TP 79-2

Sediments, Shallow Subbottom Structure, and Sand Resources of the Inner Continental Shelf, Central Delmarva Peninsula

by

Michael E. Field

TECHNICAL PAPER NO. 79-2
JUNE 1979

Approved for public release;
distribution unlimited.

U.S. ARMY, CORPS OF ENGINEERS
COASTAL ENGINEERING RESEARCH CENTER
Kingman Building
Fort Belvoir, Va. 22060

Limited free distribution within the United States of single copies of this publication has been made by this Center. Additional copies are available from:

National Technical Information Service
ATTN: Operations Division
5285 Port Royal Road
Springfield, Virginia 22161

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER TP 79-2	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (*and Subtitle*) SEDIMENTS, SHALLOW SUBBOTTOM STRUCTURE, AND SAND RESOURCES OF THE INNER CONTINENTAL SHELF, CENTRAL DELMARVA PENINSULA		5. TYPE OF REPORT & PERIOD COVERED Technical Paper 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Michael E. Field		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of the Army Coastal Engineering Research Center (CEREN-GE) Kingman Building, Fort Belvoir, Virginia 22060		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS D31235
11. CONTROLLING OFFICE NAME AND ADDRESS Department of the Army Coastal Engineering Research Center Kingman Building, Fort Belvoir, Virginia 22060		12. REPORT DATE June 1979 13. NUMBER OF PAGES 122
14. MONITORING AGENCY NAME & ADDRESS(*if different from Controlling Office*)		15. SECURITY CLASS. (*of this report*) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (*of this Report*) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*) Artificial beach nourishment Central Delmarva Peninsula Geomorphology Sediments Seismic reflection		

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

A data base consisting of 880, 180, and 35 kilometers (475, 97, and 19 nautical miles) each of high-resolution seismic reflection, bathymetric, and side-scan sonar profilings was obtained in 1970 and 1974, along with 71 vibratory cores and 3 onshore borings. These data were analyzed to assess the resource potential of sand suitable for use in beach restoration and to establish the Quaternary evolutionary framework of the northern Delmarva inner shelf.

(continued)

Shallow subsurface strata consist of gently dipping Neogene sedimentary beds that conform to the gradient and direction of the Atlantic Coastal Plain and display no evidence of tectonic deformation. Eleven major acoustic surfaces, including the presumed Tertiary-Quaternary nonconformity at about -30.5 to -61 meters (-100 to -200 feet), are present within the upper 122 meters (400 feet) of the shelf subbottom. Buried channels are common to the sea floor of the entire region; in the Delaware Bay entrance, most channels are cut to 46 meters (150 feet) below sea level and are filled laterally from both the New Jersey and Delaware shelves. Many small channels on the Maryland shelf are alined with existing onshore drainage or historical inlet sites.

The upper 6 meters (20 feet) of the inner shelf consists of terrigenous sands and silts derived from the adjacent Coastal Plain and Piedmont Province. Environments of deposition represented on the shallow shelf are: modern marine, back barrier, lagoonal, and fluvial. Gray-brown, fine to coarse, well-sorted quartz sand is the dominant lithology on the surface and decreases in relative abundance with depth. The shoal sands unconformably overlie poorly sorted fine sands and muds remnant from Holocene back-barrier and lagoonal deposition, which are periodically exposed and eroded on the sea floor.

Linear shoals are a dominant topographic feature of the U.S. mid-Atlantic shelf and off the Maryland shelf. They have a high potential as an offshore source of sand for use in beach restoration. Individual shoals typically contain between 15 and 54 million cubic meters (20 and 70 million yards) of fine to coarse, well sorted to moderately sorted quartz sand. Total estimated volume of suitable material is about 1.7×10^9 cubic meters (2.2×10^9 cubic yards).

PREFACE

This report is one of a series which describe the results of the Inner Continental Shelf Sediment and Structure (ICONS) program. The primary objective of the ICONS study is locating and delineating offshore sand and gravel deposits suitable for beach nourishment and restoration. This work was carried out under the coastal processes research program of the U.S. Army Coastal Engineering Research Center (CERC).

This report was prepared by Michael E. Field, formerly with CERC and presently with the U.S. Geological Survey (USGS), under the general supervision of D.B. Duane and W.R. James, former Chiefs of the Geological Engineering Branch at CERC. As part of the overall research program of the Engineering Development Division, the ICONS study was under the general supervision of G.M. Watts, former Chief of the Division.

The author acknowledges the following individuals at CERC who provided assistance in various aspects of this study: W.R. James, E.P. Meisburger, R.K. Schwartz, A.E. DeWall, S.J. Williams, and E. Nelson. H.D. Palmer (Dames & Moore, Inc.) assisted in the 1974 data collection phase, J.M. Wiegle (USGS) assisted in correlating certain aspects of the seismic data with onshore geology, and J.W. Pierce (Smithsonian Institution) offered criticisms on some of the ideas presented.

The data and much of the information included in this report provided the basis for Field's dissertation submitted to George Washington University in partial fulfillment of doctoral requirements (Field, 1976).

Microfilm of all seismic data is stored at the National Solar and Terrestrial Geophysical Data Center (NSTGDC), Rockville, Maryland 20852. Cores collected during the field survey program are in a repository at the University of Texas, Arlington, Texas 76010, under agreement with CERC. Requests for information relative to these items should be directed to NSTGDC or the University of Texas.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

Ted E. Bishop

TED E. BISHOP
Colonel, Corps of Engineers
Commander and Director

CONTENTS

		Page
	CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI)	8
I	INTRODUCTION	9
	1. Background	9
	2. Scope	10
	3. Field Data Collection Procedures	15
	4. Data Processing and Analysis	17
	5. Regional Setting	18
II	TOPOGRAPHY OF THE DELMARVA CONTINENTAL SHELF	22
	1. Morphologic Elements of the Shelf	22
	2. Survey of Delaware Bay to Chesapeake Bay	26
	3. Delaware Inner Shelf	29
	4. Maryland Inner Shelf	31
	5. Northern Virginia Inner Shelf	33
III	SUBSURFACE STRUCTURE AND BEDDING	36
	1. Primary Reflection Horizons and Reflection Units	39
	2. Correlation of Reflector Surfaces with Stratigraphic and Hydrologic Units	40
	3. Secondary Reflection Horizons	44
	4. Acoustic Structure of Shoals	51
IV	CHARACTERISTICS AND DISTRIBUTION OF INNER SHELF SEDIMENTS	54
	1. Background	54
	2. Lithology of Major Sediment Types	55
	3. Surface and Subsurface Sediment Distribution	59
V	DISCUSSION	72
	1. Origin and History of Sediments	72
	2. Evolution of Inner Shelf Bathymetry	77
VI	POTENTIAL SAND RESOURCES	83
	1. Depositional Patterns and Processes Along the Coast	83
	2. Requirements for Beach Restoration and Characteristics of Beach Sands	91
	3. Resource Assessment of Inner Shelf Sand Deposits	92
VII	SUMMARY	103
	LITERATURE CITED	106
APPENDIX		
A	INTERPRETED SEISMIC REFLECTION PROFILES	113
B	GRAIN-SIZE ANALYSIS	117

CONTENTS--Continued

TABLES

		Page
1	Coastal plain stratigraphic nomenclature and aquifers	19
2	Hierarchy and occurrence of morphological elements on the Continental Shelf.	23
3	Correlation of acoustic horizons with significant stratigraphic and hydrologic surfaces.	42
4	Characteristics of major sediment types	57
5	Percent abundance of major sediment types on the sea floor and below.	62
6	Fill requirements for the Maryland coast.	92
7	Textural characteristics of beach samples at Ocean City and Assateague	93
8	Extreme and typical values for size, shape, and orientation of shoals.	95
9	Estimated sand volumes of potential offshore borrow sites	99

FIGURES

1	Regional setting of the study area.	11
2	Seismic reflection tracklines and core locations for Delawaand northern Maryland inner shelf.	12
3	Seismic reflection tracklines and core locations for southern Maryland and northernmost Virginia inner shelf.	13
4	Seismic reflection, fathometer, and side-scan sonar tracklines for linear shoals in the Maryland inner	14
5	Schematic diagram of four major morphological elements of the northern Delmarva inner shelf	25
6	Topography of the Delmarva Continental Shelf showing locations of cross-sectional profiles illustrated in Figure 7.	27
7	Cross-sectional profiles of the surface of the Delmarva Continental Shelf illustrating major topographic trends.	28
8	Detailed bathymetry of the Delaware Inner Continental Shelf . . .	30
9	Detailed bathymetry of the Maryland Inner Continental Shelf . . .	32

CONTENTS

FIGURES--Continued

		Page
10	Smoothed fathometer profiles for two nearshore shoals	34
11	Detailed bathymetry of the northern Virginia Inner Continental Shelf	35
12	Acoustic records produced by the three types of seismic reflection equipment used in this study	37
13	Generalized cross-sectional profile of the shallow subsurface off northern Assateague Island showing major seismic reflection surfaces and reflection units.	38
14	Structure contour map on the surface of the acoustic reflector A_2	41
15	Structure contour map on the surface of acoustic reflector B_1	43
16	Structure contour map of the pre-Holocene erosional drainage surface off Delaware	45
17	Location map and interpreted acoustic profiles of buried and surface channels in Delaware Bay entrance	46
18	Map showing location and thalweg depths of buried channels on the inner shelf between Bethany Beach, Delaware, and Maryland-Virginia State line.	48
19	Interpreted acoustic profiles across buried channels on the inner shelf between Bethany Beach, Delaware, and Ocean City, Maryland.	49
20	Interpreted acoustic profiles across buried channels on the inner shelf between Ocean City and Virginia State line.	50
21	Plot of maximum thalweg depth of buried channels versus distance from shoreline	52
22	Interpreted seismic reflection profiles across Great Gull Banks.	53
23	Locations of vibratory cores used in this study shown in relation to shelf topography.	56
24	Map showing surface distribution of major sediment types defined in this study in relation to sea floor topography . . .	60

CONTENTS

FIGURES--Continued

		Page
25	Map showing distribution of major sediment types 5 feet below the sea floor in relation to surface topography	61
26	Map showing distribution of major sediment types 10 feet below the sea floor in relation to surface topography	63
27	Map showing distribution of major sediment types 15 feet below the sea floor in relation to surface topography	64
28	Depth and radiocarbon age of peaty sediments from the study area plotted against two published sea level curves	66
29	Composite photo of core 33	68
30	Composite photo of core 42	69
31	Geologic cross sections along the axes of Isle of Wight and Ocean City shoals	71
32	Composite photo of core 20	73
33	Generalized sediment column for the shallow subsurface of the Maryland Inner Continental Shelf	75
34	Plan view and representative cross-section profile of the Maryland inner shelf	80
35	Photos showing areas that are major exceptions to the general trend of erosion	85
36	Time series of the growth of Fishing Hook spit, Assateague Island, 1902 to 1933	88
37	Geologic cross section across central Assateague in the vicinity of Fox Hills level	90
38	Map showing location and thickness of medium and coarse (modal size) sand in relation to sea floor topography	94
39	Scatter diagram of mean grain size versus sorting for 160 sand samples collected from the upper 1 meter of the shelf floor	96
40	Base map of the shoal field of the northern Delmarva inner shelf indicating potential borrow sites	97
41	Mean grain size versus depth below sea floor for selected cores form offshore linear shoals	100
42	Mean grain size versus depth below sea floor for selected cores collected from the shoreface and shoreface shoals	101

CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1]To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.

To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

SEDIMENTS, SHALLOW SUBBOTTOM STRUCTURE, AND SAND RESOURCES OF THE INNER CONTINENTAL SHELF, CENTRAL DELMARVA PENINSULA

by
Michael E. Field

I. INTRODUCTION

1. Background.

Ocean beaches and dunes constitute a vital buffer zone between the sea and populated coastal areas, and also provide much needed recreation areas for the public. The construction, improvement, and maintenance of beaches through the placement (nourishment) of sand on the shore is one of several protection methods. This technique has gained prominence in coastal engineering largely as a result of the successful program initiated at Santa Barbara, California, in 1938 (Hall, 1952).

Where a specified plan of improvement involves shore restoration and periodic nourishment, large volumes of sandfill may be needed. In recent years it has become increasingly difficult to obtain suitable sand from lagoonal or inland sources in sufficient quantities and at an economical cost for beach-fill purposes. This difficulty is due in part to increased land value, depletion of previously used nearby sources, and added cost of transporting sand from areas increasingly remote. Material composing the bottom and subbottom of estuaries, lagoons, and bays is often too fine grained and unsuitable for long-term protection. Regardless of the source of replacement material, the loss of some fines is inevitable as replacement beach sediment seeks equilibrium with its environment. However, it is possible to estimate the amount of material that will be lost through sorting in the surf zone by a quantitative comparison of the placed material with the native material and therefore minimize losses through selection of the most suitable fill material (Krumbein and James, 1965; James, 1974; Hobson, 1977).

The problem of locating suitable sand supplies led the Corps of Engineers to a search for new unexploited deposits of sand. The search focused offshore with the intent to explore and inventory deposits suitable for future beach-fill requirements. This exploration program is conducted through the U.S. Army Coastal Engineering Research Center (CERC).

In 1964, a program was initiated to survey offshore regions of the Atlantic, Pacific, gulf, and Great Lakes coastal areas to delineate the character of sand deposits. Formerly called the Sand Inventory Program, it began with a survey off the New Jersey coast. Subsequent surveys have included the Inner Continental Shelf off Florida, Texas, New England, New York, Maryland, and parts of North Carolina, Delaware, Virginia, California, and Lakes Michigan and Erie. Recognizing a broader application to the CERC mission of information collected in conduct of the research, the program is now referred to as the Inner Continental Shelf

Sediment and Structure (ICONS) program. The ICONS program is directed not only toward the mapping of sand deposits suitable for beach restoration but also the delineation of shelf structural characteristics (Meisburger and Duane, 1969), analysis of shelf history and sediment sources (Duane, et al., 1972; Pilkey and Field, 1972; Field, 1974), and determination of regional engineering properties of shelf sediments (Williams and Duane, 1972; Field and Duane, 1972).

An early study by the Corps of Engineers in evaluating techniques for transferring offshore sand to the beach is described by Mauriello (1967). This experiment at Sea Girt, New Jersey, involved dredging of 191,000 cubic meters (250,000 cubic yards) of sand by use of the hopper dredge, *Geothals*, at a location 3.2 kilometers (2 miles) offshore from the beach segment to be restored. The loaded dredge, which had a pump-out capability, docked alongside an achored barge and the sand was pumped ashore through a submerged pipeline.

At Redondo Beach, California, in 1967-68, the U.S. Army Engineer District, Los Angeles, contracted dredging of more than 1.1 million cubic meters (1.4 million cubic yards) of sand from offshore in 12.2 meters (40 feet) of water and transferring to the beach. The dredging contractor used a 41-centimeter (16 inches) hydraulic dredge with powerful water jets for agitation in lieu of a normal cutterhead on the ladder. These operations, as well as others conducted in open-ocean inlet mouths, in the Long Island Sound, and along the gulf coast, have demonstrated the feasibility of using offshore marine and lake deposits for beach restoration and periodic nourishment operations.

2. <u>Scope</u>.

This study examines the surface and shallow subsurface sediments of the Atlantic Inner Continental Shelf off Delaware, Maryland, and northern Virginia (Fig. 1). Bounds of the study are from the mouth of Delaware Bay (38°54' N.) south to Chincoteague, Virginia (37°55' N.), and from the coastline out to the 25-meter (80 feet) depth contour or up to 36 kilometers (20 nautical miles) seaward of the beach. The prime area of concentration is the upper 30 meters (100 feet) of the Maryland sea floor between the 6- and 21-meter (20 and 70 feet) depth contours.

Field data collected consist of 880 kilometers (475 nautical miles) of high-resolution continuous seismic reflection (CSR) profiling, 180 kilometers (97 nautical miles) of fathometer profiling, 35 kilometers (19 nautical miles) of side-scan sonography, and 71 vibratory cores, 3 to 9 meters (10 to 30 feet) long and 6.4 centimeters (2.5 inches) in diameter. The cores and 700 kilometers (378 nautical miles) of CSR profiling were obtained the summer of 1970 (Figs. 2 and 3); the other data, including additional CSR profiling using improved equipment, were collected the spring of 1974 (Fig. 4). Many tracklines in the 1974 survey were rerun along lines previously surveyed to gather additional or higher quality data in areas where data quality was marginal and also to provide a basis for interpretation and correlation of the two data sets.

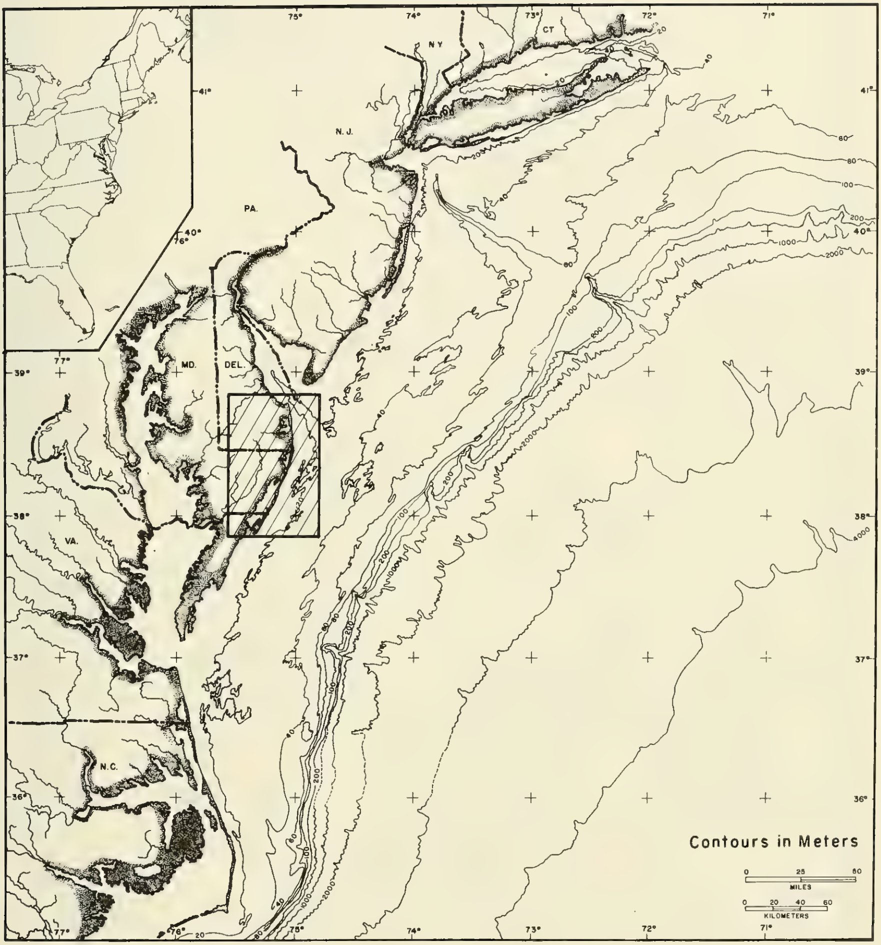


Figure 1. Regional setting of the study area. The inner shelf of Delaware, Maryland, and northern Virginia is centered in the U.S. mid-Atlantic geologic province.

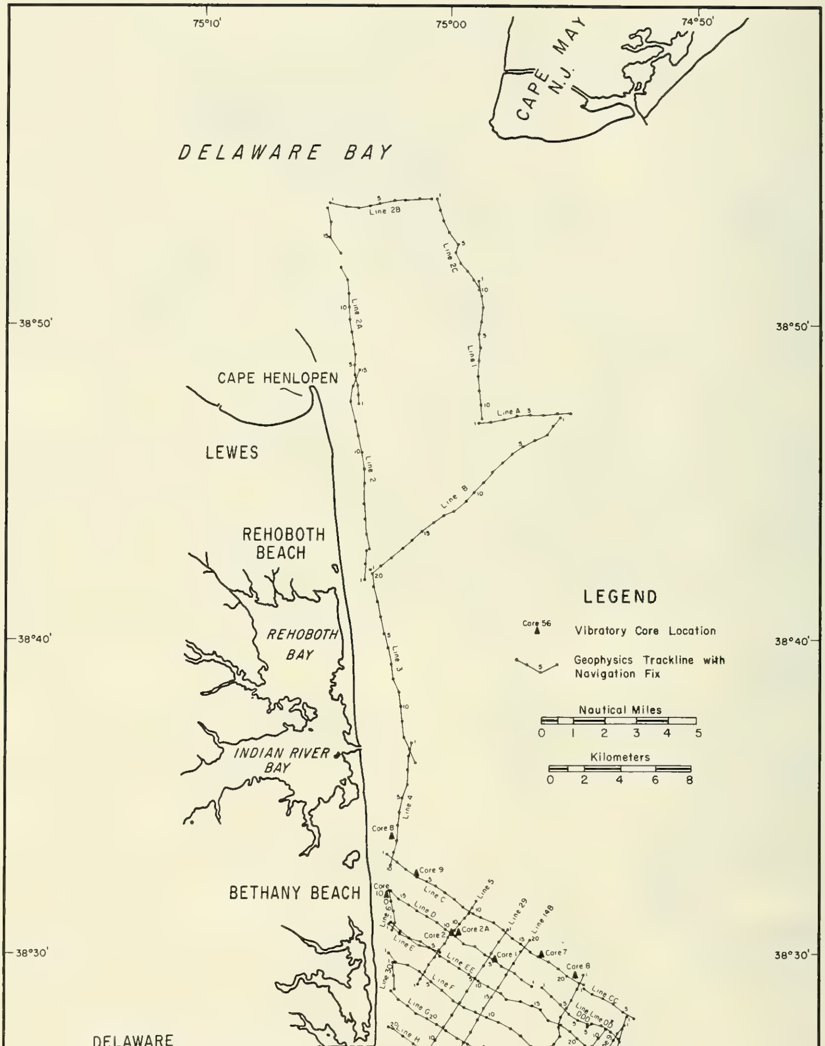


Figure 2. Seismic reflection tracklines and core locations for Delaware and northern Maryland inner shelf; field data collected summer 1970.

Figure 3. Seismic reflection tracklines and core locations for southern Maryland and northernmost Virginia inner shelf; field data collected summer 1970.

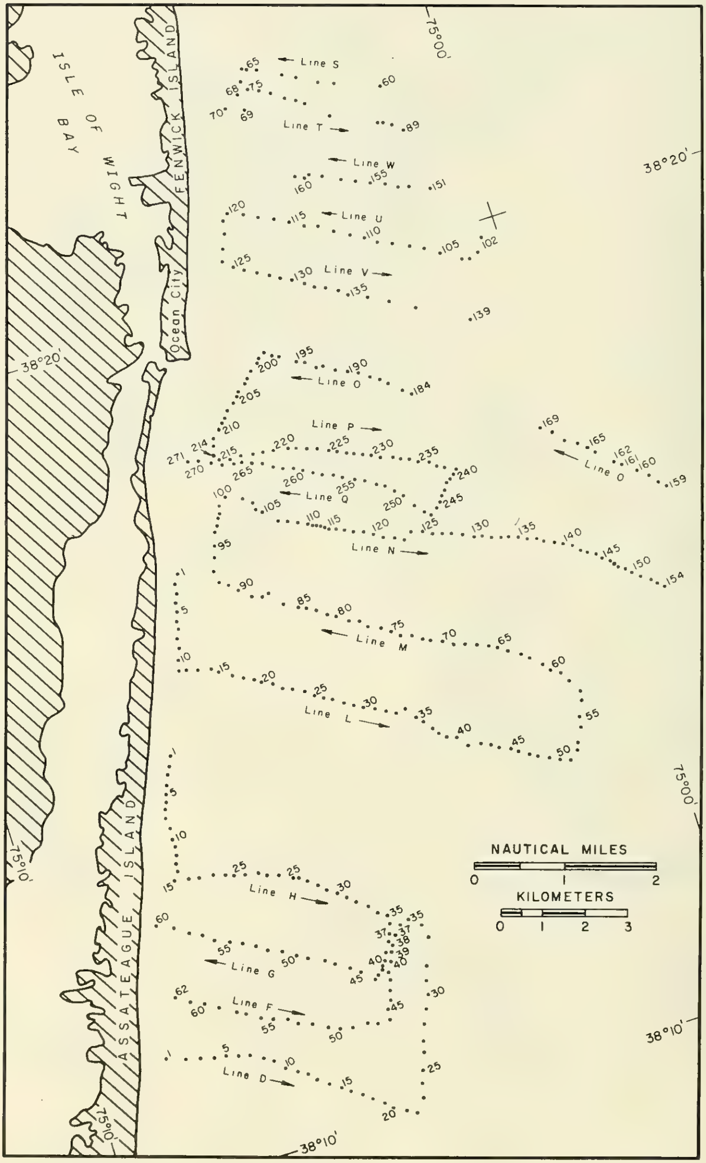


Figure 4. Seismic reflection, fathometer, and side-scan sonar tracklines for linear shoals in the Maryland inner shelf; field data collected spring 1974.

