUT DEVICE
      WRITE(11,/) "ENTER NUMBER OF OUTPUT UNIT (-9,09,10)"
      READ(11,1060) IOUT
C- IF TECTRONIX CRT READ TERMINAL NUMBER
      IF(IOUT.EQ.9) WRITE(11,/)"ENTER TERMINAL NUMBER",
     -      "S115, FOR RIGHT, S015, FOR LEFT"
      IF(IOUT.EQ.9) READ(11,1070) FILE
C-  IF MISSTAKE DON'T PLOT
      WRITE(11,/) "IS IT OKAY TO PLOT 1=NO, 2=YES"
      READ(11,1010)  NPL
      IF (NPL.EQ.1) GOTO 180
      IF(IOUT.EQ.9) CHANGE(8,TITLE=FILE)
      WRITE(11,/)  "    BEGIN PLOT"
C-  INITIALIZE VARIABLES
      HT=0.105
C-  MG(1) IS AN ASTERISK
      MG(1)=69
      CLOSE 11
      CALL PLTSRT(NAME,IOUT)
      CALL FACTOR(SIZE)
C-  REDEFINE ORIGIN
      CALL PLOT(1.9,.4,-3)
      CALL PLOT(0,90./IFT,-3)
C- PLOT AXES ENGLISH AND ? METRIC UNITS
      CALL AXIS(0,3.0/IFT,"E-W, FEET",11,120/IFT,0,0,IFT*100)
      CALL AXIS(-2./IFT,-1.*MXS/IFT,"N-S, FEET",11,MXS/IFT,90,
     -            MXS*100,IFT*(-100))
      IF (IUNTS.EQ.1) GOTO 60
      CALL AXIS(-9./IFT,-1.*MXS/IFT,"N-S, METERS",11,MXS/IFT,90,
     -            MXS*100*.3048,IFT*(-100)*.3048)
      CALL AXIS(0,10./IFT,"E-W, METERS",11,120/IFT,0,0,IFT*100*.3048)
   60 CONTINUE
C- IF MAP IS POST 1960 PLOT FERRY JETTY
      DO 70 I=1,NS
   70 IF(FILEID(I).LT."S1962")  GOTO 80
      GOTO 90
   80 CONTINUE
      CALL PLOT(3.16/IFT,-86.72/IFT,3)
      CALL PLOT(.76/IFT,-78.72/IFT,2)
      CALL PLOT(.88/IFT,-75.56/IFT,2)
      CALL PLOT(4.32/IFT,-70.96/IFT,2)
      CALL PLOT(10.68/IFT,-65.96/IFT,2)
      CALL SYMBOL(10.68/IFT,-65.96/IFT,HT*.75,MG(1),0,1)
   90 CONTINUE
C-  PLOT MAP TITLE
      CALL SYMBOL(1.2,(4.0+MXS)*(-1)/IFT,HT*2,HEADER,0,50)
C- INITIALIZE VARIABLES
      IPEN=3
C-  PLOT SHORELINES
      DO 150  I=1,NS
         IF(FILEID(I).EQ."NO    ") GOTO 150
         IT=1
         FILE(1)=FILEID(I)
C- IF POST 1900 FILL CENTER SECTION OF BREAKWATER
         IF(FILE(1).LT."S1900.") IPEN=2
         CHANGE(9,TITLE=FILE)
  100    CONTINUE
```

```
C-  READ SHORELINE X AND Y COORDINATES
          READ(9,1080,END=130) X,Y,Z,XX,YY,ZZ
          DO 130 J=1,2
C-  CORRECT SHORELINE POSITONS
              X=99.52*X
              Y=98.45*Y
C-  CHECK IF POSITON IS ON MAP
              IF(X.LT.0) GOTO 100
              IF(Y.GT.MXS) GOTO 140
C- INTEGERIZE X AND SAVE FARTHEST SOUTH POSITION FOR
C- SHORELINE IN IHAN COLUMN IN ARRAY S(M)
              M=X+.5
              IF(M.GT.MXE)  GOTO 110
              IF(M.LE.0.)  GOTO 110
              IF(Y.GT.S(M)) S(M)=Y