In addition to the offshore data, three auger borings were made 30 meters below mean low water (MLW) on central Assateague Island in June 1974. These borings were obtained for comparison with and interpretation of published borehole logs and for correlation with the inner shelf sediment column.

3. Field Data Collection Procedures.

a. Approach. The general approach to the field study was to gather large quantities of acoustic reflection data, supplemented by physical samples (cores) which provided a continuous network throughout the study area. This large data base was then used to determine group characteristics of shelf features and to generalize the subsurface configuration and lithofacies.

Survey tracklines for the 1970 study were laid out in two line patterns: grid or reconnaissance lines. A grid pattern with a line spacing of either 1.6 or 3 kilometers (1 or 2 miles), was used to cover areas where a more detailed development of bottom and subbottom conditions was needed. Off northern Delmarva Peninsula, lines were laid out both parallel and perpendicular to the pervasive north-northeast trending ridges or shoals to obtain cross sections of those features. Off the coast of Delaware and Delaware Bay, reconnaissance lines were surveyed to provide a basis for correlation with published studies of the areas and for comparison of the shelf structure off the headland region of the Delmarva Peninsula with that of the barrier island section. Selection of core sites was based on a continuing review of the seismic profiles as they became available during the survey. Tracklines and core locations are shown in Figures 2 and 3.

After a preliminary analysis of the data, a detailed survey was planned for selected parts of the ridge and swale topography of the Maryland inner shelf. Tracklines were laid out to give three or four crossings of each shoal so that detailed information could be obtained on internal structures and the surface configuration of the ridges.

b. Navigation. Position location was controlled during the 1970 survey by using a Motorola Range Positioning System (RPS) and during the 1974 survey by using a Motorola Mini-ranger. These systems accurately locate a vessel within two fixed reference points. The equipment operates on the same basic principle as a noncoherent pulse radar, utilizing an X-band interrogator unit on the survey vessel and two radar transponders positioned at reference points on land. Elapsed time between the interrogation and transponder response provides the basis for determining the range to each of the transponders. Range to range information from the transponders is triangulated to provide a position fix. RPS is capable of operating at line-of-sight ranges up to 93 kilometers (50 nautical miles), and with appropriate calibration the accuracy is better than 15 meters (45 feet).

The interrogator uses a time-delayed, coded pulse to interrogate the transponders which prevents interference from other radar signals in the area. In the field, the two radar transponders were positioned at known geographic locations with reply to the interrogator at frequencies of 9,310 and 9,490 megahertz. The transponder replies were received by the dual-channel X-band receiver with the time interval between the interrogation and transponder response precisely measured by crystal-controlled digital circuits. To obtain reasonable angles of intersection, transponders were leapfrogged from site-to-site down the coastline as the survey progressed southward. On several occasions during the 1974 survey only one transponder could be read. At these times, the ship position was tracked by triangulation from the one operating beacon and distance from shore as determined by conventional radar.

c. Acoustic Profiling. During the two field surveys five types of acoustic profiling equipment were used: three different continuous seismic reflection profilers, a fathometer, and a side-scan sonar profiler. The latter two instruments and one seismic profiler were used in the 1974 survey.

Seismic reflection profiling is a widely used technique for deliniating subbottom structures and bedding planes in sea floor sediments and rocks. Continuous reflections are obtained by generating repetitive, high-energy sound pulses near the water surface and recording "echoes" reflected from the bottom-water interface and subbottom interfaces between acoustically dissimilar materials. In general, the compositional and physical properties which commonly differentiate sediments and rocks also produce acoustic reflections at interfaces between different materials. Thus, an acoustic profile is roughly comparable to a geologic cross section. During continuous profiling the sound source is fired at a rapid rate and returning signals from bottom and subbottom interfaces are received by one or more hydrophones. Returning signals are amplified and fed to a recorder which graphically plots the two-way signal traveltime. Depth can be determined by assuming a constant velocity for sound in water and unconsolidated shelf sediments. General seismic profiling techniques are discussed in detail in Miller, Tirey, and Mecarini (1967) and Moore and Palmer (1968).

Seismic reflection profiling for the 1970 survey was conducted by Ocean Science and Engineering, Inc. (OSE), Washington, D.C., under contract to CERC with the OSE Dual-Frequency Seismic Profiler. The system consists of a 3.5-kilohertz crystal transducer and a variable power sparker with a 3-meter hydrophone array for a receiver. The initial operating power level of the sparker was 200 joules; however, reverberations in shallow water caused a loss of detail in the uppermost sediments so the sparker was operated at the 60- to 90-joule level. Acoustic data were processed, amplified, and recorded on a Gifft recorder. The spring 1974 survey used a Bolt, Beranek, and Newman, Inc. (BBN) Acoustipulse system (tracklines are shown in Fig. 4). The system utilized a electromagnetically driven diaphragm to produce a broadband acoustic pulse; the motion of the diaphragm (or transducer) is controlled to minimize the formation of a secondary or "bubble pulse." Up to three transducers, each capable of over 1,000 joules, can be mounted on a catamaran to give a depth penetration of 90 to 150 meters (300 to 500 feet).

During the 1974 survey, a standard 7-kilohertz fathometer and a side-scan sonar profiler were also used. The fathometer produced an accurate profile of bottom topography at an expanded scale (vertical exaggeration is approximately X 25, compared to about X 4 for the seismic reflection equipment). The E.G.G. side-scan sonar consists of a towed "fish" that emits a 100-kilohertz sonic beam only 1° wide in the horizontal plane and 40° wide in the vertical plane. The sonic beam extends out across the surface on either side of the fish and distinguishes by the character of the reflected signal, change in surface lithology, bed forms, and man-made structures (e.g., pipelines, wrecks). A variable-scale strip chart allows examination of the sea floor up to 150 meters (500 feet) on either side of the ship track.

d. Collection of Offshore Cores and Onshore Borings. A hydraulic vibrating hammer-driven coring assembly (OSE M30,000 corer) was used to obtain cores from the survey area. The apparatus consisted of a standard core barrel, liner, shoe, and core catcher with the driver element fastened to the upper end of the barrel. These were enclosed in a self-supporting frame which allowed the assembly to rest on the bottom during coring, thus limiting the motion of the support vessel in response to waves. Power was supplied to the vibrator by a flexible hose line from a deck-mounted air compressor. After the core was driven and recovered, the plastic liner holding the sample was removed, marked, and capped.

Three onshore borings were collected from central Assateague by using a truck-mounted power auger. The holes were cased with a slurry of driller's mud, and individual samples were collected at 1.5-meter (5 feet) increments by a split-spoon sampler. This technique yields reliable samples from each horizon; if a given sample (average thickness of 21 centimeters or 0.7 foot) extends across a lithologic contact, it can be readily determined and noted to avoid misinterpretation.

4. Data Processing and Analysis.

a. Acoustic Profiling. Seismic records were analyzed to establish the principal bedding or structural features in the uppermost part of the section. After preliminary analysis, profile data were reduced to detailed cross-sectional profiles showing all reflective interfaces within the subbottom. Selected acoustic reflectors were then mapped either to provide a real continuity or because the horizons were considered significant due to their extent and relationship to the general structure and geology of the study area. Where possible, the uppermost mapped reflector was correlated with core data to provide a measure of continuity between cores. Major emphasis was placed on the primary acoustic reflectors that represented Quaternary sediment facies. Secondary or local reflectors were analyzed for location, orientation, and depth of buried channels and for presence and trend of internal stratification in the ridge topography.

Fathometer profiles were studied to learn more about the shape (side slopes, crest orientation and character) of major ridges on the Maryland shelf. Side-scan sonar data were reviewed for information on bed forms and gross textural distribution across the ridges.

b. Lithology and Textural Analysis. Samples were obtained from the cores at 0.3-meter (1 foot) intervals by either splitting the core or drilling through the side of the plastic liner. Gross lithology of core and boring samples was determined by examination under a binocular microscope. Characteristics of the sediment noted include: color, texture, size, sorting, gross mineralogy, and faunal constituents. Particular emphasis was placed on identification of dominant and diagnostic clastic and skeletal particles. Samples from the three boreholes made on central Assateague were analyzed to provide a comparison of the adjacent barrier island with the inner shelf sedimentary record.

Textural properties of several hundred sand samples were analyzed by sieving at 0.5-phi intervals or by the settling tube method. The latter analysis was made on the CERC Rapid Sediment Analyzer (RSA) which effectively monitors grain size by measuring the fall velocity of particles in a column of water.

5. Regional Setting.

a. Geologic Setting and Stratigraphy. The Delmarva Peninsula is part of the Atlantic Coastal Plain province of the eastern United States which extends from Florida to Long Island, New York, and is bordered on the west by the Piedmont province. Bounded by Chesapeake Bay and Delaware Bay, Delmarva comprises about 5,400 square kilometers (6,500 square miles) and contains most of Delaware and parts of Maryland and Virginia.

Underlying the peninsula is a seaward-thickening wedge of unconsolidated clastic sediments dating from at least earliest Cretaceous time and possibly earlier (Jurassic). These sediments thicken in a southeast direction from less than 150 meters near Baltimore to more than 2,438 meters (8,000 feet) near Ocean City. The basement is pre-Cambrian crystalline rock. Major structural trends in the basement surface are the southeast-trending Salisbury Embayment (beneath the peninsula) and the Baltimore Canyon Trough (beneath the Outer Continental Shelf).

Characteristics and stratigraphic relationships of Cretaceous and Tertiary strata underlying eastern Delmarva, reported by Rasmussen and Slaughter (1955), have recently been reviewed by Cushing, Kantrowitz, and Taylor (1973). Their discussion is summarized below and pertinent information on stratigraphic nomenclature and hydrologic units is tabulated in Table 1.

Nearly three-fourths of the total sediment column is composed of Lower Cretaceous nonmarine rocks. The upper surface elevation of these rocks ranges from above sea level at the western edge of the Coastal Plain to more than 610 meters (2,000 feet) below sea level along the coastline; total thickness ranges from a few feet to more than 1,830 meters (6,000 feet). The sediments directly overlie the crystalline

Table 1. Coastal plain stratigraphic nomenclature and aquifers (modified from Cushing, Kantrowitz, and Taylor, 1973).

System	Series	Stratigraphic units: Virginia	Stratigraphic units: Maryland	Stratigraphic units: Delaware	Aquifer names
Quaternary	Holocene	--------[1]	--------	--------	Quaternary aquifer
	Pleistocene	Columbia Group undivided	Columbia Group undivided	Columbia Group undivided	
Tertiary	Pliocene (?)	---------	Brandywine Formation	---------	
	Miocene	Chesapeake Group: Yorktown Formation	Chesapeake Group: Yorktown Formation	Chesapeake Group undivided	Pocomoke aquifer
		St. Marys Formation	St. Marys Formation		Manokin aquifer
		Choptank Formation	Choptank Formation		Frederica aquifer
		Calvert Formation	Calvert Formation		Federalsburg aquifer
					Cheswole aquifer
	Oligocene[2]				
	Eocene	Chickahominy Formation	Piney Point Formation	Piney Point Formation	Piney Point aquifer
		Nanjemoy Formation	Nanjemoy Formation	Nanjemoy Formation	
	Paleocene	Aquia Formation	Aquia Formation	Rancocas Group: Vincentown Formation	Aquia and Kincocas aquifer
			Brightseat Formation	Rancocas Group: Hornerstown sand	
Cretaceous	Upper Cretaceous	Mattaponi Formation	Monmouth Formation	Mount Laurel sand	
			Matawan Formation	Matawan Group: Marshalltown Formation	
				Englishtown Formation	
				Merchantville Formation	
			Magothy Formation	Magothy Formation	Magothy aquifer
			Raritan Formation	Potomac Formation	Nonmarine Cretaceous aquifer
	Lower Cretaceous	Potomac Group: Patapsco Formation	Potomac Group: Patapsco Formation		
			Arundel Formation		
		Patuxent Formation	Patuxent Formation		

[1]No name assigned.
[2]Section not present.

basement, with the possible exception of some local occurrences of Jurassic deposits (Kraft, Biggs, and Halsey, 1973). The deposits, dominantly interbedded lenses of lignitic light-gray and white quartz sand and various colored suites of silt and clay, represent deposition in a deltaic environment of shifting river channels, flood plains, and swamps. Overlying the thick nonmarine Cretaceous sediments are marine Cretaceous deposits of lignitic quartz sand, glauconitic quartz sand, clay, and silt. Sand bodies are generally laterally continuous. The basal transgressive unit of this sequence is the Magothy Formation, which represents the lagoonal or estuarine phase.

Marine sediments of Paleocene and Eocene age overlie the Cretaceous deposits. Glauconite, which consists of dark-gray and greenish-gray clay, silt, and sand, is a key constituent of all deposits. Glauconite abundance is often used as a distinguishing criteria. Concentrations of presumably phosphatic material have been noted at the base of the Paleocene (Minard, et al., 1969) and of bentonite at the same stratigraphic level (Jordan and Adams, 1962). Disconformably overlying the Eocene sediments are marine Miocene sands, silts, and clays (the Oligocene is not represented). Shells and shell beds are common in these sediments; glauconite decreases markedly in abundance from that of underlying beds. In the study area, the Miocene is composed of the Chesapeake group (Calvert, Choptank, St. Marys, and Yorktown Formations, in ascending order) which contains numerous important aquifers (see Table 1). Weigle (1974) cites recent studies as questioning the presence of the Yorktown Formation in the Ocean City area. Regardless of the correct nomenclature, the top of the Miocene (Pliocene?) generally lies at about 27 to 43 meters (90 to 140 feet) below the Maryland coast; the top of the St. Marys Formation is given as about -145 meters (-475 feet) mean sea level (MSL) at Ocean City. Owens and Denny (1974) assigned the Beaverdam sand (formerly Pleistocene age) and the Pocomoke aquifer (formerly Miocene age) to a Pliocene age.

b. Quaternary Sediments. Several investigations of Quaternary deposits of Delmarva have been made (Owens and Denny, 1974; Mixon, et al., 1974; Denny, 1974). In general, the truncated surfaces of unconsolidated Coastal Plain strata of Delmarva are disconformably overlain by two types of Quaternary deposits: fluvial sands and gravels; littoral and shallow marine clay, silt, and sand. The fluvial deposits, which comprise the majority of Pleistocene-age sediments in northern and central Delmarva, are tan and brown, iron-stained, coarse sands and gravels deposited in braided and coalescing streams. South of Easton, Maryland, fluvial sediments grade into littoral and shallow marine beds. Mixon, et al. (1974) and Denny (1974) discuss the presence of beach ridge and dune deposits composing the "backbone" of the lower peninsula. According to these authors, Weigle (1974), and Owens and Denny (1974), the coastal deposits are pre-Sangamon, Sangamon, and Wisconsin in age. Upper Pleistocene sediments are primarily of barrier, back-barrier, and foreshelf origin; the lower Pleistocene comprises the Beaverdam sand (identified as Pliocene by Owens and Denny, 1974). In general, Pleistocene beds of marine or estuarine blue and gray clay and silt and fine gray sand increase in number and thickness toward the east and are interfingered with fluvial and proglacial outwash deposits (Weigle, 1974).

Onshore, Holocene deposits vary up to 12 meters (40 feet) in thickness, with an average approximate thickness of 1.5 meters (Weigle, 1974). Most of the area of Holocene deposition is restricted to coastal and marsh areas of the Atlantic coast, Delaware Bay, and Chesapeake Bay. In general, these deposits are genetically similar to the Pleistocene littoral and shallow marine sediments.

c. Hydrologic Units. Much of the available information on subsurface stratigraphy of eastern Delmarva Peninsula has been obtained through studies of water-bearing strata, the prime source for freshwater in the area. Studies by Rasmussen and Slaughter (1955), Sinnott and Tibbitts (1955), Cushing, Kantrowitz, and Taylor (1973), and Weigle (1974) have produced maps of major aquifers and aquicludes in the region. Because of their ability to transmit or restrict the flow of subsurface waters, these hydrologic units are often reliable indicators of significant lithologic changes. In the vicinity of Ocean City, Maryland, water is supplied by four major hydrologic units: the Pleistocene (or Quaternary) aquifer, the Pocomoke aquifer, the Ocean City aquifer, and the Manokin aquifer.

The Pleistocene aquifer (Beaverdam sand) is variable in extent and thickness. Beneath Ocean City, it lies at about -16.5 meters (-54 feet) MSL and is 18 to 24 meters (60 to 80 feet) thick, but is generally thinner (7.6 to 15 meters, 25 to 50 feet) elsewhere in the vicinity. Separating the Pleistocene and Pocomoke aquifers is a 4.5- to 6.1-meter-thick (15 to 20 feet) unit of blue-green silt, fine gray sand, and blue-green pebbly clay referred to as the upper confining bed or upper aquiclude. The Pocomoke aquifer, a major water producer for the Eastern Shore, lies at about -49 meters (-160 feet) MSL at Ocean City and is 12 to 18 meters (40 to 60 feet) thick (Weigle, 1974). Rasmussen and Slaughter (1955) reported a southeastward dip for the top of the aquifer at about 1.4 meters per kilometer (7.5 feet per mile). Contained within the underlying lower confining bed is the Ocean City aquifer, a unit of gray sand. This unit, composed chiefly of gray sand lies at about -73 to -61 meters (-240 to -200 feet) MSL in the Ocean City area. The Manokin aquifer, untapped before 1972, is a potentially important source of ground water for the area. At Ocean City the aquifer lies at about -107 to -145 meters (-350 to -475 feet) MSL (Weigle, 1974) and is generally below the depth range of seismic reflection equipment used in this study.

d. Oceanographic Regime. Only limited data have been obtained on large-scale water circulation patterns off the Delmarva Peninsula (Bumpus and Lauzier, 1965; Harrison and Norcross, 1967). This information is based on results of drift bottles and seabed drifters. Although results of these types of studies are often questionable because of the low recovery rate and bias in favor of shoreward transport, they do provide a useful indication of major surface-current circulation. Two aspects of particular interest in Harrison and Norcross (1967) are the apparent landward trajectory of surface currents and the flow of ocean water into the Chesapeake Bay entrance.

The Atlantic coast of the Delmarva Peninsula has a semidiurnal tide (two highs and two lows each day) with a range of about 1 meter (3.5 feet). The extreme range (spring tide) is on the order of 4 meters (12 feet), ranging from 1 meter below low water to 3 meters above low water. When these peak tides are accompanied by waves, especially storm-generated waves, the actual water level may be significantly higher.

Wind-generated waves and currents are probably the most important hydrodynamic factors affecting the form and character of the inner shelf and shoreline. Resio and Hayden (1973) studied waves generated by various types of northeasters (extratropical storms--classification based on storm track, speed, pressure, etc.). They found that *average* surf height maximums obtained from published data for 1955 to 1965 for various storms range from 1 to 2 meters (3 to 6.1 feet). In contrast, the average breaker height during the same time period was 0.55 meter (1.81 feet), as determined from more than 22,000 observations. The Delmarva Atlantic coast is open to attack by both tropical storms (hurricanes) and extratropical storms (northeasters). Hurricanes are generally the most severe type of storm along Delmarva (U.S. Army Engineer District, Baltimore, 1972); major hurricanes struck the study area in 1933, 1938, 1944, 1954, 1955, and 1960. Although many such storms undoubtedly occurred before the 1933 hurricane, this hurricane was most destructive and was responsible for breaching the barrier island to form Ocean City Inlet. Northeasters, so-called because the winds blow from the offshore northeast quadrant, have milder winds associated with them but are usually of longer duration. The longer time period results in a piling of water against the coast (storm surge) superimposed upon the daily high tides. The most devastating storm of this type was the March 1962 storm that persisted through five high tides and left the coast from North Carolina to Massachusetts as disaster areas.

II. TOPOGRAPHY OF THE DELMARVA CONTINENTAL SHELF

1. Morphologic Elements of the Shelf.

The general configuration of the major physiographic features of the Atlantic continental margin has been known for over a century (Schopf, 1968), but it is only since the advent of echo sounding, in the late 1920's, that the details of the sea floor could be charted efficiently and accurately (Emery, 1966). Until that time lead-line surveying had successfully delineated depths of major basins, banks, plateaus, terraces, and nearshore navigation hazards. However, the paucity of soundings prohibited accurate delineation of form and interpretation of processes. Veatch and Smith's (1939) study of the shelf and slope topography in the middle Atlantic Bight is recognized as the first comprehensive and significant work of this type. Since their study, numerous investigators have sought understanding of specific features of the sea floor (Emery, 1966; Uchupi, 1968). On the Continental Shelf, much effort has gone toward the study of the nonbiogenic positive-relief features (referred to as shoals, ridges, or bars), as evidenced by the works of Curray (1960), Jordan (1962), Sanders (1962), Shepard (1963), Hyne and Goodell (1967), McMaster and Garrison (1967), Uchupi (1968), Smith (1969), and Swift, et al. (1972). However, it has been only recently that features on the Atlantic shelf have been characterized and interpreted from a regional perspective relating them to Holocene events, sediment sources, and modern processes (Duane, et al., 1972; Swift, et al., 1972; Swift and Sears, 1974; Field and Duane, 1976).

Uchupi's (1968) study pointed out the existence of long linear sand swells on the Atlantic shelf south of Long Island. Duane, et al. (1972) and Swift, et al. (1972) pointed out the variation in shoal types and location. Swift, et al. (1972) incorporated the shoal patterns with other topographic features on the shelf and placed them in a hierarchal order (Table 2). This order follows the Horton hierarchal order applied in studies of fluvial morphology where the lowest number refers to the primary tributary and increasing numbers are applied to the streams they feed (Leopold, Wolman, and Miller, 1964). The same hierarchal order is used here primarily to show the relative size and sometimes genetic relationship which exists between various morphologic elements of different orders (first-order features are those that make up second-order features, etc.).

Table 2. Hierarchy and occurrence of morphological elements on the Continental Shelf.

The central and southern Atlantic shelf (from Swift, et al., 1972)	
Small-scale elements	
Ripples and sand waves	
Large-scale elements	
First order:	Shoreface-connected ridges and swales Isolated ridges and swales
Second order:	Cape-associated shoals Ridge fields
Third order:	Shoal-retreat massifs Shelf-transverse valleys Cuestas Deltas Scarps
The northern Delmarva inner shelf	
First order:	Shoreface-connected shoals Linear isolated shoals Crescentic cape shoals
Second order:	Shoreface Linear-shoal fields Shoal-retreat massifs Shelf-transverse valleys

On the Delmarva inner shelf, the main topographic features are those shown in Table 2--the shoreface, linear-shoal field, shoal-retreat massif, and shelf-transverse valley. Characteristics of these features are described below.

a. Shoreface. The term shoreface has been defined by at least three, and perhaps more, criteria, most of which are impractical to use because they rely on information that is difficult or impossible to obtain from profile or map data. For example, one definition explains shoreface as "the narrow zone seaward in terms of the area where sands and gravels actively oscillate with changing wave conditions" (American Geological Institute, 1962; Allen, 1972).

The preferred definition for this study is the one used by Meisburger and Field (1975) to refer to the relatively steep slope descending from the low water line or inshore terrace to a break in slope at the level of the shelf ramp. Using this definition, the limits of the shoreface slope and width of the seaward margin of the shoreface are readily determined from either map or profile data (Fig. 5,A). Perturbations or irregularities in the surface configuration of the shoreface are of two types--erosional and constructional. An erosional effect occurs when a stratum of different lithology, cementation, or other characteristic, which makes it more resistant than the super or subjacent material, is exposed in the shoreface of a retrograding shoreline. Constructional elements on the Delmarva shoreface are the large shoals that interrupt the usually smooth shoreface (Fig. 5,B).

b. Linear-Shoal Field. Linear-shoal field refers to inner shelf areas containing groups of linear shoals with the same orientation and of similar scale in relief and length. Well-developed linear-shoal fields have been mapped by Duane, et al. (1972) in the vicinity of Fort Pierce, Florida; False Cape, Virginia; Ocean City, Maryland; and central New Jersey. The shoals are oriented at a small acute angle (~20°) to the shoreline and are comprised of clean medium sand. A schemetized plan view of a linear-shoal field is shown in Figure 5,B. Note that innermost shoals are connected to, or are part of, the shoreface and are called shoreface shoals. Those farther offshore are termed isolated shoals. Duane, et al. (1972) interpreted these features as Holocene features that formed in the submarine environment and were consequently stranded as sea level rose and the shore retreated.

Shoals are large bodies of unconsolidated, medium to coarse, moderately well sorted sand which overlie planar mud layers. There is sufficient evidence (e.g., historical surveys, limited current metering, polished grains several feet below shoal surface, etc.) that transport and deposition of sediments in the vicinity of the linear shoals is an active process and the shoals are not "relict" or inactive features. Because of the economic significance of these linear shoals and because of their importance to the evolution of the shelf surface they will be discussed more extensively in later sections.