  110         CONTINUE
C- IF AT FIRST POSITION OF SHORELINE TO BE PLOTTED MOVE
C-  TO THAT POSITION WITH THE PEN UP
              IF(IT.GT.1)  GOTO 120
              CALL PLOT(X/IFT,Y/(-1)/IFT,3)
              IT=2
  120         CONTINUE
C-  MOVE TO EACH SHORE POSITION WITH THE PEN DOWN
              CALL PLOT(X/IFT,Y/(-1)/IFT,2)
              X=XX
              Y=YY
  130     CONTINUE
          GOTO 100
  140     CONTINUE
C-  SAVE FILE
          CLOSE 9
  150 CONTINUE
C-  PLOT BREAKWATER
        CALL SYMBOL(62.52/IFT,-32.72/IFT,HT*.75,MG(1),0,1)
        CALL PLOT(39.32/IFT,-24.52/IFT,2)
        CALL PLOT(27.4/IFT,-16.44/IFT,IPEN)
        CALL PLOT(15./IFT,-20./IFT,2)
        CALL SYMBOL(15./IFT,-20./IFT,HT*.75,MG(1),0,1)
C-  SET ALL COLUMNS OF S(J) WITHOUT SHORELINE TO SOUTH EDGE OF MAP
        DO 160 J=1,120
  160 IF(S(J).EQ.0) S(J)=MXS
C-  ESTABLISH CORRECTION FACTORS DESIGNATED EARLIER
        CORFCT=0
        IF(ICOR.EQ.2) CORFCT=.011*(1977-IDATE)
        IF(ICOR.EQ.3) CORFCT=.011*YEARS
        IF(ICOR.EQ.4) CORFCT=.011
C-  GO TO EACH GRID POINT, CONVERT POSITON TO INCHES
        DO 170 J=1,MXX
           X=1.0*(J-1)*INKX/IFT
           DO 170 I=1,MXY
C-  CHECK IF ON LAND
              IF(I*INKY-(INKY-1).GT.S(J*INKX-(INKX-1)))  GOTO 170
C-  CORECT VALUE
              STORE=AMAP(I,J)+CORFCT
              Y=-1.0*(I-1)*INKY/IFT
C- CHECK FOR DATA
              IF(AMAP(I,J).GE.95) GOTO 170
C-  PLOT NUMBER AND POSITION AFTER CORECTING TO RIGHT UNITS
              CALL NUMBER(X,Y+0.1,HT,CONV*STORE,0,NRGT)
              CALL SYMBOL(X,Y,HT/3,MG(1),0,1)
```

```
  170 CONTINUE
C-  FINISH EDGE OF MAP
      CALL PLOT(-2./IFT,-1.*MXS/IFT,3)
      CALL PLOT(125./IFT,(-1.)*MXS/IFT,2)
      CALL PLOT(125./IFT,3.0/IFT,2)
      CALL PLOT(120./IFT,3.0/IFT,2)
C-  REDEFINE ORIGIN AT ORIGINAL PLACE
      IF(IOUT.EQ.-9)  CALL PLOT(136./IFT,-100./IFT,-3)
      CALL PLOT(0,-90./IFT,-3)
      CALL PLOT(-1,9,-.4,-3)
C-  CLEAR PLOTTER
      CALL PLOT(0,0,IOUT)
      CALL HOME
      CLOSE 8
C-  WAIT FOR OPERATOR TO HIT RETURN
      READ(11,1010) CONTIN
      CALL PLOT(0,0,8)
  180 CONTINUE
      WRITE(11,/)"DO YOU WANT TO RE-PLOT THIS MAP 1=NO , 2=YES"
      READ(11,1010) NPL
      IF(NPL.EQ.2) GOTO 10
      RETURN
C-  READ FOR CONTINUE OR REPLOT
 1010 FORMAT(I1)
 1020 FORMAT(C6)
 1030 FORMAT(I4)
 1040 FORMAT(12A6)
 1050 FORMAT(F5.2)
 1060 FORMAT(I2)
 1070 FORMAT(A6)
 1080 FORMAT(8X,6(1X,F7.3))
      END