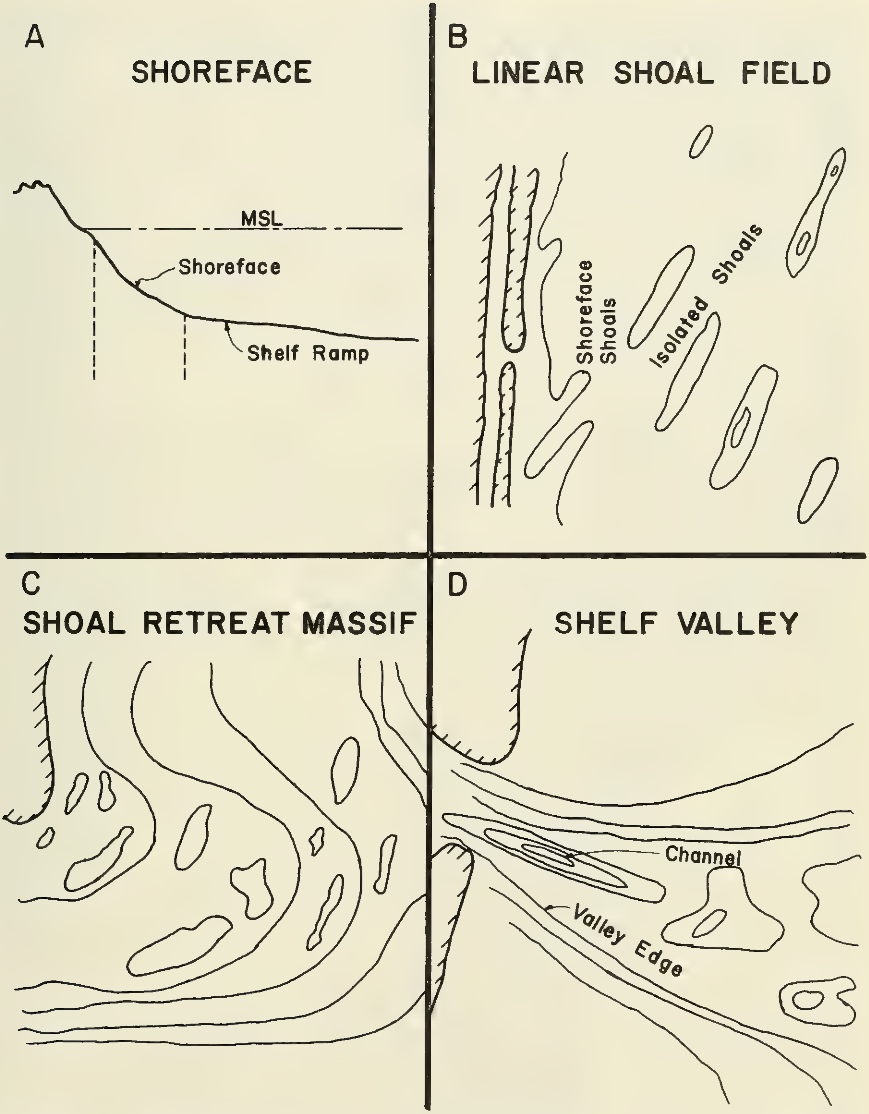


Figure 5. Schematic diagram of four major morphological elements of the northern Delmarva inner shelf.

c. Shoal-Retreat Massif. The term, shoal-retreat massif (Swift, et al., 1972) refers to the clusters or fields of relict shoals that extend seaward from old depositional centers. Such centers of sediment accumulation may be adjacent to sites of previous (or existing) inlets or they may be adjacent to cape features or cuspate forelands. Shoal-retreat massifs are large arcuate submarine sand bodies with linear and curvilinear shoals or ridges superimposed on the surface (Fig. 5,C). Individual ridges are seldom parallel to each other or to the general trend of the entire massif. Their orientation with respect to each other is not constant, and although they are generally subparallel, they often change in orientation with distance offshore. Shoal-retreat massifs are commonly associated with the large capes-cuspate forelands of the Atlantic southeast (Capes Canaveral, Romain, Fear, Lookout, and Hatteras). Along the mid-Atlantic Bight shoreline, shoal-retreat massifs occur adjacent to estuarine openings and adjacent to discontinuities in each of the barrier island compartments. Along the Delmarva coastline, this discontinuity occurs at the southern end of Assateague Island.

d. Shelf-Transverse Valleys. The most apparent erosional features on the Atlantic Continental Shelf are the shelf transverse valleys which extend from the coastline out across the shelf (Fig. 5,D). The major valleys in the mid-Atlantic region have been identified by Swift, et al. (1972) as the Block, Long Island, Hudson, Great Egg, Delaware, Susquehanna, Virginia Beach, and Albermarle Valleys. These valleys, originally cut during periods of lower sea level, have been modified and topographically subdued by the deposition of coastal sands into the retreating river-estuary mouths. The Delaware shelf valley at the northern limit of the study area is one of the more prominent shelf valleys of the Atlantic coast.

2. Survey of Delaware Bay to Chesapeake Bay.

As pointed out by Fisher (1968), Duane, et al. (1972), Kraft, Biggs, and Halsey (1973), and Field and Duane (1976), the coastline of the mid-Atlantic Bight is comprised of a series of separate coastal compartments, each containing a headland area, a small northward-growing spit, and a long convex barrier spit followed by a chain of small barrier islands extending south of the headland. The morphology of the adjacent shelf varies as much in detail along each of the coastal compartments as does the shoreline.

Cross-shelf profiles plotted from map data (Fig. 6) clearly show regional changes both in slope and width of the shoreface and also the presence and relative relief of shoals (Fig. 7). Profile A-A' crosses a large ebb shoal (Hen and Chicken), a channel of the ancestral Delaware River, and part of the main shelf valley. The large, broad positive-relief features along the profile are depositional features associated with the estuary shoal complex at the mouth of the retreating Delaware Bay. The shoreface is relatively steep and smooth in this area and has no perturbations.

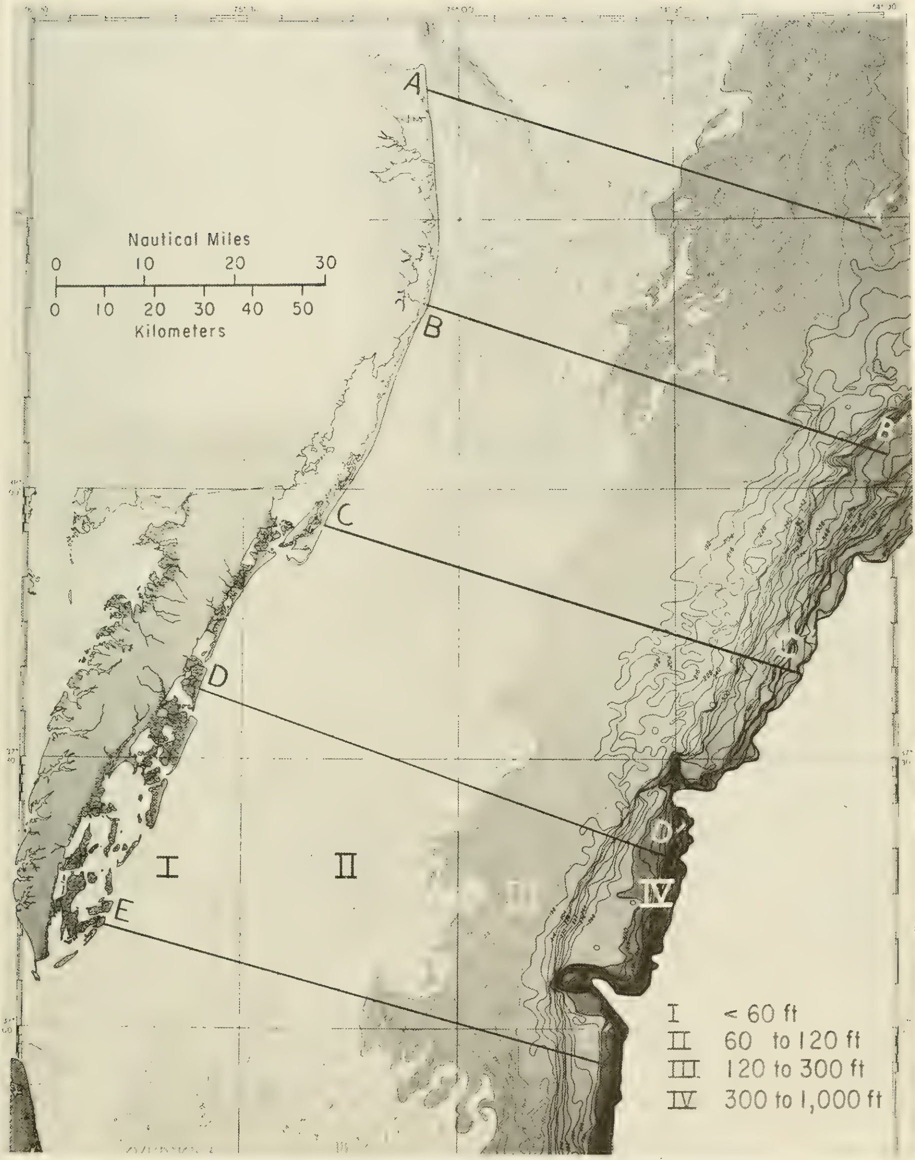


Figure 6. Topography of the Delmarva Continental Shelf showing locations of cross-sectional profiles illustrated in Figure 7.

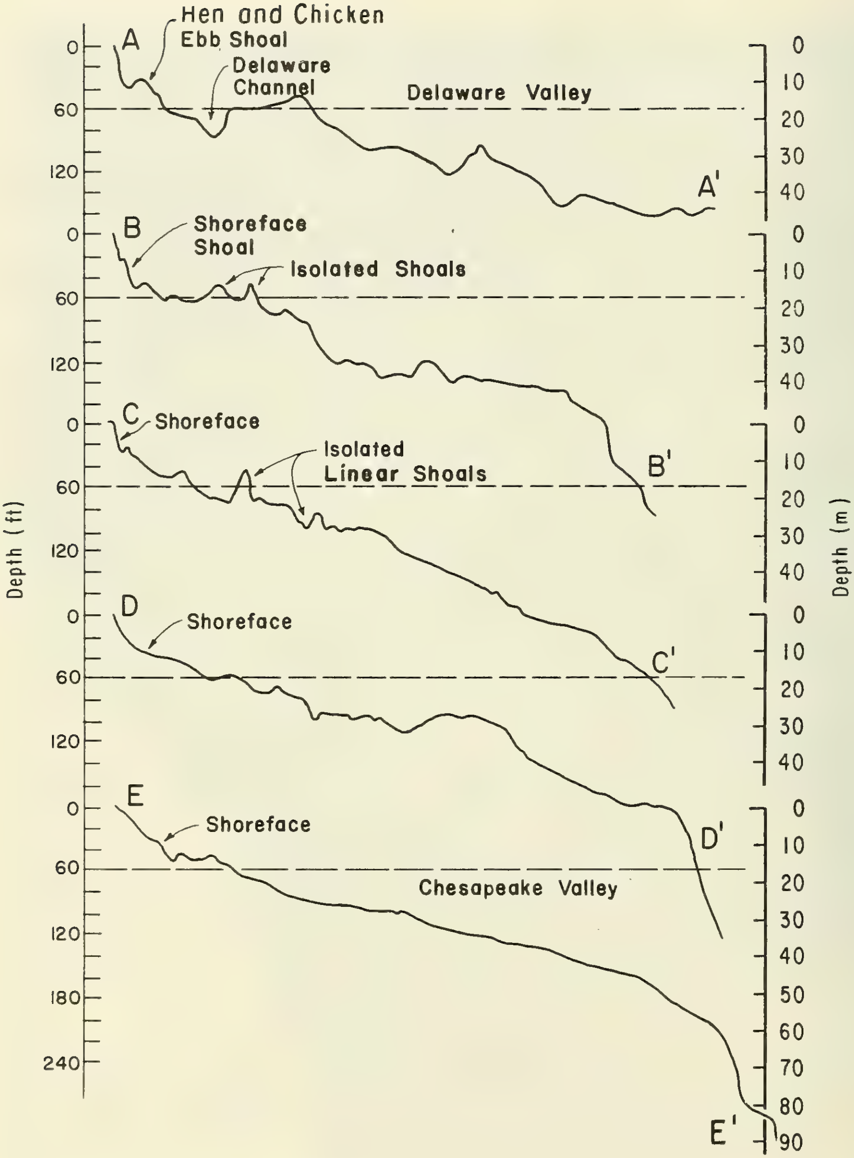


Figure 7. Cross-sectional profiles of the surface of the Delmarva Continental Shelf illustrating major topographic trends. Profile locations are shown in Figure 6.

On profile B-B', off Ocean City, the shoreface has approximately the same steepness, but its otherwise smooth configuration is interrupted locally by "bulges" or shoreface shoals. Seaward of the shoreface, isolated linear shoals are common on the inner shelf. Profile C-C', off southern Assateague Island, is similar to B-B' in most aspects. Individual shoals show as much as 10 meters (30 feet) of relief. Profile D-D', off the chain of small barrier islands, shows some distinct changes from preceding profiles. The shoreface has a more gentle slope and the transition to the inner shelf ramp is less marked. Individual shoals are poorly defined and do not exhibit much relief. Profile E-E', at the southern end of Delmarva, represents the smoothest profile of the region. The shoreface slope is more gentle than the more northern profiles and the entire shelf surface is relatively featureless.

3. Delaware Inner Shelf.

The morphology of the Delaware inner shelf owes its origin to the influence of the adjacent headland coast and the proximity of the Delaware estuary. The Atlantic coast of Delaware, approximately 35 kilometers (21 miles) long, comprises the headland section of the Delmarva Peninsula (Fig. 8). It is composed of headland beaches (Rehoboth and Bethany Beach areas), baymouth barriers (extending across the mouths of Rehoboth and Indian River Bays), and a small northward-growing spit (Cape Henlopen).

The ancestral valley of the Delaware River and estuary trends southeast from the present bay mouth and diagonally cuts the inner shelf. Seaward of the shelf valley lie remnants of former estuary mouth shoals, also termed a shoal-retreat massif, which are similar in origin to the present-day shoals (McCrie, Overfalls, Somer, etc.) lying south of Cape May, New Jersey (Fig. 8). Swift (1973) examined the morphology of Delaware Shelf Valley and concluded that it "reflects mainly its shallow marine stage of evolution, rather than the earlier subaerial stage." Hence, the shelf valley may be genetically classified as a flood-channel retreat-path (Swift, 1973). Evidence for this interpretation is based on an evaluation of modern topography and processes and on the discovery of the ancestral, subaerial fluvial channel lying stratigraphically lower and laterally offset from the present shelf valley (Sheridan, Dill, and Kraft, 1974). The topographic evidence consists mainly of the apparent similarity of the shelf morphology with the present-day estuary mouth. The shelf valley is continuous with the flood tidal channel in the mouth. The series of large shoals extending across the shelf parallel and north of the shelf valley is an apparent predecessor to the large shoal complex (McCrie, Overfalls, Sommer, etc.) lying south of Cape May (Fig. 8). This shoal complex has been referred to as a cape platform by Field and Duane (1976) and is analogous to the north side of the Chesapeake Bay entrance. Caldwell (1966) estimated that the volume of littoral drift (sediment transported alongshore by littoral currents) delivered to the Cape May shoreline is 536,000 cubic meters (700,000 cubic yards) annually.

Landward of the shelf valley the Delaware shelf is relatively featureless, with the exception of five distinct features: Hen and Chicken shoal,

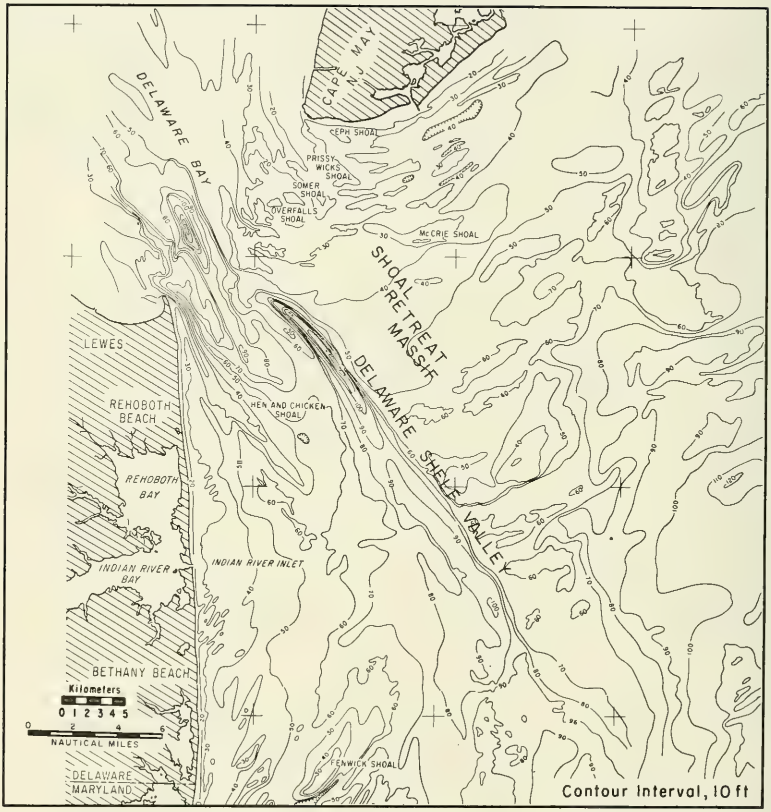


Figure 8. Detailed bathymetry of the Delaware Inner Continental Shelf. Contours compiled from data on National Ocean Survey (NOS) chart 1219, scale 1:80,000.

two small sediment aprons adjacent to Rehoboth Bay and Bethany Beach, a shoreface shoal complex just north of the Delaware-Maryland State line, and Fenwick shoal. Hen and Chicken is a large shoal extending southeast from Cape Henlopen for approximately 19 kilometers (10 nautical miles). The shoal shows a maximum relief of nearly 6 meters over the surrounding sea floor on the southwest side; on the northeast side the water depths increase steadily into the thalweg of the estuary entrance (Fig. 8). Minimum water depth over the crest is approximately 1.5 meters. Sheridan, Dill, and Kraft (1974) found that this large sand body overlies a steeply dipping (12.2 meters in 4 kilometers or 40 feet in 2.5 miles) surface of estuarine--shallow marine silt and gravel.

The two "aprons" or "lobes" of sediment north and south of Indian River Inlet are contained within a general bulge in the shoreface, as defined by the 12-meter contour, and comprise sets of small linear ridges or mounds rising to depths of less than 6 meters below MLW. Surface sediments and morphology of the southern lobe off Bethany Beach were studied in detail by Moody (1964), who made a prestorm and poststorm comparison of changes in shoal morphology after the study area was devastated by the storm of March 1962. During the survey period (1961-63), the ridges migrated 76 meters (250 feet) to the southeast, compared to an average rate of 3 meters per year over a 42-year average.

South of Bethany Beach, the dominant ridge and swale topography of the northern Delmarva shelf begins. The northernmost shoal lies between Bethany Beach and the Maryland State line. As outlined by the 12-meter contour, the ridge is broad with low relief, and has four low crests which increase in relative relief in a seaward direction. Seaward of the shoreface ridge system is a large isolated linear ridge (Fenwick shoal) which is the northernmost feature of this type in the study area. The shoal is 9.7 kilometers (6 miles) from shore, 6.4 kilometers (4 miles) long and 2.4 kilometers (1.5 miles) wide, and rises from the intervening swale area 15 to 18 meters (50 to 60 feet) below MLW up to within 7.6 meters of the water surface.

4. Maryland Inner Shelf.

The entire inner shelf area of Maryland (Fig. 9) is dominated by a prevailing ridge and swale topography. Ridges exist as either isolated shelf features or shoreface-connected features (Fig. 6, profile B-B'). Some shoal crests are shallow enough to be classified as navigation hazards. The length of many of the shoals exceeds 9 kilometers (5 nautical miles); widths are commonly on the order of 1.8 kilometers (1 nautical mile). Relief varies from 3.1 meters (arbitrarily defined here as the minimum relief for recognition of a shoal) up to 10 meters. Without exception, the shoals are oriented northeast-southwest, creating a small acute angle with the shoreline.

Duane, et al. (1972) and Field and Duane (1976) noted that the distribution of linear-shoal fields on the mid-Atlantic shelf is related to the convex barrier spits of each coastal compartment. The entire Maryland

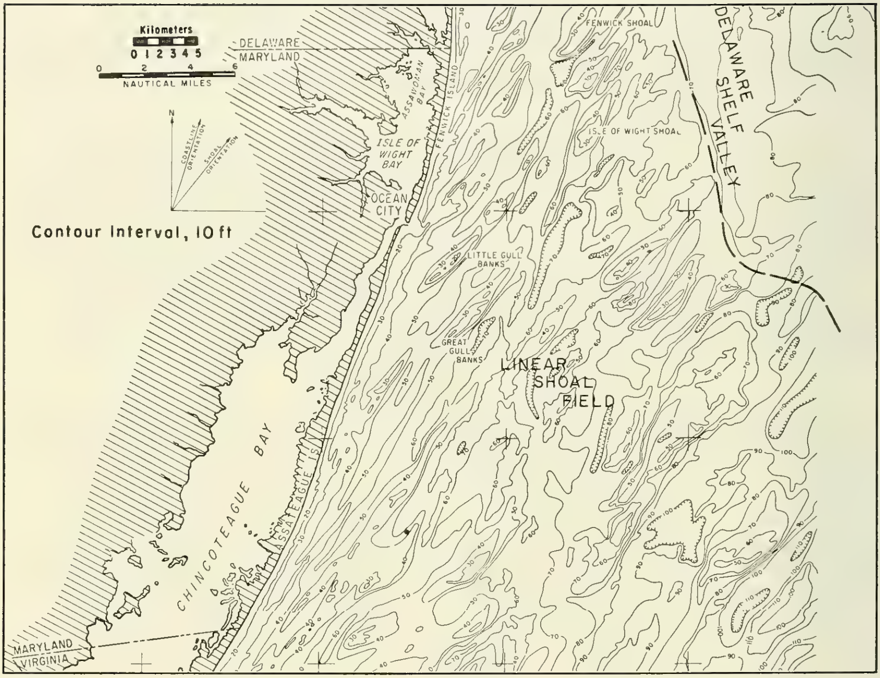


Figure 9. Detailed bathymetry of the Maryland Inner Continental Shelf. Contours compiled from data on NOS chart 1220, scale 1:80,000. Dashline is the approximate boundary between Delaware shelf valley and linear-shoal field.

barrier is such a coast. It is a convex (bowed seaward), barrier spit interrupted by only one inlet at Ocean City (Fig. 9). Fathometer transects were made across selected shoals in the region in 1974 and profiles were constructed by direct tracing of fathograms. Perturbations in the records caused by wave motion of the boat were smoothed out.

Profiles of Little Gull and Great Gull Banks, two shoals lying offshore of Ocean City Inlet in an *en echelon* configuration (parallel but offset to the southeast) with Ocean City shoal, are shown in Figure 10. Both shoals are similar in cross section and display certain distinct trends in shape that may yield some information on how they evolved or are evolving. The shoals, relatively narrow and single-crested on their southern ends, gradually become broader and multicrested toward the northern ends. Width increases by a factor of 1.5 to 5. The crest shape of Little Gull Banks changes progressively from single-crested (line N) to bicrested (line Q) to tricrested (line P) to an irregular multicrested shape (line O) (Fig. 10). The initial subdivision of the crest of Great Gull Banks (Fig. 10) appears as a "furrow" or slight depression (lines L and M) as was noted along the northern end of the Ocean City shoal. Both of these shoals are larger and better defined as a single feature than either the collection of ridges composing Ocean City shoal or the relatively small shoreface shoal just south of Ocean City Inlet.

By comparing the surface configuration of shoals along the shoreface with those just offshore and those lying farther offshore, Field (1976) observed a changing pattern in symmetry, slope, and shape. He noted several possible explanations for the different patterns. Differences in crest shape and side-slopes are significant, indicating either completely different modes of formation or alternately different evolutionary patterns of features initially formed in a similar fashion. Field (1976) concluded that the "furrows" on nearshore shoals, such as Little Gull and Great Gull Banks, are inherited from a previous evolutionary stage and are in the process of being degraded or smoothed over.

5. Northern Virginia Inner Shelf.

The coast of northern Virginia marks the transition between the convex barrier spit (Ocean City-Assateague) to the concave barrier island chain (Wallops Island and south) as shown in Figure 11. The inner shelf also demonstrates a marked change in configuration in the vicinity of Chincoteague. The dominant ridge and swale topography changes abruptly nearshore and more transitional offshore, to a subdued topography. An extensive area of smooth, gently dipping or "flat" bottom lies adjacent to Wallops Island in the lee of Assateague Island. The surface slopes southeasterly at about 0.6 meter per kilometer (4 feet per nautical mile); within the 12- to 15-meter (40 to 50 feet) depth area the slope is only 0.4 meter per kilometer (2.5 feet per nautical mile). This contrasts sharply with the local slopes of 12.2 meters per nautical mile common on the flanks of shoals north of Chincoteague. Seaward of the 16-kilometer-wide (10 miles) "level bottom area," the sea floor retains the northeast-southwest orientation common to the linear-shoal field farther north, but

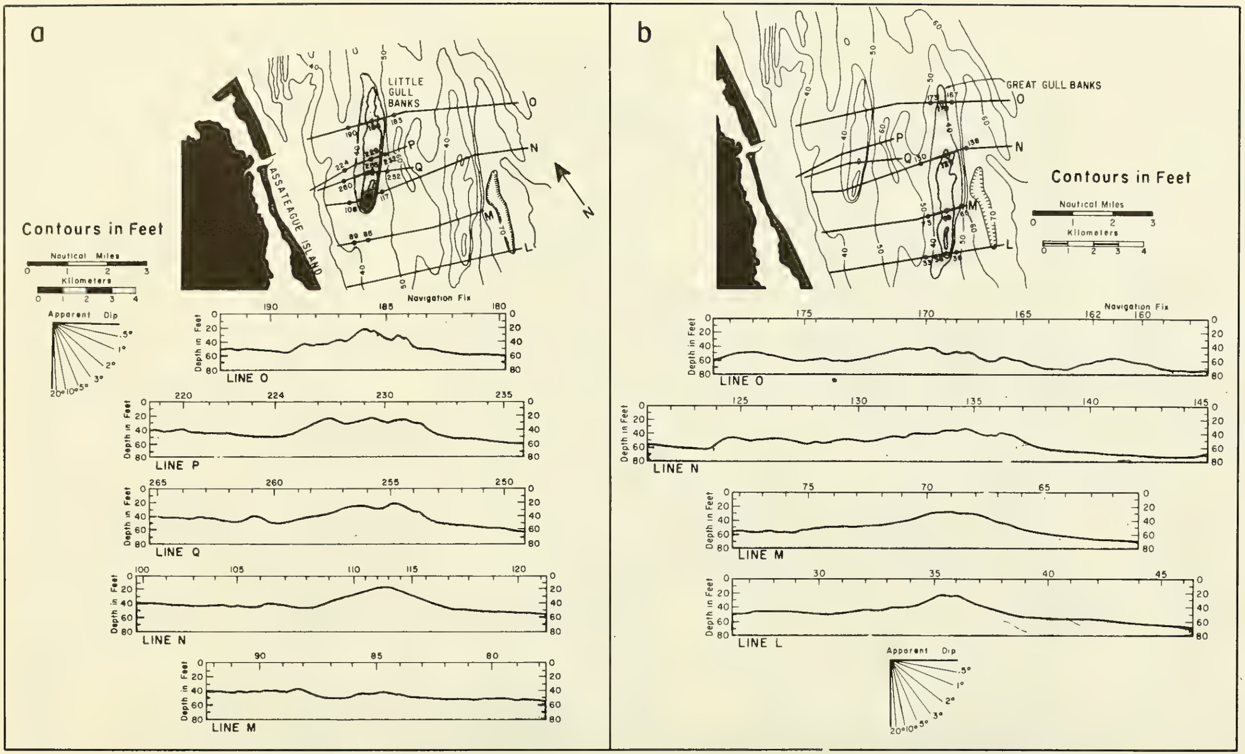


Figure 10. Smoothed fathometer profiles for two nearshore shoals--(a) Little Gull Banks and (b) Great Gull Banks. Note similarity in shape trends between the two.

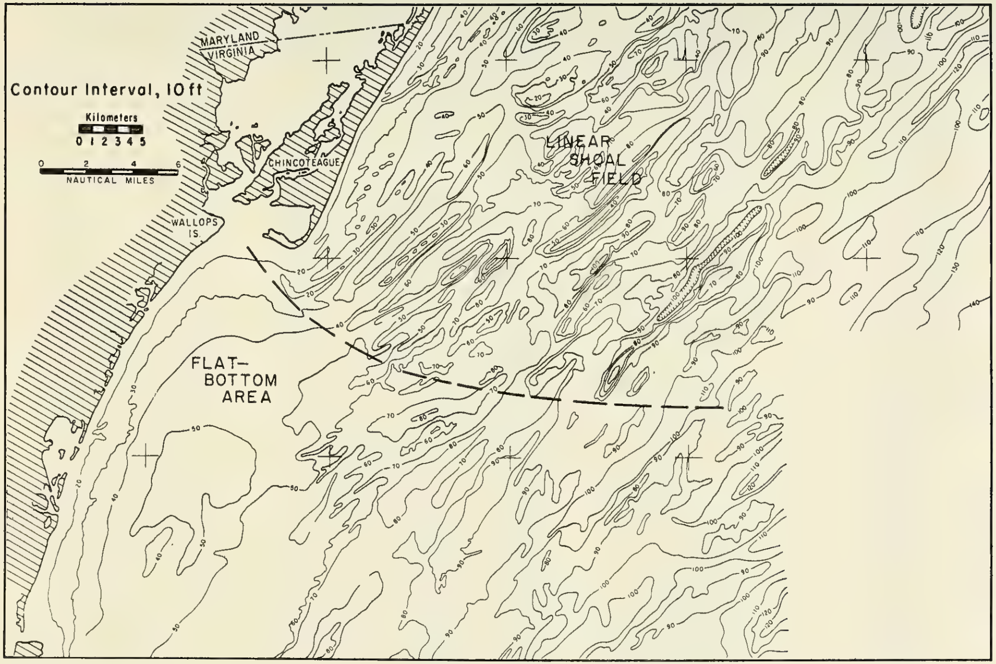


Figure 11. Detailed bathymetry of the northern Virginia Inner Continental Shelf. Contours compiled from data on NOS charts 1220 and 1221, scale 1:80,000. Dashline is approximate boundary between the linear-shoal field and the flat-bottom and subdued areas to the south.

relief is more subdued. Ridges, where present, exhibit relief of about 3 meters (10 feet), which contrasts with the 3.1 to 9.1 meters of relief noted farther north. Swales are more prominent than individual ridges in this area. The dashline in Figure 11 shows the approximate locations of the change from linear-shoal field to the flat-bottom area inshore and subdued topography offshore. Just north of this line and within 9.1 kilometers of the shore are a series of well-defined shore-parallel shoals. The presence of these shoals adjacent to the end of Assateague Island, and especially the occurrence of a spit or elbow-shaped shoal offshore, have led some investigators to conclude that the ridges represent drowned spits.

III. SUBSURFACE STRUCTURE AND BEDDING

Continuous seismic reflection records obtained from the two field studies show subbottom acoustic reflectors down to nearly 122 meters below sea level. Each seismic source used (3.5-kilohertz transducer, sparker, Acoustipulse) differs in energy and frequency, hence the resulting records differ in penetration, resolution, and record quality. Correlation between the different types of records is possible, but differences in record scales and acoustic response of the substrata occasionally make correlation difficult. The Acoustipulse system provided the best overall data; penetration often exceeded -61 meters (-200 feet) MSL and definition of shallow strata was of high quality. Sparker data were most useful for recognizing deeper horizons (30 meters below sea level) whereas strata lying between 12.2 and 30.5 meters (40 and 100 feet) were best defined on the records obtained with the 3.5-kilohertz and Acoustipulse equipment. The 3.5-kilohertz data provided an extra advantage in allowing qualitative estimates to be made of surface sediment character based on the nature of the return signal. The main difficulty with the 3.5-kilohertz data, and to some degree with the Acoustipulse data, is lack of penetration (often less than -37 meters (-120 feet) MSL). Difficulties encountered with the sparker data include a general lack of resolution and a masking effect from multiple reflections of the sea floor. Examples of the three types of continuous seismic reflection records are shown in Figure 12.

The acoustic data show that all strata have a nearly consistent seaward dip and a relatively smooth surface. Strata dip generally toward the east and southeast at a slope ranging from 1 on 250 to 1 on 1,600. Those reflectors, which persist and are identified on several profile lines, and especially those which are mappable over a large area (tens of square miles), are called primary reflectors. Secondary reflectors are either local in extent (erosional discontinuities in channels) or occur as internal bedding surfaces between primary reflectors (e.g., foreset bedding).

As many as 11 primary reflectors are visible on the reflection records. Trend, relative depth, and associated secondary reflections of each primary reflector for the central part of the study area are schemetized in Figure 13. Detailed cross sections of selected seismic

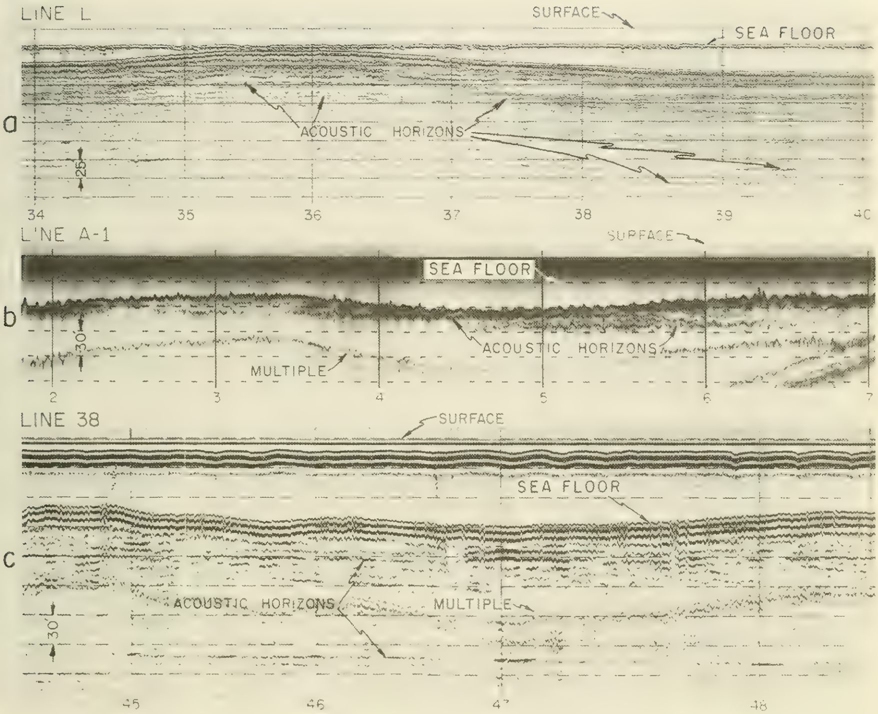


Figure 12. Acoustic records produced by the three types of seismic reflection equipment used in this study--(a) Acoustipulse (multiple transducers) record, (b) 3.5-kilohertz (single transducer) record, and (c) engineering sparker records.

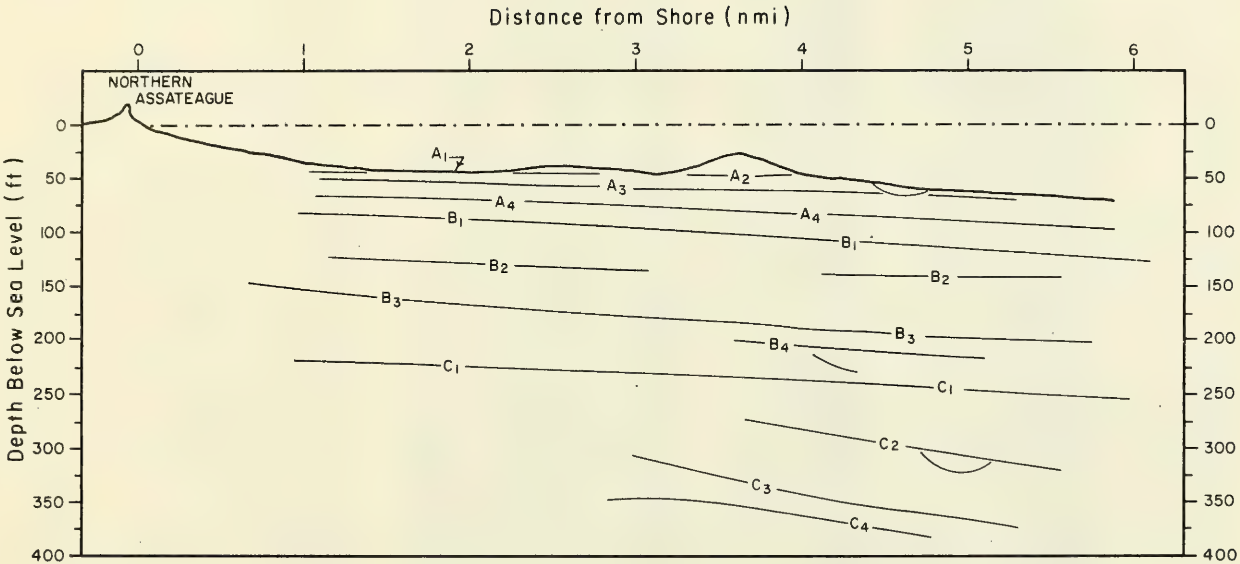


Figure 13. Generalized cross-sectional profile of the shallow subsurface off northern Assateague Island showing major seismic reflection surfaces and reflection units.

profile lines, on which Figure 13 was based, are shown in Appendix A. It should be noted that most reflectors are not present everywhere; they tend to "fade in and out" for different reasons (geologic changes, acoustic artifacts on the records). Because of this, primary reflectors are more easily identified on shore-normal (down-dip) lines where slopes may be projected across "fade-out zones" than on shore-parallel (essentially along strike) lines where a "fade-out" reflector does not appear at all.

Reflection units are arbitrarily defined sections of the subsurface bounded by relatively persistent primary reflection horizons. The convention established here for units and horizons is numbers and letters increasing downward, which will permit addition of new units by other investigators using deeper penetration seismic sources.

1. Primary Reflection Horizons and Reflection Units.

a. Reflection Unit C. The lowermost reflection unit, identified as unit C, is bounded by C_4 on the bottom and C_1 on the top. Maximum thickness of the unit is about 38 meters (125 feet), but this may be exceeded beyond the seaward limit (10 kilometers or 5.5 miles) in Figure 13. Horizons in unit C slope relatively steep compared to overlying strata. Slopes for C_1, C_2, C_3, and C_4 are 1 on 1,000, 250, 350, and 400, respectively. If no change in slope occurs inshore in the deeper strata, then they may pinch out against C_1; available data are not adequate for these deeper reflection horizons to determine their overall slope or changes in slope, except for the noted change in C_3. A small channel 610 meters wide and 7.6 meters deep is incised into horizon C_2 along profile line L (see App. A) at a depth of more than 90 meters (300 feet) below sea level. The recording of such a feature at that depth indicates a strong lithologic contrast between the channel fill (probably sand) and the incised unit (probably mud). The top of reflection unit C is defined by horizon C_1, a strong and relatively flat reflector ranging in depth from -67 meters (-220 feet) just offshore to about -76 meters, 9.6 kilometers from the shoreline.

b. Reflection Unit B. The middle reflection unit, unit B, is bounded by two strong, low-relief, nearly parallel reflectors, B_1 and C_1 (Fig. 13). Within the unit, which is about 38 meters thick, are three other primary reflection horizons. Slopes of the reflectors B_1, B_2, B_3, and B_4 are 1 on 750, 1,600, 550, and 600, respectively. Reflecting horizon B_3 is both strong and steep relative to other B unit horizons. It lies at about 46 meters below MSL, 1 mile off the beach and drops to over 61 meters within 8 kilometers (5 miles) of the beach. The top of unit B is also a strong reflector and ranges from -26 to -38 meters (-85 to -125 feet) between 1.6 and 10 kilometers (1 and 6 miles) from northern Assateague. Some internal structures, such as scarps and possible channels, are present in reflection unit B.

c. Reflection Unit A. The uppermost reflection unit identified in this study, unit A, is bounded on the bottom by horizon B, and on the top by the modern sea floor (identified as A_1 in Fig. 13). Excluding the steeply sloping shoreface region and topographic irregularities (shoals, swales), the modern shelf floor has a slope of about 1 on 800. Internal reflection horizons, A_2, A_3, and A_4 are flatter than either bounding surface and have slopes of 1 on 1,500, 1,600, and 1,000, respectively. Horizon A_2 lies at between 12 and 18.3 meters and therefore is present only in the inner half of the study area. The seismic reflection data, especially that obtained with the 3.5-kilohertz seismic profiler, show that in low areas (swales between linear ridges) horizon A_2 "crops out" or is exposed at the water sediment interface. Seaward of about the 18-meter (60 feet) contour, the horizon is no longer present in the subsurface. A structure contour map on the surface of reflector A_2 (Fig. 14) shows that the reflector has a north-northeast strike and is generally smooth and featureless, with the exception of several broad depressions and highs exhibiting about 1.5 meters of relief. The comparison between this surface and the sea floor (horizon A_1) is quite marked.

Sufficient data were collected from the 3.5-kilohertz profiler to construct a contour map of the A_3 and A_4 subsurfaces (Field, 1976). In general, horizon A_3 is flat-lying. The slope gradient varies from 1 on 1,200 to 1 on 3,500. Horizon A_4 is a persistent mappable reflector lying between 18.3 and 30 meters (60 and 100 feet) below sea level in the study area. Its slope is fairly consistent at about 1 on 1,000 to 1 on 1,500, and there are no discernible perturbations in the surface.

2. Correlation of Reflector Surfaces with Stratigraphic and Hydrologic Units.

Acoustic reflections are generated by a change in acoustic impendence within the sediment column. This change is normally attributed to some lithologic change such as grain size, matrix content, degree of cementation, water content, etc. Therefore, as a working assumption, reflecting surfaces revealed by the records are considered stratigraphically significant. These changes often relate to previous lithologic changes mapped onshore as formational boundaries or provide the contrasts that define aquifer-aquiclude contacts. The age of different substrata is difficult to accurately label, since the stratigraphy of Delmarva is presently being revised by the U.S. Geological Survey; this revision includes reassignment of some ages. A major aspect of the revision includes reevaluation of criteria delineating the Quaternary-Tertiary boundary. Earlier studies placed the eroded upper surface of the Tertiary (Yorktown Formation, Miocene age) at about 30 meters below sea level at Ocean City (e.g., Rasmussen and Slaughter, 1955). Since new terminology or ages have not been formally proposed, the stratigraphic nomenclature of Rasmussen and Slaughter (1955) and hydrologic nomenclature of Weigle (1974) are used here for correlation.

The top of the St. Marys Formation is a well-defined boundary in boreholes and well logs in the Maryland coastal area. At Ocean City this surface lies at about 146 meters (480 feet) below sea level and is beyond the depth penetration obtainable by the acoustic equipment used in this study.

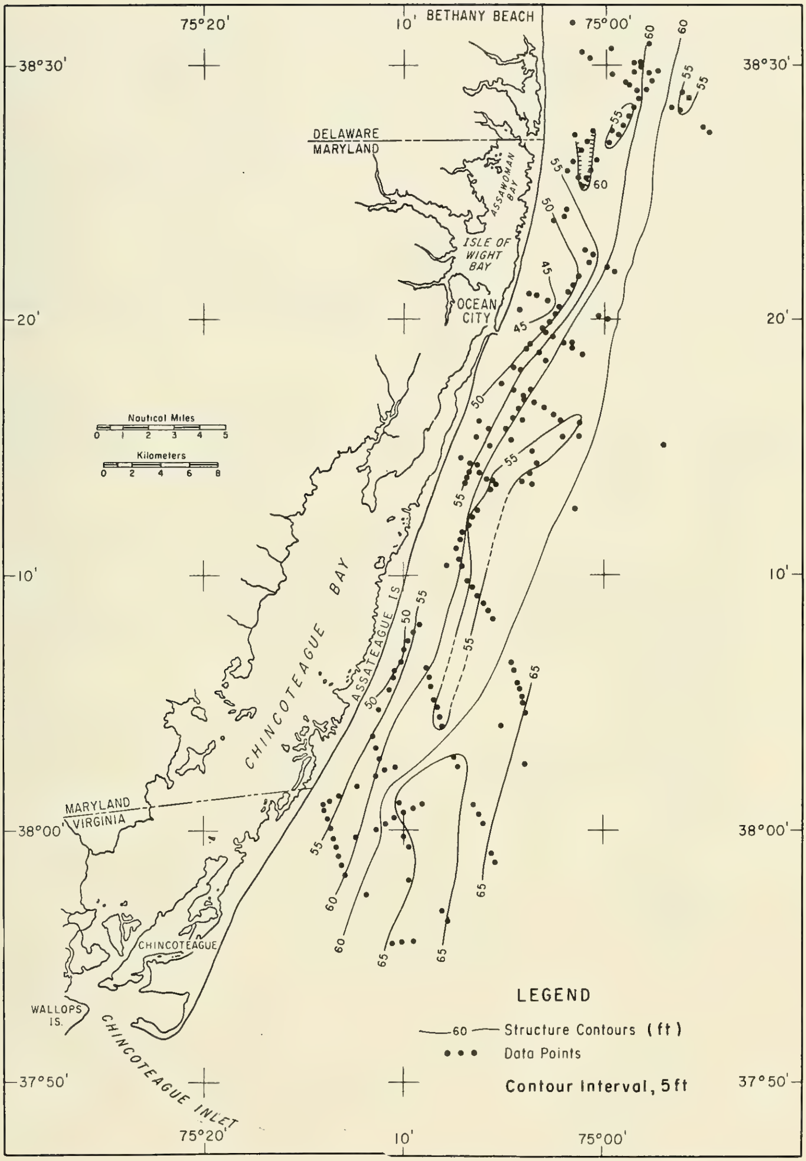


Figure 14. Structure contour map on the surface of the acoustic reflector A_2. Data points taken from 3.5-kilohertz seismic profile records.

Overlying sediments are divided into Quaternary and Tertiary sediments, the latter questionably identified as the Yorktown Formation and Miocene in age. The contact between the two lies between 26 and 32 meters (85 and 105 feet) below sea level along the Maryland coast. This contact between the eroded Tertiary and Pleistocene sediments is also the base of the Pleistocene aquifer, a sand and gravel ground-water unit. The seismic reflection horizon that appears to correlate with this surface is horizon B_1. A structure contour map of horizon B_1, best identified in the southern part of the study area, shows that the surface is rather steep and even with a southeasterly slope (Fig. 15). Locations of borings and the depth to the base of the Pleistocene along the barrier island, as defined by Rasmussen and Slaughter (1955), are also shown in Figure 15. That the horizon could not be traced throughout the study area indicates either a lateral acoustic change in the nature of the horizon or abrupt changes in elevation of the horizon.

Reflection unit A is Quaternary in age and units B and C are interpreted as Tertiary. Most of the horizons correspond to hydrologic units and some of the correlations are uncertain due to the variation in elevation and discontinuous nature of many of the horizons. Tentative correlations are shown in Table 3.

Table 3. Correlation of acoustic horizons with significant stratigraphic and hydrologic surfaces.

Stratigraphic units	Acoustic horizons	Hydrologic units
Quaternary	A_2	
Holocene	A_3	
Pleistocene (Columbia Formation)	A_4	Pleistocene aquifer
	B_1	
Tertiary	B_2?	Upper confining bed
	B_3	
	B_4?	Pocomoke aquifer
Miocene (Yorktown Formation?)	C_1	
		Lower confining bed
	?	
		Ocean City aquifer
	C_2	
		Lower confining bed
	C_3 or C_4	
		Manokin aquifer
Miocene (St. Marys Formation)		

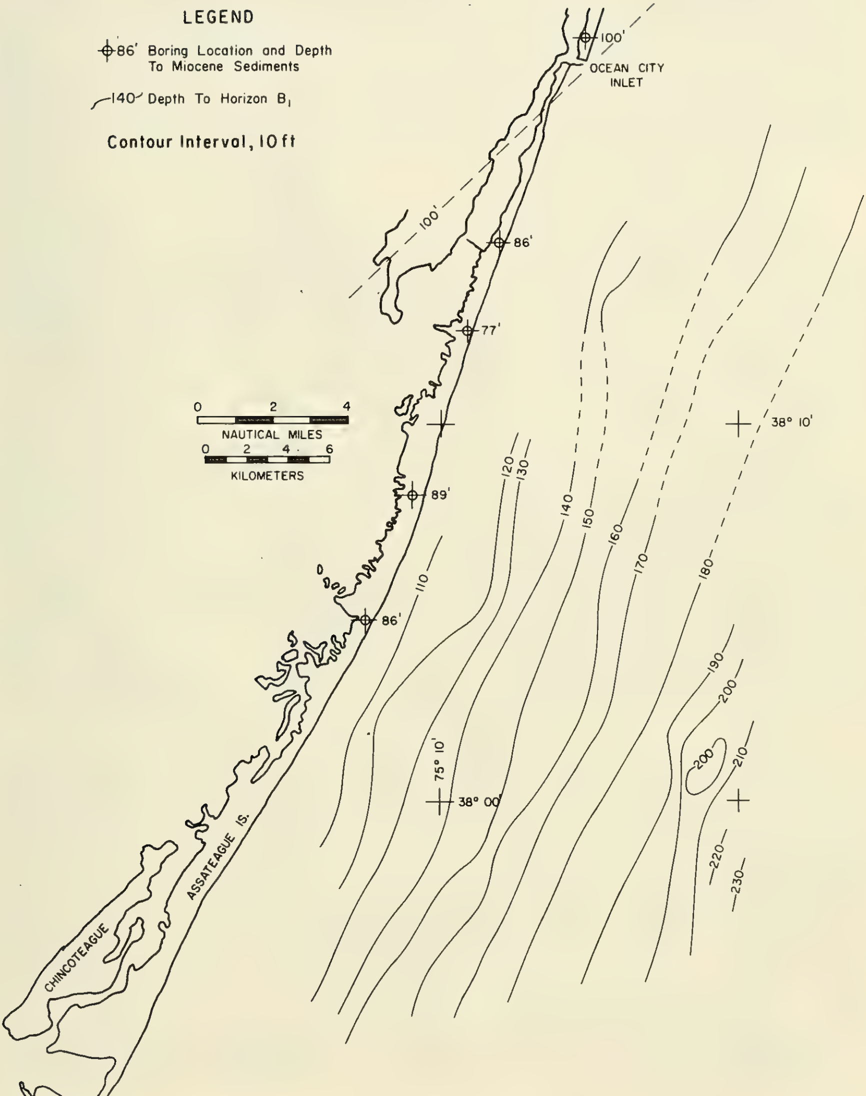


Figure 15. Structure contour map on the surface of acoustic reflector B_1, the presumed top of the Miocene section. Dashlines were interpolated. Onshore boring data and contour lines are from Rasmussen and Slaughter (1955).