```

SUBSHRPLT (09/01/77)

```
$SET SEPARATE
C- CREATE FILES
FILE  9(TITLE="FILEID", KIND=DISKPACK, FILETYPE=7)
FILE  10(TITLE="FILEID", KIND=DISKPACK, FILETYPE=7)
FILE  11(KIND=REMOTE,MYUSE=IO)
FILE  8(KIND=REMOTE)
          SUBROUTINE SHRPLT(MXE, MXS)
C-  DIMENSION ARRAYS
          DIMENSION AMAP(35,35), NAME(2), FILEID(9), FILE(1), S(120)
          DATA NAME/'DEMARE 00115'/
          COMMON HEADER(12), MAP(100,120), FRAY(5), MG(64), VALUE(4),
        -    CLOSE(4)
          LOGICAL VA
C-  INITIALIZE VARIABLES
     10 IFT=10
          DO 20 J=1,120
     20 S(J)=0.0
C- DEFINE AXIS AS ENGLISH OR METRIC
          WRITE(11,/)"ENTER 1=FEET, 2=METRIC"
          READ(11,1010) IUNTS
C- DEFINE SHORELINES TO BE PLOTTED
          WRITE(11,/)"ENTER NUMBER OF SHORELINES TO BE PLOTTED"
          READ(11,1010) NS
          DO 40  I=1,NS
     30     WRITE(11,/)"ENTER SHORELINE DATAFILE * * * AND PERIOD, OR NO"
             READ(11,1020)  FILEID(I)
           FILE(1)=FILEID(1)
             IF(FILE(1).EQ."NO")  GOTO 40
             CHANGE(9, TITLE=FILE)
             INQUIRE(9,RESIDENT=VA)
           CLOSE 9
             IF(VA) GOTO 40
             WRITE(11,/)"DATA FILE DOESN'T EXIST  - - RE-ENTER!!"
             GOTO 30
     40 CONTINUE
C- SET HEADER EQUAL TO BLANKS AND READ TITLE OF MAP
          DO 50 I=1,12
     50 HEADER(I)="        "
          WRITE(11,/) "    ENTER MAP HEADING FOR PLOTTER"
          READ(11,1030) HEADER
C-  DEFINE SCALING FACTOR
          WRITE(11,/) "     ENTER SCALE FACTOR - "
          READ(11,1040) SIZE
C-  DEFINE OUTPUT UNIT
          WRITE(11,/) "ENTER NUMBER OF OUTPUT UNIT (-9,09,10)"
          READ(11,1050) IOUT
C- IF TEKTRONIX CRT INPUT TERMINAL NUMBER
          IF(IOUT.EQ.9) WRITE(11,/)"ENTER TERMINAL NUMBER",
        -      "S115, FOR RIGHT, S015, FOR LEFT"
          IF(IOUT.EQ.9) READ(11,1060) FILE
C- IF MISTAKE DON'T PLOT
          WRITE(11,/) "IS IT OKAY TO PLOT 1=NO, 2=YES"
          READ(11,1010)  NPL
          IF (NPL.EQ.1) GOTO 150
C- START PLOT
          IF(IOUT.EQ.9) CHANGE(8,TITLE=FILE)
          WRITE(11,/)  "    BEGIN PLOT"
```

```
C- INITIALIZE VARIABLES
      HT=0.105
      MG(1)=69
      CLOSE 11
      CALL PLTSRT(NAME,IOUT)
      CALL FACTOR(SIZE)
C-  REDEFINE ORIGIN
      CALL PLOT(1.9,.4,-3)
      CALL PLOT(0,90./IFT,-3)
C-  PLOT AXES
      CALL AXIS(0,3.0/IFT,"E-W, FEET",11,120/IFT,0,0,IFT*100)
      CALL AXIS(-2./IFT,-1.*MXS/IFT,"N-S, FEET",11,MXS/IFT,90,