Within unit A, reflection horizon A_4 is Pleistocene in age and perhaps represents the upper surface of the Pleistocene aquifer. Horizon A_3 is judged to be pre-Holocene erosion surface. A map of the pre-Holocene erosion surface on the Delaware shelf prepared by Sheridan, Dill, and Kraft (1974) clearly indicates that in the northern part of the study area, configuration of the local drainage pattern was the dominant influence on pre-Holocene topography (Fig. 16). It appears that this influence was obliterated during the Holocene, leaving few if any traces on the modern sea floor.

3. Secondary Reflection Horizons.

a. Buried Channels Beneath Delaware Bay Mouth. Relict channels incised into the Delmarva shelf surface can be divided into two groups: the channels associated with the ancestral Delaware River drainage system, and the channels which may or may not be related to existing drainage patterns. The broadest and deepest channels are those in the mouth of the Delaware Bay. Although survey coverage is minimal in that area, several lines completely cross the estuary entrance and provide some interesting information about the original channel depths and positions.

Positions of tracklines crossing the bay mouth are shown in Figure 17 in relation to the position of present channels. Line 2A crosses the western channel (a closed depression defined by the 24-meter contour) up to the Cape May shoal platform. The reduced seismic profile of line 2A shows that several episodes of channelization occurred and that the deepest channel, approximately 67 meters below sea level, lies beneath the present western channel. The cut and fill substructure extends across the bay mouth and beneath the shoal topography. Line 2B, a west-east line on the shoal platform, also shows that construction of the platform occurred on a stream-eroded topography. More than 10.7 meters (35 feet) of Holocene sediment has been deposited over the channeled topography, the deepest part of which lies about 49 meters below sea level.

The three lines crossing the eastern channel show the present channel to be narrower than the original channel. Flat-lying reflectors beneath the channel indicate the ancestral thalweg did not extend more than 6.1 meters below the channel; if it was deeper but displaced, it was displaced to the west side (see line B, Fig. 17). It is difficult to determine the mechanism for filling the channels; however, the lines crossing the eastern channel, especially line B, give some indication, by the steeply dipping progradational secondary reflections, that lateral movement of sand has infilled the channel. This contrasts with the classical longitudinal filling by fluvial processes and indicates that the majority of filling has been by marine and littoral processes. South of the Delmarva Peninsula, the main channel in the Chesapeake Bay entrance has been filling in by lateral migration during historic migration (Meisburger, 1972; Field and Duane, 1976); the history of both of these large estuary entrances may be quite similar.

b. Buried Channels on the Inner Shelf. Excluding those channels associated with the ancestral Delaware River, the northern Delmarva shelf

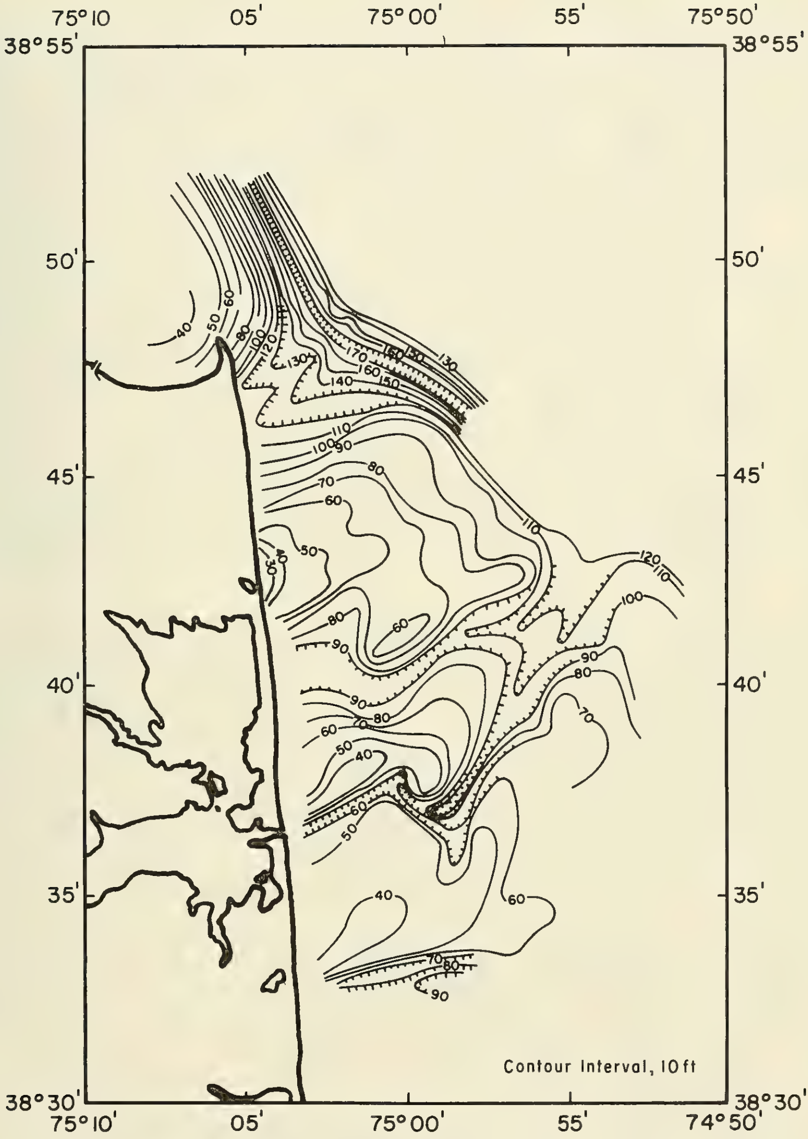


Figure 16. Structure contour map of the pre-Holocene erosional drainage surface off Delaware, modified after Sheridan, Dill, and Kraft (1974).

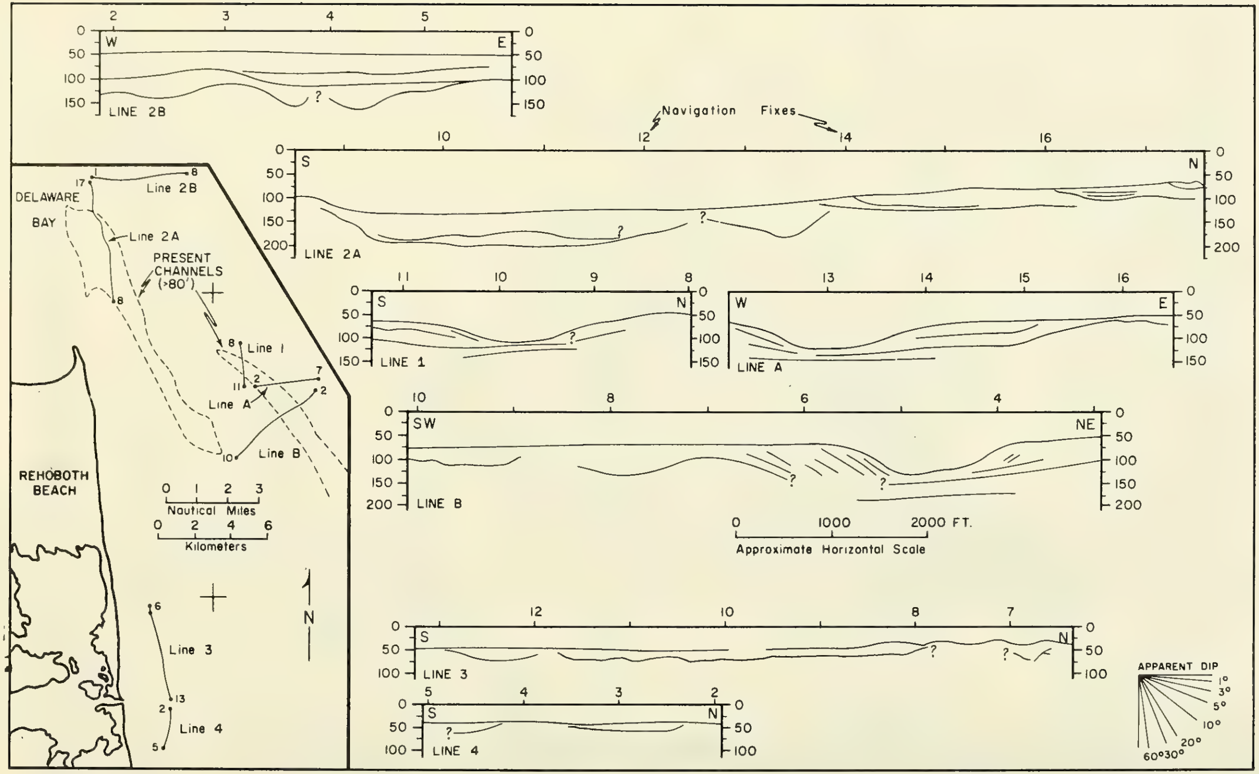


Figure 17. Location map and interpreted acoustic profiles of buried and surface channels in Delaware Bay entrance.

surface is incised by at least 25 small, relict, buried channels. The width of the channels varies from several hundred to several thousand feet; thalweg depths range from 15.8 to 30 meters (52 to 98 feet) below sea level. Side slopes and orientation are variable and since most channels were depicted on records from a single crossing, side slopes may be only apparent. Two long profile lines parallel to the baymouth barrier that closes off Rehoboth and Indian River Bays show numerous ancestral channels (Fig. 17). Sheridan, Dill, and Kraft's (1974) study shows the trend of these channels across the inner shelf quite clearly (Fig. 16).

The location and thalweg depths of shelf channels between Bethany Beach, Delaware, and the Maryland-Virginia line are shown in Figure 18. Channel orientation is presumed perpendicular to the coast, although single crossings of channels make this difficult to substantiate. Channel location appears to be somewhat related to adjacent coastal geomorphology. Some of the channels are adjacent to or directly down-dip from present-day streams; others have no obvious fluvial source and may be either fluvial or tidal in origin. Approximately one-half of the channels lie off the headland or barrier island embayed stream coastline (e.g., Isle of Wight Bay) and the other half are adjacent to the barrier island lagoon system (Ocean City to Virginia). With the exception of channels 1 and 2, which are probably fluvial in origin, and channels 16 and 17, which are probably tidal in origin, the majority of channels form an arc around Ocean City.

Plotted along the shoreline in Figure 18 are the approximate positions of historic inlet sites, as given by Truitt (1967). According to Truitt, these inlets appeared and are historically documented in maps and writings at various times between 1649, when Fenwick Inlet was charted, and 1933 when Ocean City Inlet and Inlet Shallows were formed by a hurricane. Since that date Ocean City Inlet has been periodically swept over by storms; the largest was the 1962 storm, which also temporarily reopened Sandy Point Inlet. Most of the inlets have a history of opening and closing at least several times within the past century or two. The number, spacing, and position of these historic inlets are similar to that of the shelf channels and serve to illustrate that a tidal inlet origin for at least some of them is a valid hypothesis.

To further investigate channel origins, an attempt was made to assess possible trends between channel shape (Figs. 19 and 20) and position on the shelf (i.e., northern versus southern channels, inshore versus offshore channels, and channels which lie along a projected channel path). No such trends were noted. For example, channel 8, which is alined with an apparent fluvial source onshore, does not differ in a discernible way from channel 13 to the south or from channel 3 to the north and onshore.

There exists an apparent clustering of channel locations with respect to distance from shore. Most channels are within 3.6 kilometers (2 miles) of the shore or between 5.4 to 10.8 kilometers (3 and 6 miles) from the shore. This gap, which does not appear to be an artifact of the data coverage (Figs. 2, 3, and 4), is particularly noticeable in the Ocean City

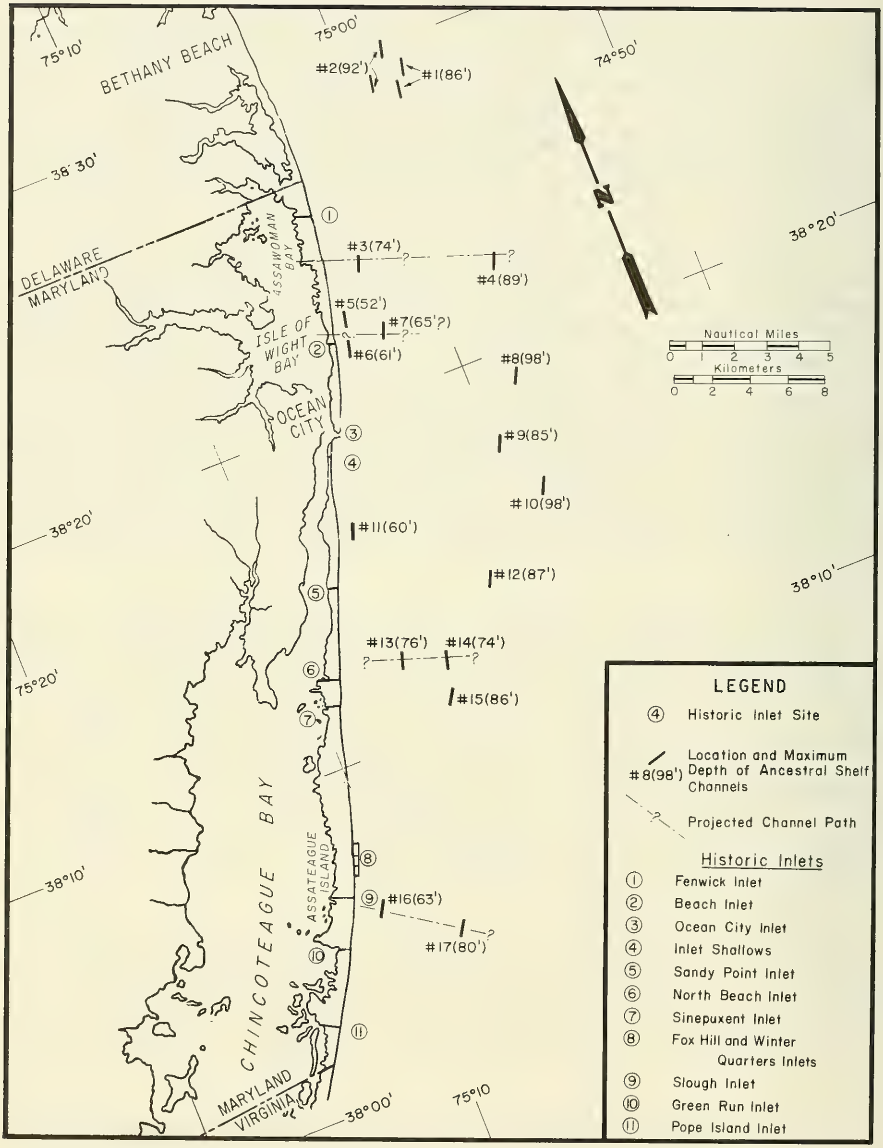


Figure 18. Map showing location and thalweg depths of buried channels on the inner shelf between Bethany Beach, Delaware, and Maryland-Virginia State line. Also shown are locations of historic inlets along the Maryland coast (Truitt, 1967). Channel cross sections are shown in Figures 19 and 20.

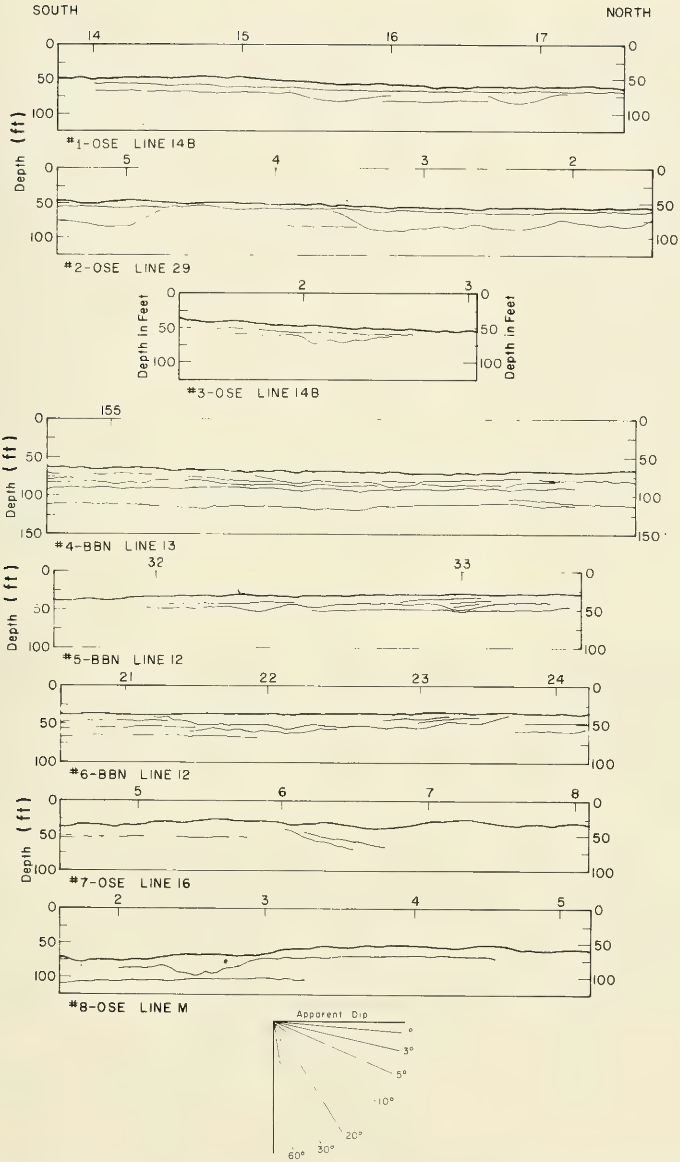


Figure 19. Interpreted acoustic profiles across buried channels on the inner shelf between Bethany Beach, Delaware, and Ocean City, Maryland. A key is provided beneath each profile. The number refers to location in Figure 18; BBN and OSE refer to the Bolt, Beranek and Newman Acoustipulse and Ocean Science and Engineering 3.5-kilohertz transducer; and the line number refers to the tracklines in Figures 2, 3, and 4.

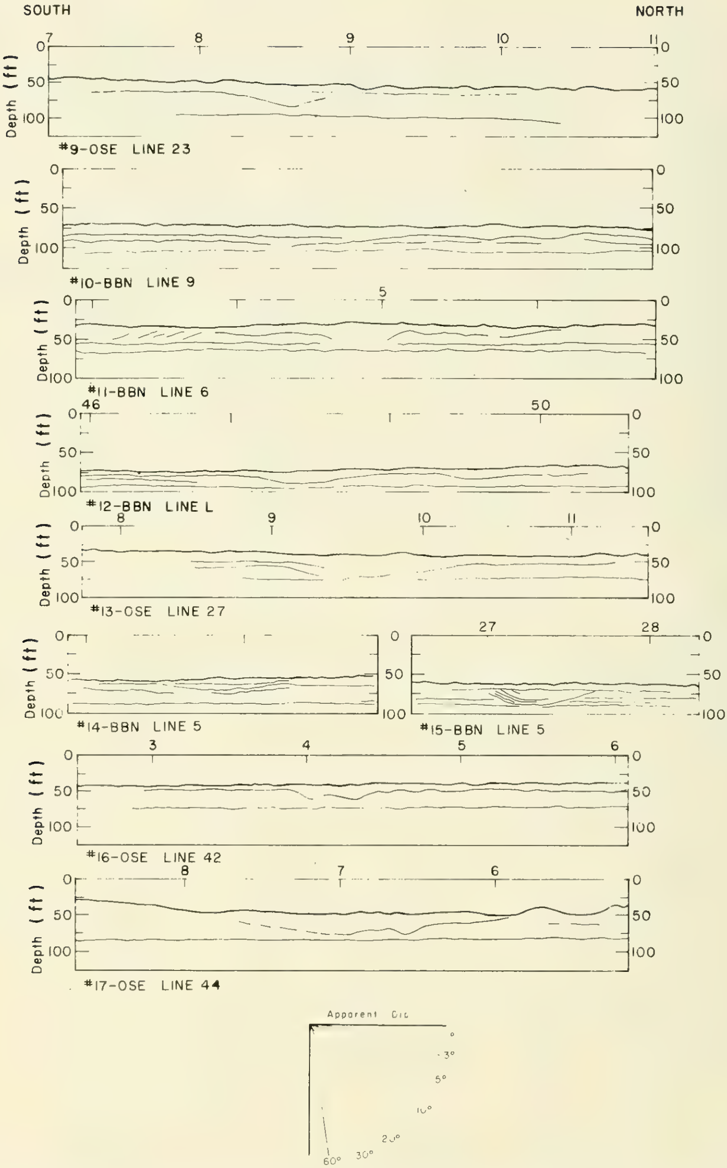


Figure 20. Interpreted acoustic profiles across buried channels on the inner shelf between Ocean City and Virginia State line. A key is provided beneath each profile. The number refers to location in Figure 18; BBN and OSE refer to Bolt, Beranek and Newman Acoustipulse and Ocean Science and Engineering 3.5-kilohertz transducer; and the line number refers to the tracklines in Figures 2, 3, and 4.

area; the cause of the gap is unclear. One distinctive difference between different groups or clusters of channels is the maximum thalweg depth. There is a well-defined relation between maximum channel depth and distance from shore for 25 channels. The trend appears to be nearly linear, but this may be an artifact of a lack of data very near the shoreline or farther offshore. The gap between the two clusters (3.2 to 5.4 kilometers or 1.8 to 3 nautical miles) is apparent in the plot, as are other more narrow gaps (0.9 to 2.2 kilometers or 0.5 to 1.2 nautical miles, 7 to 8.5 kilometers or 3.9 to 4.7 nautical miles, and 9.9 to 11.9 kilometers or 5.5 to 6.6 nautical miles). The gap farthest offshore may be an artifact resultant from insufficient data coverage. Figure 21 can be used as a potential application for extrapolating channel depths farther offshore and beneath the shoreline. The trend of the plot may not remain linear beyond the area of data coverage in either direction, but there is no valid reason to suspect that it would not, at least for short distances. Thus, to locate or identify remnant channels beneath the Delmarva shoreline, the base of the channel could be assumed to lie between 15.2 and 19.8 meters (50 and 65 feet) below sea level. Weigle (1974) located such a channel--an area beneath 66th Street at Ocean City intruded by saltwater. Borings in this area show medium and coarse sand down to 16.8 meters (55 feet) below MSL; adjacent borings contain sand to only about half that depth (Weigle, personal communication, 1975). This apparent channel is plotted as an "X" along the shoreline in Figure 21.

4. Acoustic Structure of Shoals.

Duane, et al. (1972) reported that Atlantic shelf shoals were underlain by a relatively flat reflector which projected beneath the shoals and often cropped out in intervening swales. Although seismic data were available for over 50 shoals in that study, only 1 shoal, located off Fort Pierce, Florida, showed internal, secondary stratification. Kraft (1971) reported that a shoal off Delaware was not flat on the underside but rather contained a core of Pleistocene beach ridge.

In the study area, linear shoals characteristically are defined by a strong, relatively flat basal reflector (reflection horizon A_2) which intersects the sea floor on either side of the shoal, and little or no internal structure. The sparse indications of internal stratification are restricted to (a) occasional single bedding planes in deeper strata, (b) fill-in structures in buried channels (Figs. 17, 19, and 20), and (c) occasional bedding planes within the prominent linear shoals. The lack of strong internal bedding planes is probably a result of the random movement of shoals in different directions at different rates (Field, 1976). For example, in Figure 22, none of the four lines obtained from Great Gull Banks indicate acoustic contrasts within the body of the shoal. They show, however, numerous acoustic contrasts (reflectors) down to 45.7 meters (150 feet) below sea level, including the shoal basal reflectors. As with the other shoals, some of these reflectors appear to intersect the sea floor (e.g., line L, fix 38-39).