     -          MXS*100,IFT*(-100))
      IF (IUNTS.EQ.1) GOTO 60
      CALL AXIS(-9./IFT,-1.*MXS/IFT,"N-S, METERS",11,MXS/IFT,90,
     -          MXS*100*.3048,IFT*(-100)*.3048)
      CALL AXIS(0,10./IFT,"E-W, METERS",11,120/IFT,0,0,IFT*100*.3048)
   60 CONTINUE
      DO 70 I=1,NS
C- IF PRE-1960 PLOT FERRY JETTY
   70 IF(FILEID(I).LT."S1962")  GOTO 80
      GOTO 90
   80 CONTINUE
      CALL PLOT(3.16/IFT,-86.72/IFT,3)
      CALL PLOT(.76/IFT,-78.72/IFT,2)
      CALL PLOT(.88/IFT,-75.56/IFT,2)
      CALL PLOT(4.32/IFT,-70.96/IFT,2)
      CALL PLOT(10.68/IFT,-65.96/IFT,2)
      CALL SYMBOL(10.68/IFT,-65.96/IFT,HT*.75,MG(1),0,1)
   90 CONTINUE
C-  PLOT TITLE OF MAP
      CALL SYMBOL(1.2,(4.0+MXS)*(-1)/IFT,HT*2,HEADER,0,50)
      IPEN=3
C-  PLOT SHORELINES
      DO 140  I=1,NS
         IF(FILEID(I).EQ."NO") GOTO 140
         IT=1
         FILE(1)=FILEID(I)
         IF(FILE(1).LT."S1900.") IPEN=2
         CHANGE(9,TITLE=FILE)
  100    CONTINUE
         READ(9,1070,END=130) X,Y,Z,XX,YY,ZZ
         DO 120 J=1,2
            X=99.52*X
            Y=98.45*Y
            IF(X.LT.0) GOTO 100
            IF(Y.GT.MXS) GOTO 130
            IF(IT.GT.1)  GOTO 110
            CALL PLOT(X/IFT,Y/(-1)/IFT,3)
            IT=2
  110       CONTINUE
            CALL PLOT(X/IFT,Y/(-1)/IFT,2)
            X=XX
            Y=YY
  120    CONTINUE
         GOTO 100
  130    CONTINUE
         CLOSE 9
  140 CONTINUE
C- PLOT BREAKWATER
```

```
      CALL SYMBOL(62.52/IFT,-32.72/IFT,HT*.75,MG(1),0,1)
      CALL PLOT(39.32/IFT,-24.52/IFT,2)
      CALL PLOT(27.4/IFT,-16.44/IFT,IPEN)
      CALL PLOT(15./IFT,-20./IFT,2)
      CALL SYMBOL(15./IFT,-20./IFT,HT*.75,MG(1),0,1)
      CALL PLOT(-2./IFT,-1.*MXS/IFT,3)
      CALL PLOT(125./IFT,(-1.)*MXS/IFT,2)
      CALL PLOT(125./IFT,3.0/IFT,2)
      CALL PLOT(120./IFT,3.0/IFT,2)
C- REDEFINE ORIGIN AT ORIGINAL PLACE
      IF(IOUT.EQ.-9)  CALL PLOT(136./IFT,-100./IFT,-3)
      CALL PLOT(0,-90./IFT,-3)
      CALL PLOT(-1.9,-.4,-3)
C- CLEAR PLOTTER
      CALL PLOT(0,0,IOUT)
      CALL HOME
      CALL PLOT(0,0,8)
C- WAIT FOR RETURN PUNCH
      READ(11,1010) CONTIN
      CLOSE 8
  150 CONTINUE
C- REPLOT OR RETURN
      WRITE(11,/)"DO YOU WANT TO RE-PLOT THIS MAP 1=NO , 2=YES"
      READ(11,1010) NPL
      IF(NPL.EQ.2) GOTO 10
      RETURN
 1010 FORMAT(I1)
 1020 FORMAT(C6)
 1030 FORMAT(12A6)
 1040 FORMAT(F5.2)
 1050 FORMAT(I2)
 1060 FORMAT(A6)
 1070 FORMAT(8X,6(1X,F7.3))
      END
```