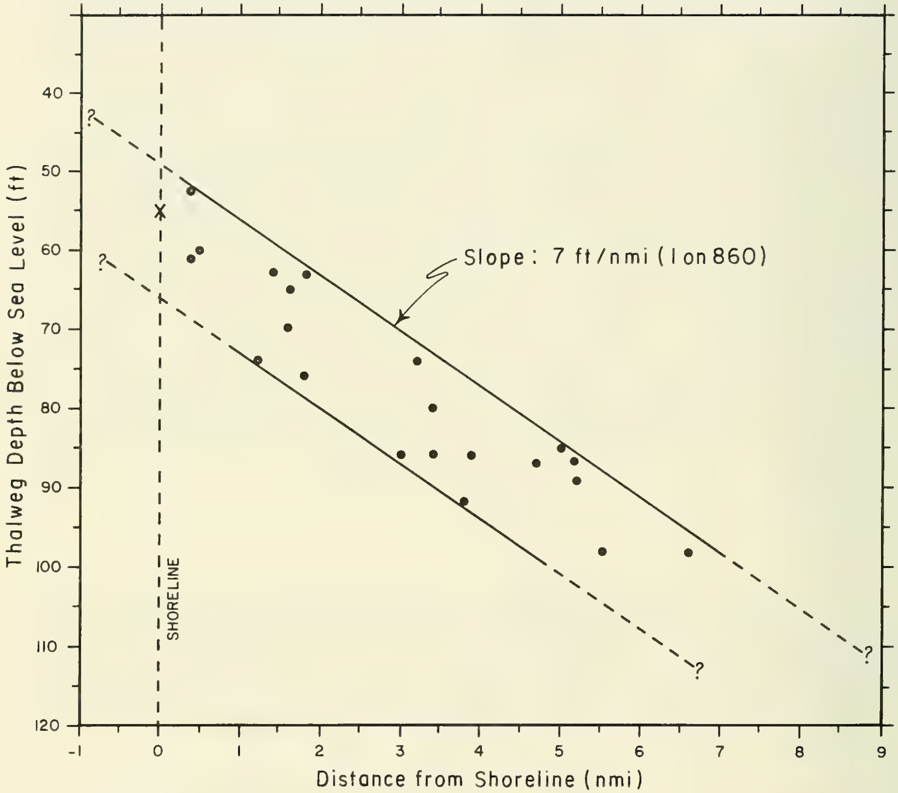


Figure 21. Plot of maximum thalweg depth of buried channels versus distance from shoreline. The X plotted along the shoreline represents sandfilled channel under Ocean City at 66th Street (Weigle, 1974).

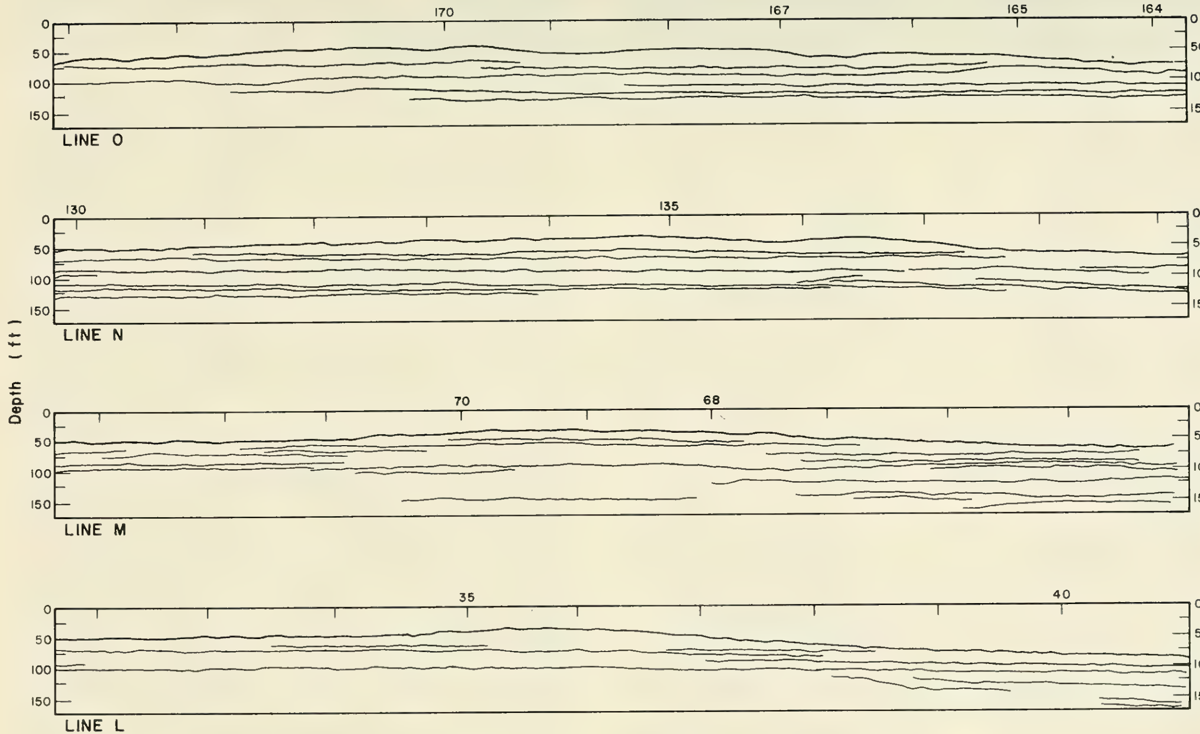


Figure 22. Interpreted seismic reflection profiles across Great Gull Banks. Trackline locations are shown in Figure 4.

Seismic profiles from shoreface shoals also clearly show the shoals to be underlain by a relatively flat reflecting surface. A basal reflector is traceable beneath the shoreface shoal off northern Assateague to where it intersects or "crops out" on the sea floor, thereby indicating a change in surface sediment character in that region. Profiles from the shoreface shoal complex just offshore of Ocean City also show no acoustic evidence of internal bedding or structure that might indicate mode or direction of growth. The shoals composing the shoal complex are all underlain by a flat reflector that can be projected to intersect the sea floor.

IV. CHARACTERISTICS AND DISTRIBUTION OF INNER SHELF SEDIMENTS

1. Background.

The availability in recent years of a low-cost coring technique (as opposed to continuous borings) for obtaining information on shallow-subsurface lithostratigraphy and the spatial distribution of sand bodies has provided much insight, and on occasion, has led to revision of previous concepts on shelf Quaternary history (Swift, et al., 1971; Duane, et al., 1972; Stahl, Kozan, and Swift, 1974; Field, 1974; Sheridan, Dill, and Kraft, 1974; Field and Duane, 1976). Vibratory cores collected for this study are no exception; they have yielded much information on three-dimensional sediment relationships, and when compiled with shallow seismic reflection data, they provide a strong basis for understanding the Quaternary evolution of the shallow Delmarva shelf.

There are few published studies on sediments of the study area. Milliman (1972) discusses mineralogy of Atlantic shelf surface sediments, including the Delmarva inner shelf, but few samples were obtained during this investigation. Most of the detailed studies of this region have been conducted on the Delaware inner shelf (Moody, 1964; Neiheisel, 1973; Sheridan, Dill, and Kraft, 1974). By analyzing the heavy mineral content of samples from Delaware Bay and the New Jersey and Delaware shelves, Neiheisel (1973) concluded that sediment mixing does not occur across the bay entrance. Based on the frequency abundance of nonopaque heavy minerals, particularly sillimanite, he identified four mineralogic provinces: (a) fluvial Piedmont, in the Upper Bay; (b) glacially derived continental shelf source, on the southern New Jersey inner shelf (sillimanite content <4 percent); (c) a mixed Delaware Bay and glacially derived shelf source in the center of Delaware Bay (sillimanite content 4 to 8 percent); and (d) a mixed fluvial Piedmont and Coastal Plain source in the west-central Bay and on the Delmarva Atlantic shelf (sillimanite content >8 percent). Neiheisel further concluded that sediment has moved north and into the bay mouth from the Delaware shelf.

Based on feldspar to feldspar plus quartz ratios (10 percent to 25 percent), Milliman (1972) classed the Delmarva inner shelf sands as subarkosic to arkosic. He also reported several anomalies for heavy mineral grains along the central section (Maryland shelf) of the study area. In this region garnet ranges from 31 to 45 percent, but decreases to between

16 and 30 percent south of Chincoteague and north of Bethany Beach. Epidote also increases to the north from between 6 and 10 percent off Maryland to between 11 and 15 percent off Delaware.

By studing 16 vibratory cores and correlating the results with high-resolution seismic reflection data, Sheridan, Dill, and Kraft (1974) were able to map subsurface sediment types on the Delaware inner shelf. They identified the following major sediment types: nearshore marine sand, lagoonal mud and clay, estuarine-shallow marine silt, peat and fringing marsh mud, and gravel and oxidized sand. All of the lithologies except the last were interpreted as Holocene in age.

Moody's (1964) study was one of the few intensive investigations of ridge and swale topography on the inner shelf. He analyzed the sediments, topography, and changes in shoal configuration on the Delaware inner shelf. The emphasis of his sediment studies is on texture. He notes that nearly all samples are sand or gravelly sand and cites other referenced material to show their mineralogic content. The sands are dominantly quartz (75 to 80 percent) with 10 to 20 percent altered feldspar. They contain a few percent nonopaque heavy minerals (dominantly staurolite, sillimanite, tourmaline, and pink garnet) and small amounts of mica, limonite, glauconite, calcium carbonate, rock fragments, and organic carbonaceous material (Shepard and Cohee, 1936; Edsall, 1955; U.S. Army Engineer District, Philadelphia, 1956; Moody, 1964).

2. Lithology of Major Sediment Types.

The lithologic character of Delaware and Maryland inner shelf deposits was determined by macroscopic and microscopic examination of samples from 70 vibratory cores varying in length from 2.4 to 9.1 meters (8 to 30 feet). Samples were extracted from cores at 1-foot intervals and cataloged; nearly one-half of the cores were split for detailed logging and photographing. Samples of sand units were selected for textural analysis by sieve and fall velocity techniques. The results of the studies are presented in Appendix B. Core locations are shown in Figure 23 in relation to the fabric of the ridge and swale topography. Core numbers range from 1 to 77; however, core 76 was collected outside of the study area and double-numbered cores (e.g., 24 and 25, 66 and 67) indicate single sites where an effort was made to obtain 12.2 meters of core, twice the standard length of a nominal 6.1-meter core.

Surface and subsurface sediments can be broadly classed into five major sediment types. The main basis for classification is grain-size distribution (modal size and sorting); secondary emphasis is on color and minor variation in grain types. Major sediment types are as follows: type I--medium to coarse, well-sorted sand; type II--fine, well-sorted sand; type III--very fine to fine, poorly sorted sand; type IV--gray mud; and type V--atypical sediments. The last sediment type is a general heading to include rarely occurring sediments such as gravels or atypical colored sands or muds. General characteristics of each sediment type are given in Table 4.

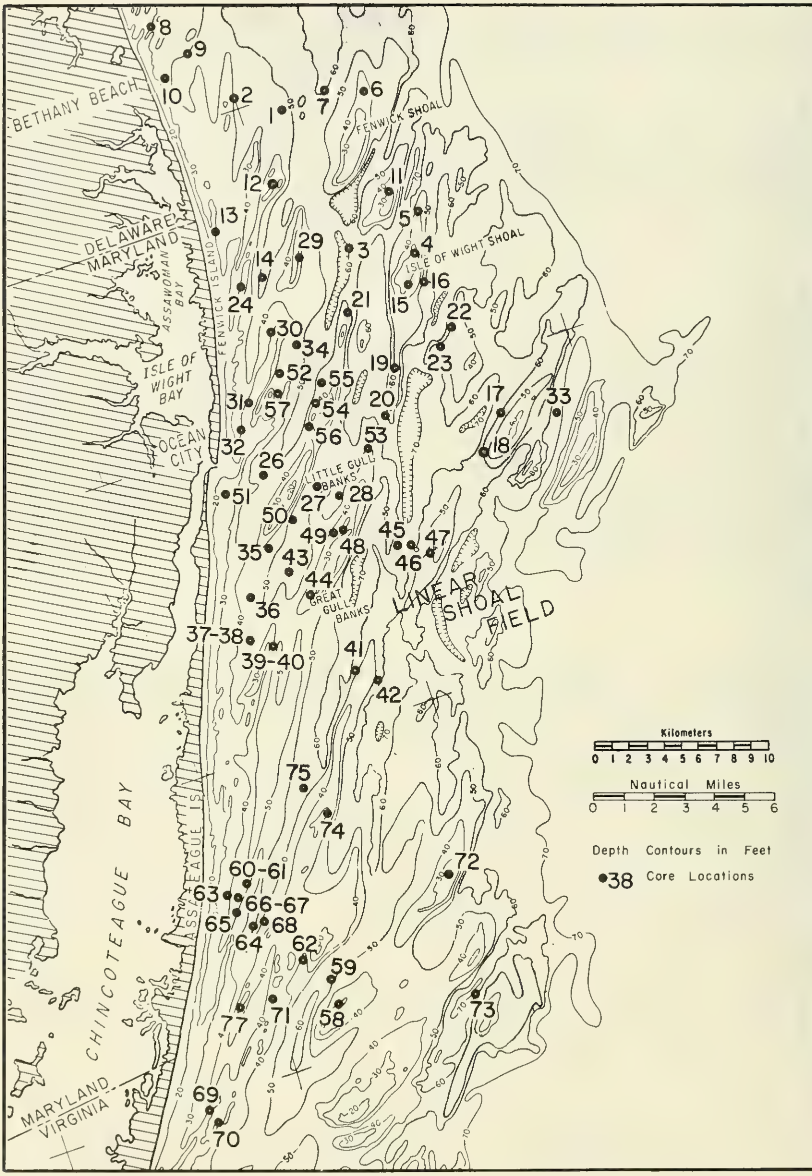


Figure 23. Locations of vibratory cores used in this study shown in relation to shelf topography. Double number (e.g., 37-38) indicates site where attempt was made to obtain one extra long core.

Table 4. Characteristics of major sediment types.[1]

Type	Color	Grain-size distribution Modal size	Grain-size distribution Sorting	Grain types	Description
Type I	10 yr 7/2 to 6/3 light gray to pale brown	Medium-size sand (1.9 to 2.0 phi)	Well and moderately well sorted σ = 0.35 to 0.80 phi	Quartz, feldspar, few percent heavy minerals, rock fragments and mollusk fragments; in trace glauconite, forams.	Medium-grained, well-sorted subarkosic arenite.
Type II	10 yr 5/2 grayish brown	Fine-size sand (2.0 to 3.0 phi)	Well sorted to moderately well sorted σ = 0.35 to 0.80 phi	Quartz, feldspar; 1 to 3 percent each heavy minerals, benthic forams, and echinoid fragments; trace glauconite and mollusk fragments.	Fine-grained, well-sorted subarkosic arenite.
Type III	10 yr 5/1 to 3/1 gray to very dark gray	Very fine to fine-size sand (2.5 to 4.0 phi)	Poorly sorted	Quartz, feldspar, heavy minerals mica and unidentified silt grains; benthic forams and echinoid fragments, 1 to 4 percent each; trace plant material.	Fine-grained, poorly sorted subarkosic arenite.
Type IV	5 yr 5/1 gray	Medium- to coarse-size silt (4.5 to 6.5 phi)	Very poorly sorted	Detrital grains dominant, with few percent of biogenic grains (chiefly biogenic forams).	Slightly sandy mud.
Type V (a)	5 yr 6/4 light reddish brown	Medium-size silt (5 to 6 phi)	Very poorly sorted	Detrital grains and clay, organic material abundant.	Very slightly sandy mud.
(b)	10 yr 8/1 to 7/1 white to light gray	Medium-size sand (1 to 2 phi)	Well sorted	Quartz and feldspar; heavy minerals and rock fragments rare.	Medium-grained, well-sorted subarkosic arenite.
(c)	10 yr 5/6 ped	Very coarse size sand to pebbles (0 to -4 phi)	Very poorly sorted	Quartz, feldspar, rock fragments abundant, weathered grains abundant.	Coarse-grained, poorly sorted feldspathic litharenite.

[1]After Pettijohn, Potter, and Siever (1972).

Sediment designated type I is a medium-grained, clean quartz sand. Actual size ranges from about 0.215 to about 0.707 millimeter (2.2 to 0.5 phi). Sorting of the sand ranges from 0.35 to 0.80, which is within the well sorted and moderately well sorted classification (Friedman, 1962). Characteristics of the grain-size distribution and significant grain types for all sediment classifications are summarized in Table 4. The dominant components of all sands are detrital quartz and feldspar. Individual quartz grains are subrounded to subangular; most are clean, but frosted and milky grains are not uncommon. Feldspar grains, including rare twins, are easily identifiable under reflected light on the basis of color and cleavage. Samples contain several percent each of heavy minerals and rock fragments. Glauconite is present in trace quantities and mica is virtually absent. Approximately 1 to 2 percent of the sand is composed of biogenic calcium carbonate. Individual grains of carbonate are white and coarse sized; the majority are derived from mollusk shells. Also present in trace quantities are benthonic foraminifera and ostracods.

Type II sediment is a fine-grained, well sorted to moderately well sorted, quartz sand that is similar to type I sand in all but two respects. One significant difference is the finer modal size (Table 4). A second difference is the composition of the biogenic fraction of the two sediment types. Benthonic foraminifera are more abundant in the fine sand than in the medium sand. Dominant types are *Elphidium* sp. and *Quinqueloculina* sp. Fragments of molluskan fauna are less abundant and more fragile than in the medium-grained sand, and spines and fragments of echonoids are present in small quantities. Both sands (types I and II) can be described as well-sorted subarkosic arenites (Table 4).

Type III sediment is also fine sand, but it differs from the other sands slightly in modal size and differs significantly in sorting. The sand is very fine to fine grained and poorly sorted (1.4 to 2.0) (Friedman, 1962). Composition is similar to that of the fine, clean sands of type II with two minor exceptions. Echinoid fragments are more common and plant material in the form of grains and fibers is present.

Type IV sediment, which is a very poorly sorted silt or slightly sandy mud, contrasts sharply with the clean sands (types I and II). The dominant size of particles is 0.625 to 0.039 millimeter (4 to 8 phi), but both clay particles (<0.039 millimeter or >8 phi) and sand grains (>0.625 millimeter or >4 phi) are present in varying proportions. Grain types are difficult to identify under reflected light because of their small size, but the majority are terrigenous silicate grains. Benthonic foraminifera are common; dominant species are *Ammonium* sp., *Quinqueloculina* sp., and *Elphidium* sp. Plant fibers and debris are common in places.

Type V sediment is a classification comprising several different sediment types that are restricted in thickness and distribution. Included within this group are organic-rich silts, clean sands, and poorly sorted gravels. The organic-rich silt is a poorly sorted medium silt; the organic fraction is unidentifiable plant remains. At least four cores contained this type of sediment, and two of them contained enough organics for radiocarbon age dating. The sand included in the "atypical" (of this locale) sediment category is a white, medium-sized, well-sorted quartz sand. The sand is much whiter than type I sands and contains a much less diverse mineral assemblage. Heavy minerals, glauconite, and mica are nearly absent. A very coarse sand, or gravel, was noted in one core (33). Diagnostic of this sediment is its red color (fine-grained limonite), weathered silicate grains, abundance of rock fragments, and complete absence of fauna. The sand is poorly sorted to very poorly sorted; the overall size of the deposit ranges from clay to cobbles.

3. Surface and Subsurface Sediment Distribution.

a. Spatial Nature of the Surface Sand Body. The dominant grain size of surface sediments of the U.S. Atlantic Inner Continental Shelf is sand (Trumbull, 1972; Milliman, 1972). These sands have been interpreted as dominantly relict-fluvial in origin (Emery, 1968) with modern sands restricted to a nearshore band (Milliman, 1972). Swift, et al. (1971) pointed out that although inner shelf sands bear mineralogic and faunal evidence of deposition in other environments, they have been partially reworked and their textural characteristics reflect their response to the present marine environment. They coined the term "palimpsest" to describe these sediments. The spatial nature of these shelf sands is generally unknown.

The term "surficial sand sheet" has been commonly used in reference to the mantle of sand covering the inner shelf (e.g., Swift, 1970). This term is somewhat misleading, as recently discussed by Field and Duane (1976), for it connotes both a specific geometry (as defined by Krumbein and Sloss, 1963) and certain uniformity or continuity. When examined by dense sampling patterns, most shelf areas show a high degree of variability in texture of surface sediments. In areas characterized by irregular topography, such as the study area, distribution of surface sediment types is often controlled or strongly influenced by the local shelf morphology (Fig. 24).

The dominant surface sediment in the study area is medium- to coarse-grained, clean sand (type I). Poorly sorted fine sands and gray muds (types III and IV) account for only 10 to 14 percent of the samples, and these are all from swales or intervening flat areas between shoals. Clean, fine sands are also relatively uncommon in surface samples (11 percent) and are generally restricted to the shoreface-shoal complex in the southern part of the study area. It is quite evident that any attempt to "contour" or group similar sediment types, without considering their relation to the local topography, could easily lead to erroneous conclusions. Sediment distribution is a function of the shape of the sea floor, and unless the sample population is very dense, interpolation of shoal sands across a swale area is not justified.

b. Shallow Subsurface Sediments. The distribution of sediments in the shallow subsurface is markedly different than on the surface, except in the vicinity of shoals, where surface sands are thicker (Fig. 25). Clean sands are still relatively common at the shallow sediment depth of

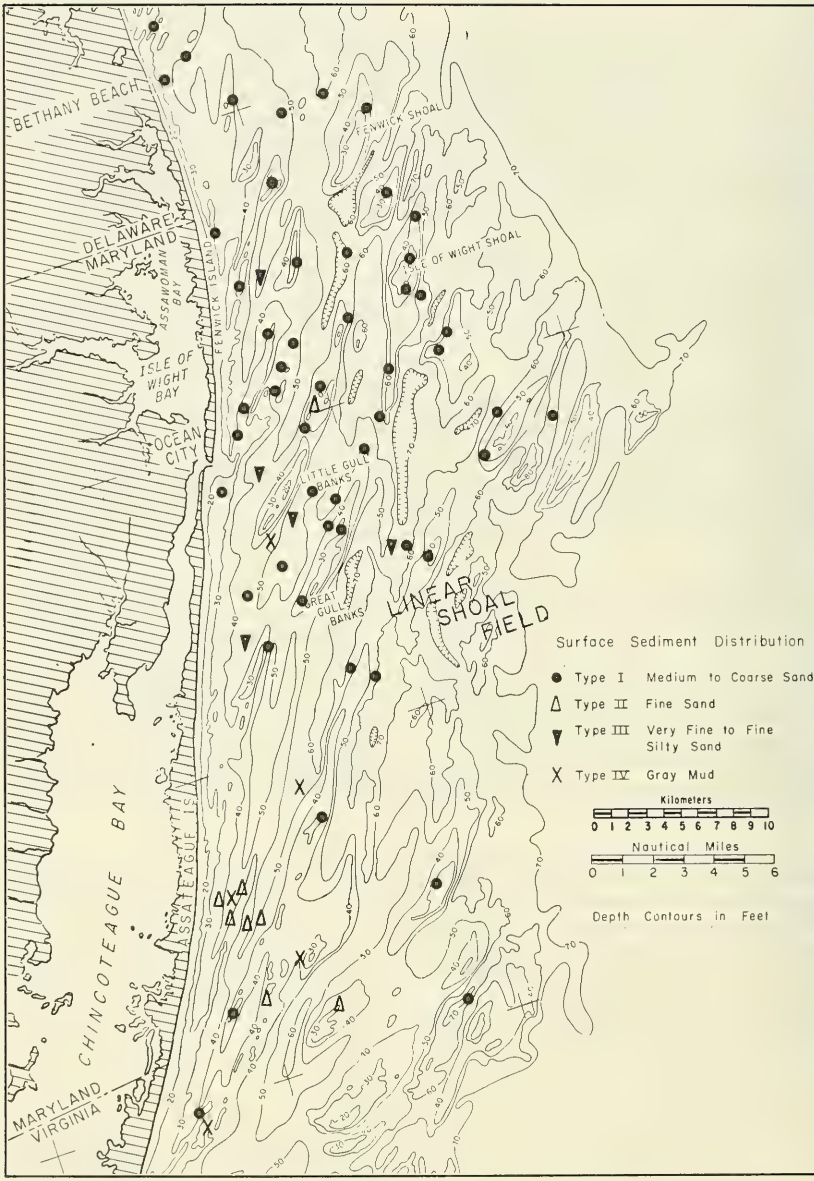


Figure 24. Map showing surface distribution of major sediment types defined in this study in relation to sea floor topography.

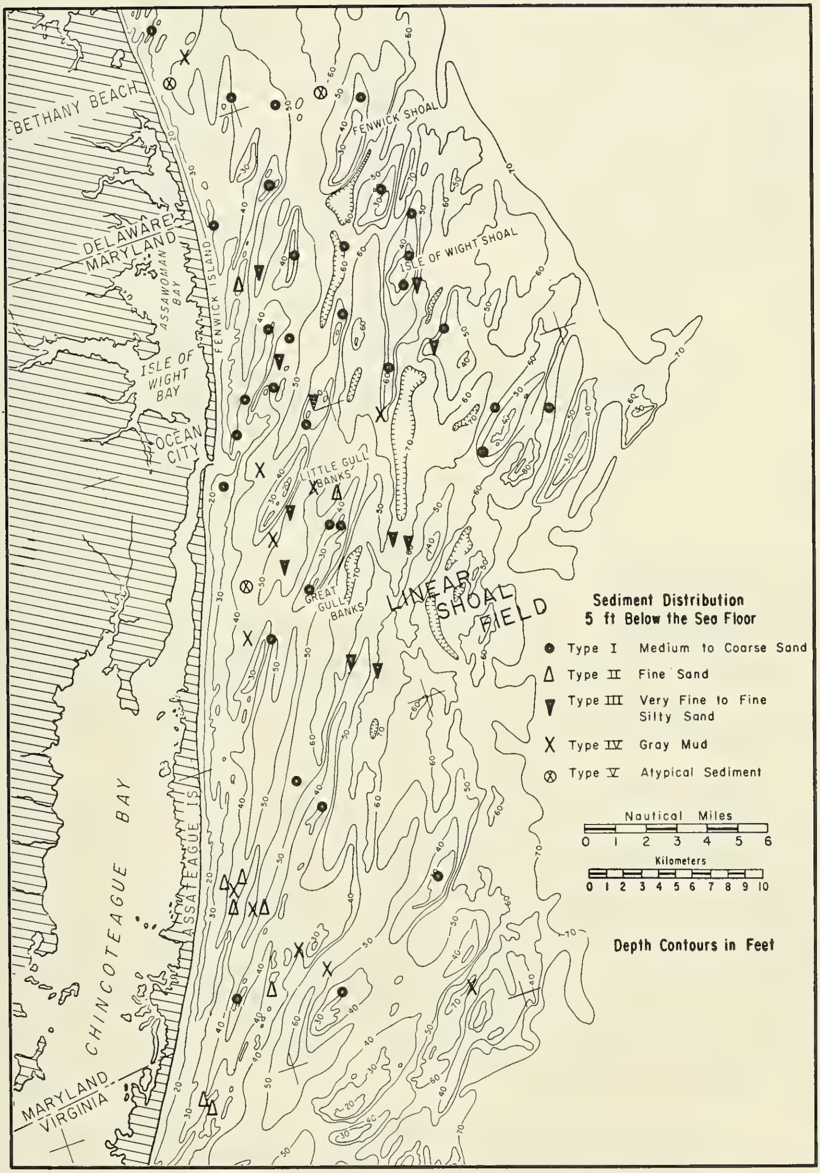


Figure 25. Map showing distribution of major sediment types 5 feet (1.5 meters) below the sea floor in relation to surface topography. Note the close association of type 1 sands (dots) with shoal areas.

1.5 meters, particularly beneath shoals, but their relative abundance decreases (Table 5). However, there is a significant increase in abundance of poorly sorted sands and muds (types III and IV). These sediment types account for over one-third of the samples, compared to only 14 percent on the surface. Clean, fine sands show only a slight increase from about 11 to 14 percent. Atypical sediments account for only about 5 percent. The distribution of muds and very fine silty sands at -1.5 meters MSL is almost entirely restricted to flats or swales between shoals, as for surface sediments. The clean, fine sands associated with the shoreface-shoal complex in the southern part of the study area also persist at shallow depths.

Table 5. Percent abundance of major sediment types on the sea floor and below.

Depth (ft)	Samples (No.)	Type (pct)				
		I	II	III	IV	V
Sea floor	68	74	12	7	7	0
-5	63	46	14	17	18	5
-10	54	39	11	15	31	4
-15	33	24	18	12	46	0

There are no abrupt changes in sediment distribution 3 meters below the sea floor (Fig. 26). The trend of increasing muds and silty sands concommitant with a decrease in abundance of clean, medium sands continues at this depth. Types III and IV account for about 45 percent of the sediment, compared to 39 percent of clean, fine- and medium-size sand; the location of type I is restricted primarily to the shoal areas.

Only 33 of the cores penetrated deep enough into the shelf to plot distribution of lithologies at 4.6 meters (15 feet) below the sea floor, as shown in Figure 27. At this depth, 46 percent of the samples are gray mud (type IV) and 12 percent are silty sand (type III). Clean, medium to coarse sand has decreased in abundance to 24 percent, and clean, fine sand is still confined to the central Assateague shoreface region. The relative abundance of different sediment types at -3 meters and particularly -4.6 meters is subject to some error due to the assumption that cores penetrating to those depths sampled a representative population. There is no precise way to test this assumption, but based on an examination of core locations with respect to topography, it appears that deep-penetrating cores are representative and certain features or areas are not selectively excluded.

c. Radiometric Age Dates. Two cores (13 and 51) contained organic material in sufficient quantity to obtain radiocarbon age dates. Both cores are located close to shore in relatively shallow water, but have significantly different C^{14} ages. Core 13 was collected in 9.1 meters

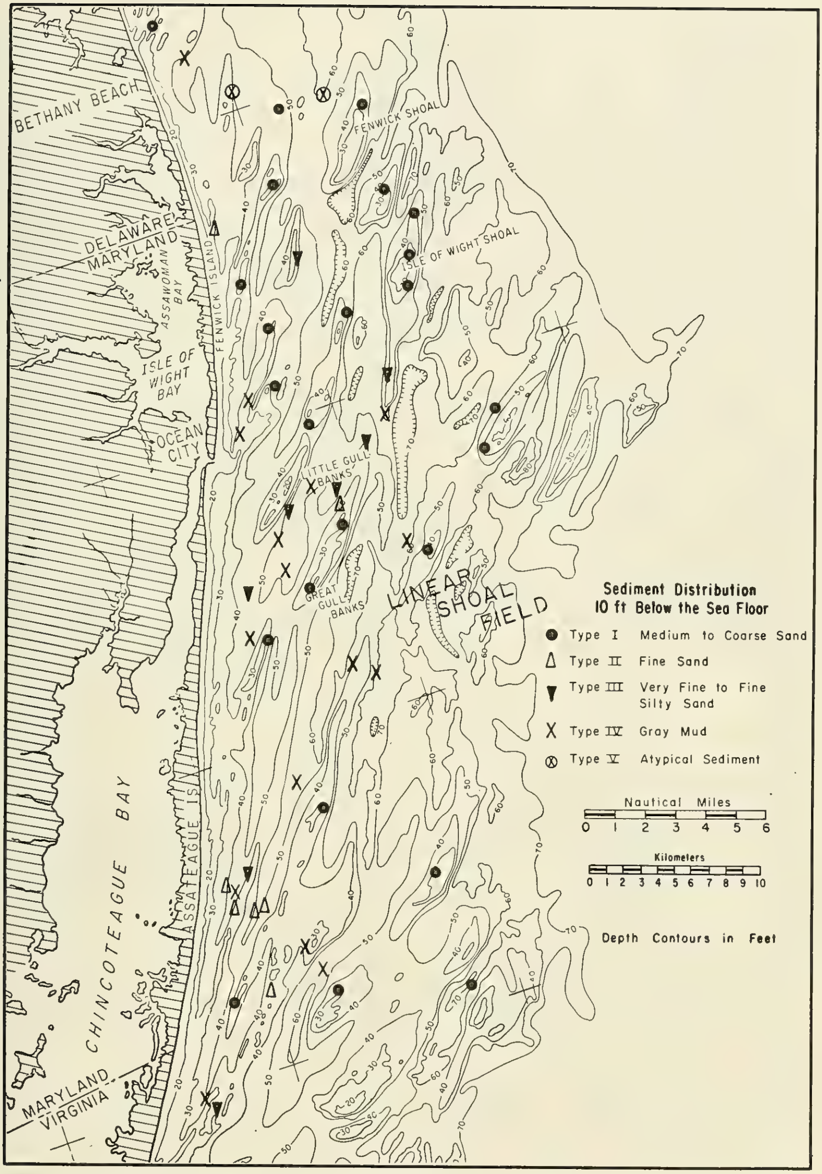


Figure 26. Map showing distribution of major sediment types 10 feet (3.0 meters) below the sea floor in relation to surface topography. Note the close association of type I sands (dots) with shoal areas and the general increase in abundance of mud (X's).

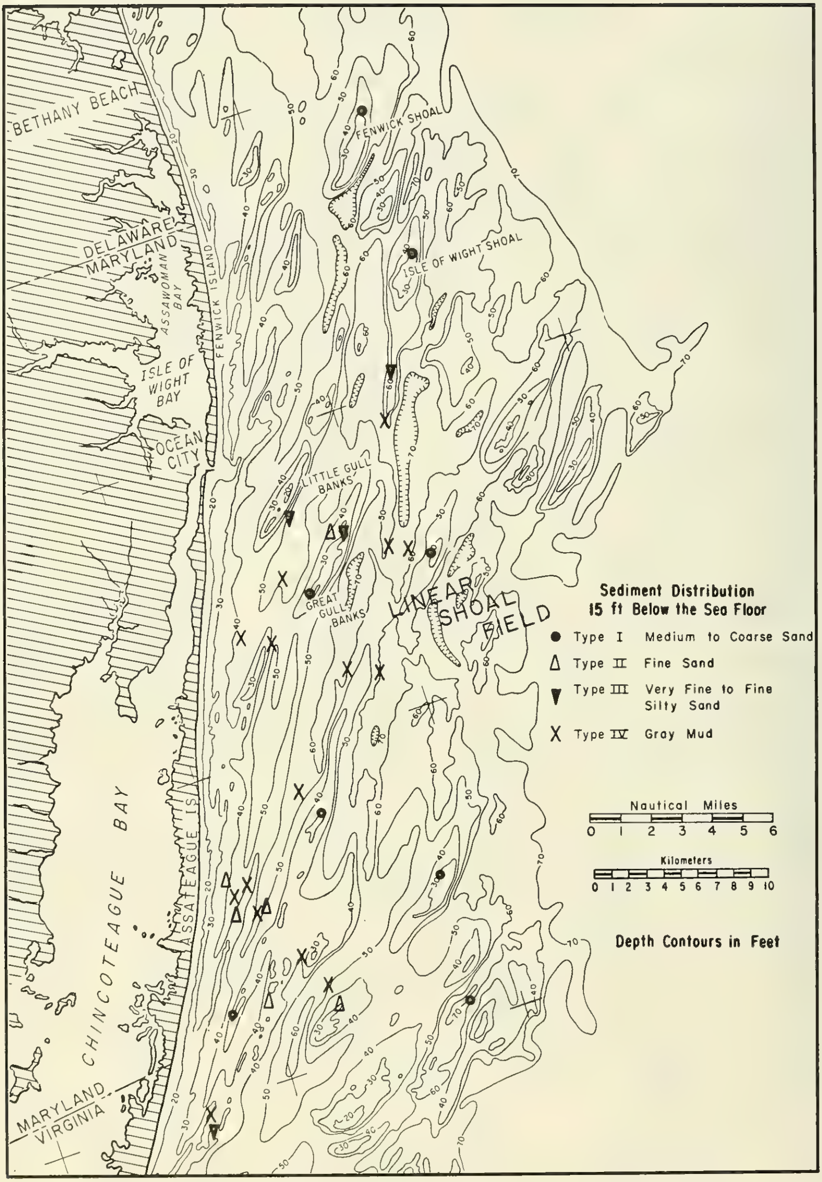


Figure 27. Map showing distribution of major sediment types 15 feet (4.5 meters) below the sea floor in relation to surface topography. Note the close association of typo I sands (dots) with shoal aroas and tho general increase in abundance of mud (X's).

of water; the peat sample was retrieved from 1.7 meters (5.6 feet) below the sea floor, for a total subsea elevation of -10.8 meters below sea level. The sample was age-dated by Isotopes, Inc. (Lab No. I-7441) and a C^{14} age of 5,765 ± 105 years before present (B.P.) obtained. The top of core 13 is a gray, fine- to medium-grained, clean sand extending from the top down to about 1.2 meters (3.8 feet). This sand unit is massive (structureless), contains no macrofauna, and has a gradational lower contact characterized by alternating layers of silt and fine sand. Between -1.2 and -1.8 meters (-3.8 and -6 feet), the sediment is black, slightly silty clay with some thin <3-centimeter (<0.1 foot) layers of silt and a 9-centimeter (0.3 foot) layer of sand at -1.5 meters. Sediment between 1.7 and 1.8 meters (5.5 and 6 feet) down in the core was suitably enriched in organic carbon for C^{14} dating. From the base of this layer to the bottom of the core, sediments were predominantly gray-brown, slightly silty, very fine sand.

Core 51 was obtained from the shoreface just south of Ocean City Inlet in about 7.6 meters of water (see Fig. 23 for location). The organic material retrieved for dating lies 2.1 meters (7.0 feet) below the sea floor, for a total depth of 9.7 meters (32 feet) below sea level. The C^{14} age date for this sample (I-7438) is 32,730 ± 1,650 years B.P., a marked contrast to that obtained for core 13. Weigle (1974) reported two peats beneath Ocean City and Assateague Island that lie at about the same depth and bracket the position of core 51. The peat beneath Assateague State Park (elevation of -8.2 meters or -27 feet) yielded a C^{14} age date of about 31,000 years. The sample from Ocean City was recovered from a depth of 9.7 meters below sea level, and has a radiocarbon age date greater than 27,000 and less than 40,000 with an uncorrected direct reading of 33,000 years.

Age and elevation for the two peats recovered in this study and for those reported by Sheridan, Dill, and Kraft (1974) and Weigle (1974) are plotted in Figure 28. The sea level curves are from Curray (1965) and Milliman and Emery (1968). Data points show good agreement with the curve of Milliman and Emery, which is constructed from Atlantic shelf data. The peaty samples recovered offshore show the presence of preserved lagoonal-estuarine deposits of both mid-Holocene and late Pleistocene (mid-Wisconsin age) in the shallow subsurface. Other investigations of inner shelf subsurface sediments have reported similar age relationship patterns. Field (1974) discussed the presence of Holocene lagoonal peats and late Pleistocene strandline deposits off of Cape Canaveral, Florida; dates and position of the samples also showed good agreement with the Milliman and Emery (1968) sea level curve. In a study area similar to this one, 11 peats obtained by coring and boring techniques just offshore of southern New Jersey were reported by Stahl, Kozan, and Swift (1974). These materials range in age from 6,685 to 29,320 years B.P., and most dates cluster around the mid-Holocene and late Pleistocene dates of this study.

d. Vertical Relationships of Sediments. As evidenced by the distribution of major lithologies at different depths in Figures 24 to 27 and

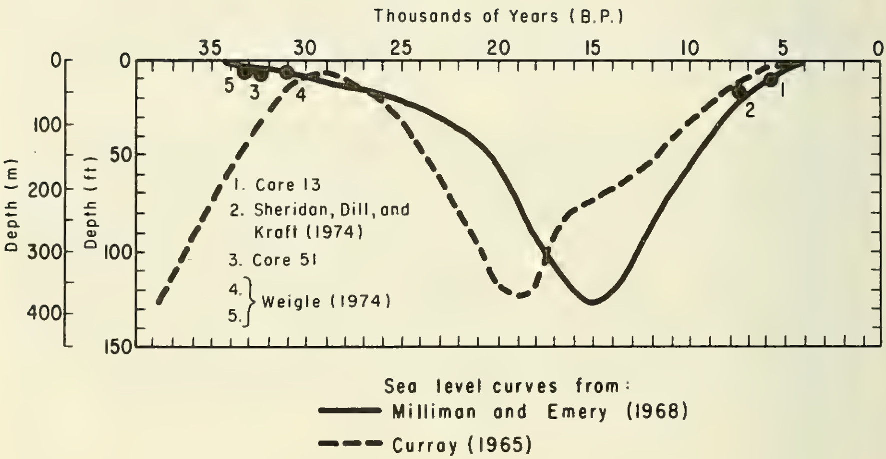


Figure 28. Depth and radiocarbon age of peaty sediments from the study area plotted against two published sea level curves.

Table 5, there are several vertical trends in sediment patterns. Gray-brown, fine to coarse, well-sorted quartz sand is the dominant lithology on the surface and decreases in relative abundance with depth. Increases in sand thickness occur locally in shoal areas. The sand overlies poorly sorted, very fine to fine sands and muds that are locally exposed at the surface and that increase in relative abundance with depth. Well-sorted, fine sands are restricted almost entirely to shoreface shoals off central and southern Assateague and are relatively thick. Atypical sediments (white sands, brown muds, organic muds, and red iron-stained gravels) are absent on the surface and occur at different levels in the shallow-sediment column. The muds lie beneath clean surface sands; the sands and gravels lie at the base of cores and represent the top of sediment units that were rarely sampled but are probably widespread. Of equal importance to distribution of sediment types is their vertical relationships to one another, including the nature of contacts and internal variations such as lamination, burrows, size grading, etc. This information may be obtained through careful logging and photographing of cored sediments.

Core 33, collected about 20 kilometers (11 miles) offshore of Ocean City in over 18.2 meters of water, is composed of five sediment units, one of which is an iron-stained gravel (Fig. 29). The top 0.43 meter (1.4 feet) of the core is composed of gray-brown, medium quartz sand with some shell material. This upper unit is massive (structureless) and has a sharp lower contact. Hamblin (1965) showed that many apparently massive or homogeneous sandstones are actually very finely laminated, and it seems likely that under closer scrutiny (e.g., radiographic studies) many of the sands described as massive would show some structure. The next lower unit is a 3-centimeter-thick dark-gray sand silt. From 0.45 to 2.0 meters down in the core, gray and gray-brown, fine to medium, massive, quartz sand is dominant. Mollusk fragments and shells are common near the top and silt lamina are present throughout the unit. There is a sharp contact between this unit and the next lower one, a 18.2-centimeter (0.6 foot) dark-gray, laminated and interbedded silt, and very fine sand. Contact is sharp with the lowest unit, an admixture of clays, silt sands, and gravels. As noted earlier, the gravels and sands are deeply iron-stained and contain a high percentage of rock fragments. The brown and red clays are tough, cohesive, and interbedded at irregular spacing and thickness with the sandy gravels. No fauna are present. This unit is typical of fluvial (point bar) deposits. Kraft (1971) and Sheridan, Dill, and Kraft (1974) noted that the common presence of Pleistocene fluvial gravels in the shallow subsurface of the Delaware inner shelf and this sample probably represents a similar or related deposit.

Core 42, collected in the central part of the study area from a region of subdued topography (location shown in Fig. 23), displays several typical sediment relationships (Fig. 30). The upper 2 feet is typical gray-brown, medium-sized surface sands and contains shell fragments of *Spisula solidissima*. A gradational change exists at about 2 feet, to a gray, fine to medium, quartz sand with numerous white shell fragments. Between 2.2 and 3.9 meters (7.3 and 12.9 feet) is a complex sediment unit consisting

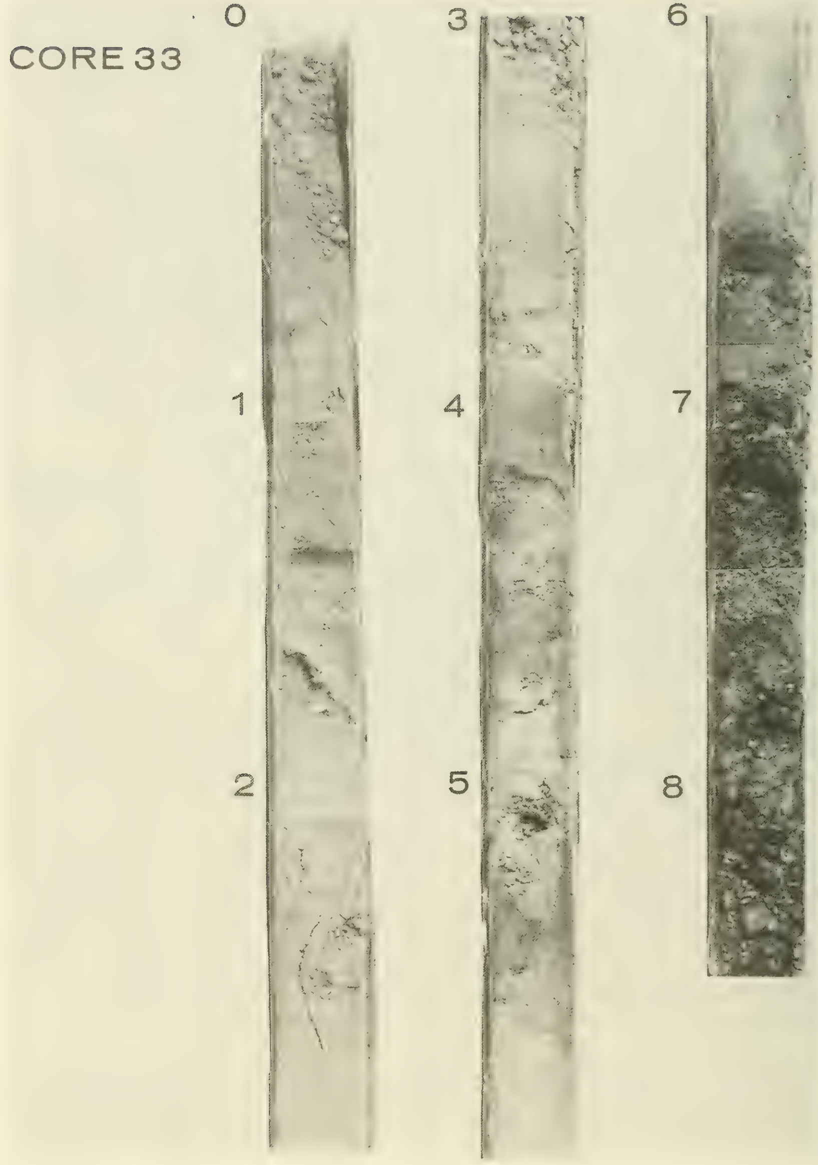


Figure 29. Composite photo of core 33, with sediment depths shown in feet. Lithologic boundaries occur at 1.4, 1.5, 6.6, and 7.2 feet (0.43, 0.46, 2.0, and 2.2 meters). The lowermost unit is a striking red gravel.

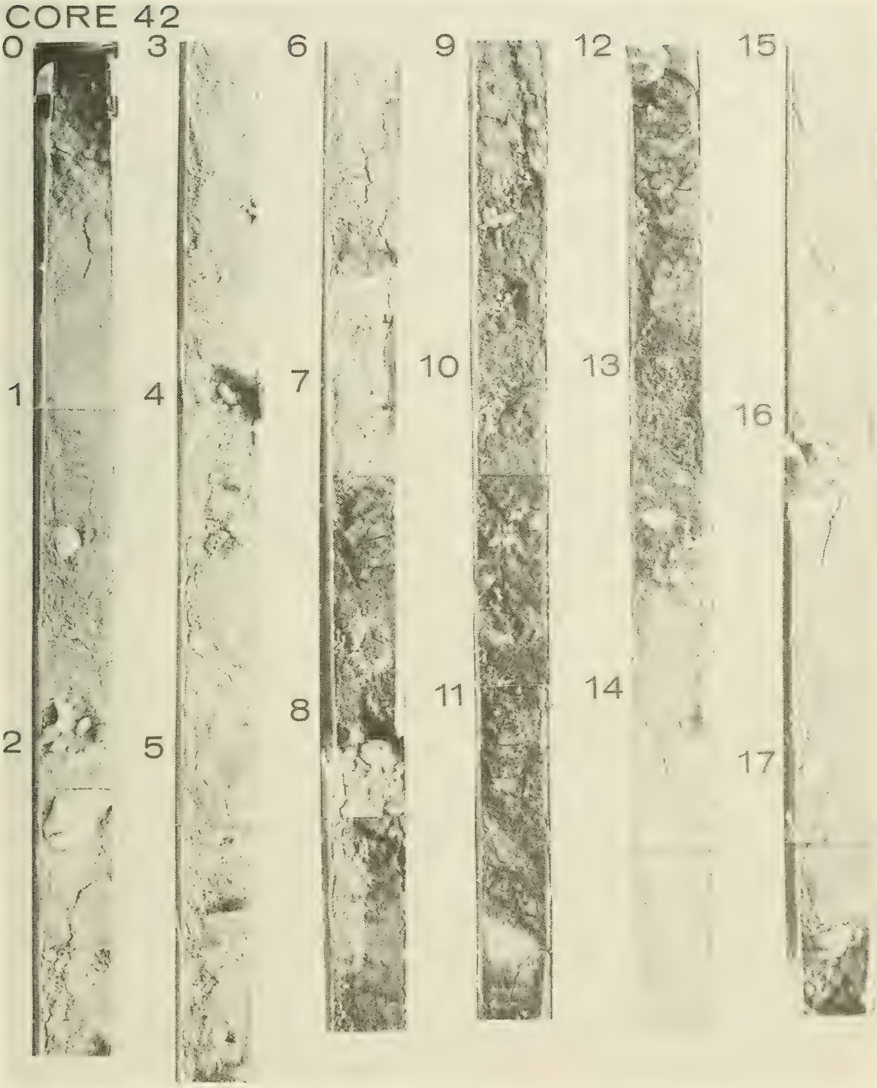


Figure 30. Composite photo of core 42, with sediment depths shown in feet. Lithologic boundaries occur at 2.0, 7.3, 12.9, and 13.7 feet (0.6, 2.2, 3.9, and 4.2 meters). Note whole pelecypod valves at 1.4 and 2.2 feet (0.43 and 0.67 meter).

of interbedded dark-gray silty clays, brown coarse silts, and light-gray fine sands, all of which vary in thickness from 3 to 15 centimeters (0.1 to 0.5 foot). Beneath this unit lies a brown, very coarse to coarse, quartz sand containing highly weathered-altered shell fragments; the unit terminated abruptly at 4.2 meters (13.7 feet). The underlying and lowest unit in the core is a gray, fine quartz sand with molluskan shell fragments evenly distributed throughout. In simplest form, the entire sequence represented by this core demonstrates two high-energy depositional environments separated by a low-energy environment. It differs from core 33, which showed the same sequence, by the presence of marine organisms in all sand units. The color (brown) and altered state of carbonates in the coarse sand unit at 3.9 to 4.2 meters suggest the sand was previously exposed under subaerial conditions and thus predates the last transgression. Overlying fine-grained sediments are probably marginal marine (estuarine, lagoonal) and the upper sands are modern shelf and possibly relict barrier island deposits.

e. Changes in Sediment Character. The large number of vibratory cores collected on and near the shoals provides a strong basis for interpreting the internal and underlying sediments. Cores obtained along shoal crests recovered only sand in most instances, indicating thicknesses in excess of 6.1 meters (see Fig. 25); those obtained from the edges often penetrated the first subsurface horizon (acoustic horizon A_2) that appears beneath each shoal. The shoal sands almost exclusively type I gray-brown, well-sorted, medium quartz sands. Underlying sediments are variable, but the most common are type IV gray muds and type III poorly sorted fine sands. This association, particularly that of the medium, clean sands overlying muds, produces the strong acoustic contrast generating an identifiable reflector.

Figure 31 shows lithostratigraphic cross sections along the long axes of two shoals, Ocean City shoal and Isle of Wight shoal. The cross sections were constructed solely in the basis of lithology and are discussed in more detail by Field (1976). Ocean City shoal is a shoreface shoal-complex extending northeast from the vicinity of Ocean City Inlet; the shoal comprises several individual arms or ridges. The shoal appears to be perched upon a layer of sandy, clayey silt, overlying silty sand that rises toward the southwest. The age of subsurface deposits on the onshore profile indicates that the base of the shoal is not simply a remnant Holocene lagoonal facies after it had been transgressed and reexposed, but rather a former (mid-Wisconsin) lagoonal or estuarine deposit that has been covered by modern barrier-shoreface facies. A marked hiatus exists between the surface sand body and these underlying relict deposits.

A cross section of an isolated or offshore shoal is shown in Figure 31, profile B-B'. Five cores were collected along the long axis of Isle of Wight shoal. Cores 4, 5, and 15 contained gray-grown, fine- to medium-sized quartz sand throughout their entire length. Cores 19 and 20, however, penetrated into fine-grained deposits underlying the shoal. These two cores provide some significant information about the formation of this

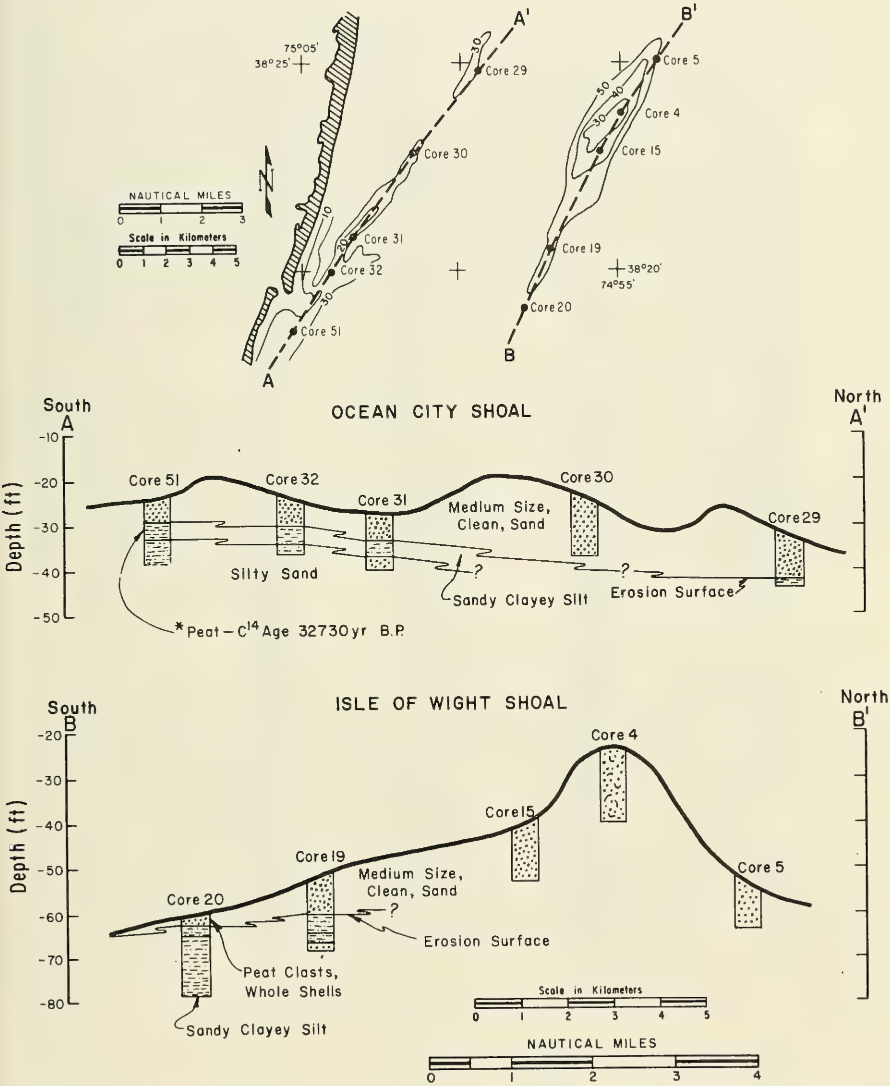


Figure 31. Geologic cross sections along the axes of Isle of Wight and Ocean City shoals. Correlations are based on lithologic comparisons.

surface. Core 19, collected well within the confines of the shoal in 15.5 meters (51 feet) of water, contains 2.7 meters (9 feet) of sand overlying the mud surface. Core 20 (Fig. 32), however, was obtained from the extreme edge of the shoal in water 18.3 meters deep. Cored sediments represent the feather edge of shoal sand as it migrates across a mud substrate. Included in the relatively thin (1 meter) surface sand are components derived from the mud substrate (Fig. 32). At about 0.5 meter (1.6 feet) below the core surface is a peat clast approximately 3 centimeters in diameter. Between 0.61 and 0.73 meter (2.0 and 2.4 feet) are four large pelecypod valves (oysters, clams). Both components (peat, shells) are characteristic of the underlying mud and show that as the shoal sand shifted southward, certain components of the underlying mud unit were deposited in the shoal. Sediments below the surface sand down to about 2.4 meters are dark-gray, fine sandy, clayey silt with few or no shells. From 2.4 meters to the bottom of the core are alternating silty clays and clayey sandy silts which contained a large white oyster shell at 2.5 meters (8.2 feet).

In summary, shoals are composed of medium-grained, well-sorted quartz sand that is megascopically massive and locally bioturbated. Mollusk shells (both whole and fragmented) are common. The sand rests on a nearly flat interface with the underlying, typically fine grained sediments. This underlying mud unit is a relict deposit from a low-energy environment (lagoon, estuary). The upper surface of the mud unit was, and is, being eroded by current scour. As shoals migrate over this surface, constituents of the mud are incorporated into the base of the shoal sand.

V. DISCUSSION

1. Origin and History of Sediments.

Shallow-subsurface sediments of the northern Delmarva inner shelf range from Pliocene age to modern and represent the entire sequence of marginal marine depositional environments from fluvial to inner shelf. All sediments are representative of lateral facies existing today in the mid-Atlantic Coastal Plain; there is no sedimentary or structural evidence of ancestral glacial or tropical reef environments.

Sediments consist almost entirely of terrigenous sand and silt. Clay is present in significant quantity in only one lithologic type. Nonterrigenous materials include biogenic carbonates (principally mollusks, echonoids, and foraminifera) and reworked authigenic grains, such as glauconite. The terrigenous fraction is dominated by quartz and feldspar. Mica and various high-density silicate minerals compose a few percent. Composition of the heavy mineral fraction indicates derivation from the adjacent coastline and ultimate derivation from the complex metamorphic rocks of the Piedmont province. Nieheisel (1973) showed that sediments from the New Jersey shelf are not transported south beyond the Delaware Bay entrance and that sediments from the northern Delaware shelf are transported north into the entrance. Mineral suites indicate derivation of shelf sediment from a combination of land sources (Piedmont, Coastal Plain, Pleistocene terraces).

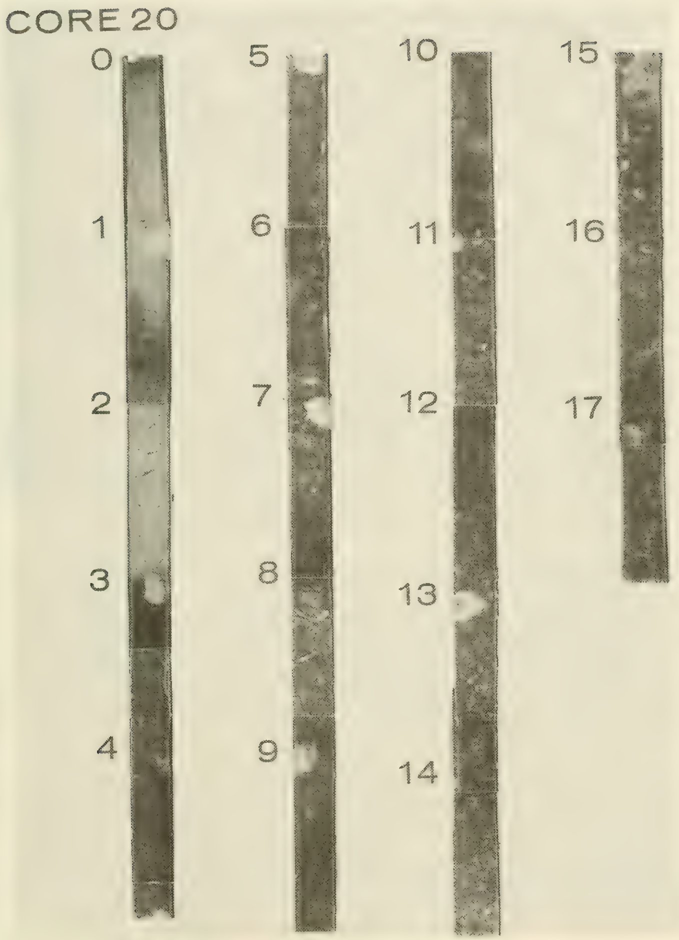


Figure 32. Composite photo of core 20. Location is shown in Figure 31.

Surficial sands on the inner shelf have been reworked by waves and currents and are inner shelf deposits only in the context of their most recent history. The sands were originally deposited as fluvial, estuarine, lagoonal, barrier island, and shoreface deposits. These shelf sediments that have been sorted and redeposited and are nearly in textural equilibrium with the shelf hydraulic regime, although still bearing mineralogic or component evidence of a former, different depositional environment, are neither truly relict nor truly modern sediments. Swift, et al. (1971) termed such sediments "palimpsest."

Major sediment types in the upper 15 meters of the sea floor are both vertically consistent and laterally continuous, as shown by subsurface sediment distributions in Figures 24 to 27. The vertical succession records the passing of adjacent coastal facies during the most recent transgression, from nonmarine to open marine. From the core samples collected in this study a generalized sediment column for the shallow subsurface of the shelf was constructed to show age, dominant lithology, and depositional environment of major sediment units (Fig. 33, units A to E). The uppermost unit comprises type I fine to coarse, well-sorted sands and is characterized by an undulating thickness that is related to surface topography (distribution of linear thickening beneath shoals and thinning or pinching out in swale areas). In general, the unit is thin on the Delaware shelf and thickens to the south, with a maximum thickness of about 12 meters. Unit E is nearly ubiquitous in the study area and is absent only where it has been locally eroded.

Unit D is a Holocene, very fine to fine, clean sand representing a back-barrier environment. The unit is locally thick off central Assateague; elsewhere it is generally less than 1.2 meters (4 feet) thick and does not generally occur at the specific sediment depths mapped in Figures 25 to 27 for type II sand. Interpretation of the specific environment is based on stratigraphic position, texture, and biogenic constituents, which are indicative of low salinity water. The transition to unit E is usually gradational.

Unit C is a rarely occurring organic-rich silt (type V) deposited in a marsh environment. Only two samples of unit C were suitably enriched in organic material to permit radiocarbon dating and they were of distinctly different ages. The peat deposit, dated as Holocene age, may have actually been deposited in a terrestrial environment. Several other cores contain thin layers (<0.3 meter) of fine sand and silt with plant remains but were not suitable for radiocarbon dating.

Unit B is a clayey, sandy silt and very fine, poorly sorted sand that represents sediment types III and IV. This unit is very common in the shallow subsurface and is exposed on the sea floor in depressions or flats between shoals. In many places it directly underlies unit E, and the contact between the two is usually abrupt, with clasts of unit D present in the base of unit E. The upper surface of unit D is a strong acoustic reflector, identified in this study as horizon A_2. This widespread mud unit is interpreted as lagoonal and estuarine facies of

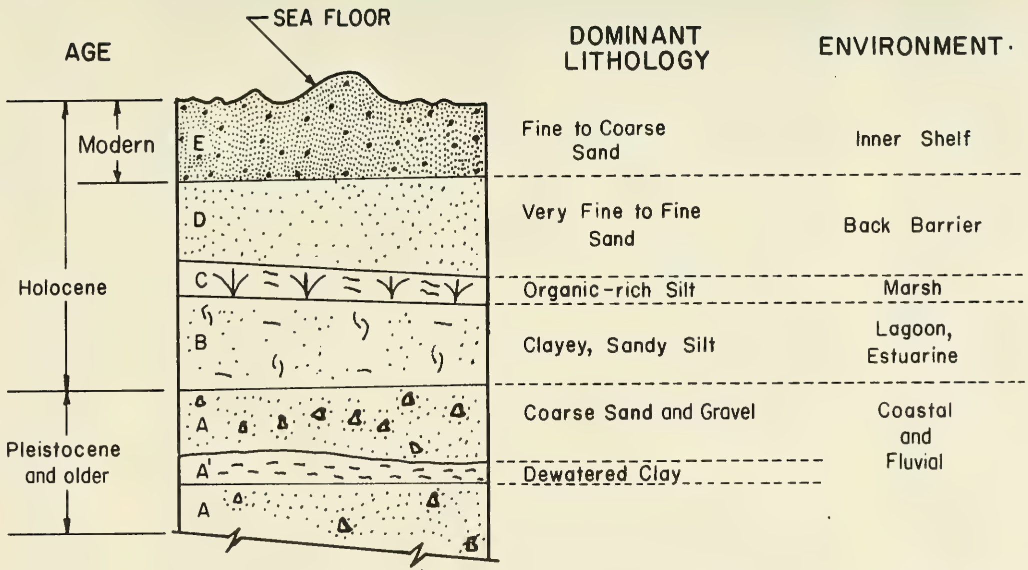


Figure 33. Generalized sediment column for the shallow subsurface of the Maryland Inner Continental Shelf. Units A and B are almost always present; unit E, usually present; unit D, only locally present; and unit C, rarely present. Thickness of units is variable, but some approximations can be made for the Holocene part of the section: unit B, 1 to 3 meters; unit C, less than 1 meter; unit D, about 1 meter; unit E, less than 1 meter up to 12 meters.

Holocene age. The small grain size and poor sorting, as well as diagnostic benthonic forams, pelecypods, and plant debris, suggest a protected brackish environment.

The lowermost sediment unit sampled is unit A, a sequence of Pleistocene sediments. Included in this unit are rarely occurring leached sands and iron-stained gravels (sediment type V). The unit represents a number of different environments of deposition ranging from fluvial to estuarine, lagoonal, and subaerial. Muds are not abundant but they do exist locally and are identifiable by their compact, dewatered nature which indicates a probable history of subaerial exposures.

It is generally accepted that streams of the U.S. east coast no longer contribute significant quantities of sand to the shelf (Meade, 1969; Nieheisel, 1973). Sands transported from the upper reaches of major streams are trapped in the estuaries, which are apparently also filled by transport of material from the shelf. In the mid-Atlantic Bight, sediment sources that are significant to other shelves, such as authigenesis, biogenesis, aeolian and glacial transport, are either completely lacking or of little importance. This suggests that shelf sands in the study area are all locally derived, presumably by reworking of older shelf deposits. The presence of gravelly sands of fluvial origin in the shallow subsurface of the northern Delmarva shelf is supported directly by at least one core and indirectly by geophysical data showing channels. Few cores were collected off Delaware; however, there are many areas on the inner shelf where iron-stained, gravelly sands lie within 0.3 meter of the sea floor. The fine-grained, lagoonal and estuarine deposits lying beneath the surficial sand body contain appreciable quantities of sand-size material, perhaps up to 10 percent by volume. Geophysical and sediment data presented elsewhere in this study show that this unit is periodically exposed on the shelf and subject to erosion. Certain identifiable constituents (peat clasts and brackish water mollusks) are found in the base of the overlying shoal sands and it seems reasonable that sand grains eroded from unit A are included in the shoal sand. The coastline itself is predominantly sand. In plan view, the back-barrier lagoons are a major part of the coastal facies; however, three-dimensional data show that the mud deposits are not exceedingly thick or laterally extensive. Deposition of sand in tidal deltas and inlet throats tends to maintain a coarse texture for the retreating barrier complex. As the barrier retreats, older subsurface sediments are exhumed on the shoreface and although they are often poorly sorted, they comprise adequate quantities of sand-size material for sorting and deposition of the surface sand unit.

The foregoing discussion can be simplified to summarize the Quaternary evolution of the shallow sedimentary record of the inner shelf subsurface. Sediments on the shelf were derived originally from the adjacent landmass and were transported and deposited under fluvial conditions. Delaware River was a major avenue of transport but other numerous streams crossed the Maryland Eastern Shore. At times of high sea level (interglacials) ancestral coastal deposits were repeatedly laid down and partially eroded by the migrating coast. Much of the sedimentary record from repeated transgressions and regressions has been erased by erosion during the transgressive phase. Surficial sands are generated by continuing reworking of older deposits, some of which represent reworking of original fluvial deposits. Enormous volumes of sand are contained in the barrier island chain and the surface sand unit, which includes the linear-shoal field. This abundance of sand is probably due, in part, to the proximity of the Delaware River which was fed in upland regions by glacial melt water. The transport of sand from an external source to the coast and shelf was terminated several thousand years ago, at least, when the gradients of streams decreased and they became embayed in estuaries or closed off by spits.

2. Evolution of Inner Shelf Topography.

Results from this study are applicable to understanding the Quaternary evolution of shelf topography on a shallow Coastal Plain shelf, and may yield some insight into how shoals, channels, and other such features originated. Most of the Atlantic shelf is mantled by sand (Milliman, Pilkey, and Ross, 1972) which has originated through vastly different processes in different periods of time. Even within the relatively limited confines of the study area, surface sediments represent a complex of multistory and multilateral sand bodies, each having a different history of transportation and accumulation. They are pods or ribbons (length to width ratios of less than and greater than 3:1, respectively) and represent a near-final configuration of sands that have passed through a fluvial, estuarine, and beach cycle.

The Delaware and Susquehanna Rivers, bracketing the Delmarva Peninsula, are major streams draining terrain that was directly glaciated during the Pleistocene. Field and Duane (1976) hypothesized that the mid-Atlantic shelf received large volumes of sand, perhaps more than the New England shelf and probably more than the south Atlantic shelf, during the Pleistocene and early Holocene. The dominant influence of streams in shaping the northern Delmarva shallow shelf is quite evident from the data accumulated in this study. Shelf topography (Delaware Valley), structure (buried channels), sediments (iron-stained gravels), as well as the lithostratigraphic record beneath the coast (climbing channel sands) all document an initial surge of sediment into the study area by fluvial processes (Field, 1976). Once deposited, these sediments were subject to erosion and reworking, as evidenced by the absence of gravels on the surface, the lack of unfilled channels, except in Delaware Bay, and the presence of several overlying coastal facies.

The role of coastal depositional processes in the evolution of the inner shelf sedimentary record is important because barrier sands are a volumetrically and economically important facies in the rock record (Pettijohn, Potter, and Siever, 1972). However, as Davis, Ethridge, and Berg (1971) point out in their comparison of Holocene, Cretaceous, and Jurassic barrier environments, deposition and preservation of these sediment suites presuppose a locally *regressive* situation. Sequences resulting from a locally *transgressive* situation would be different, as elucidated by Fischer (1961), and would range from complete preservation to complete erasure of the barrier sequence. As discussed here and in Field (1976), the subsurface stratigraphy of the Delmarva shelf contains a partial record of the passing of the Holocene barrier. The coastline of the study area is a submerging one (Kraft, 1971; Hicks, 1972) and from information discussed previously, it appears that the barrier is continuing to retreat. As it retreats, the sand of the fore barrier is stripped off and used in back-barrier construction, inlet filling, or spit progradation, and shelf sand body accumulation. The barrier sequence as an entity has a short life expectancy; it continuously erodes at the base along the shoreface as it retreats.

On the northern Delmarva inner shelf, sand bodies occur in identifiable patterns in discrete areas that can be related directly to the gross geomorphology. Within the Delmarva Valley are fluvial and estuarine sands that can be identified by their surface and subsurface configuration. North of the shelf valley lie subsurface fluvial sands overlain by estuary-retreat shoals. Adjacent to the headland and baymouth barrier coast of Delaware there are relatively few shelf sand bodies, and those can be related genetically to ancestral, fluvial, or modern tidal processes of inlets. The northern limit of the linear-shoal field nearly coincides with the beginning of the long barrier island-spit comprising Fenwick and Assateague Islands. Termination of the barrier at Fishing Hook Spit marks the approximate southern limit of the shoal field. Field (1976) indicated a zone in the center of the shoal field that is devoid of shoals which may represent an ancestral stream valley, a supposition that is supported by the group of buried channels that form a cluster in the vicinity of Ocean City Inlet (Fig. 18).

The origin of the large sand shoals that lie on the Atlantic Continental Shelf between Long Island and Florida is not clearly understood. Sanders (1962), Kraft (1971), and McClennen (1973) described these features as possible remnants of transgressed barrier islands. From systematic studies of shoal morphology, structure, and lithology (Uchupi, 1968; Duane, et al., 1972) and investigations of sediments and processes of individual ridges (Moody, 1964; Swift, Stanley, and Curray, 1971), it was concluded that the ridges are submarine in origin and have no history as a subaerial landform. Within the past 5 years many studies on these ridges or shoals, particularly those in the mid-Atlantic Bight (Long Island to Cape Hatteras), have been published and more studies have been initiated. An understanding of their behavior in response to fluid processes is becoming clearer, but *a priori* evidence for their genesis is still lacking. This is due in part to the difficulty in separating and identifying those processes which may have initially *formed* the shoals versus those processes that merely *modify* them, regardless of the original mode of formation.

Seismic reflection profiles of hundreds of linear shoals have been collected and reported by Swift, Stanley, and Curry (1971); Duane, et al. (1972); McClennen (1973); Sheridan, Dill, and Kraft (1974); and Stahl, Kozan, and Swift (1974). The reports all show that ridges are not controlled or formed by subsurface strata but rather rest disconformably on an essentially flat base, a convincing argument for a depositional origin.

It has been argued that these shoals are the remnants of Pleistocene barrier islands that had been stranded by a drop in sea level and then resubmerged during the Holocene transgression (Sanders, 1962; Kraft, 1971). Duane, et al. (1972) and Field (1976) believe the linear ridges are *not* pre-Holocene in age. They suggest that regardless of where formed originally (subaerial, estuarine, or open marine environment), shoals would retain evidence of having been subaerially exposed and then resubmerged. The shallow structure of the ridges would show a core of Pleistocene sediments, and subsurface sediments would consist of modern marine sands overlying iron-stained relict sands. Seismic reflection and vibratory core data presented in this study indicate the shoals are essentially planoconvex in cross section and that the flat-lying reflector beneath the shoals is the contact between modern shoal sands and Holocene lagoonal deposits. A generalized cross section of the northern Delmarva inner shelf depicting these relationships is shown in Figure 34. Constructed from seismic and core data, the diagram illustrates general shallow-stratigraphic relationships as interpreted from many actual cross sections. For illustration purposes, uncommon or discontinuous lithologies (units C and D in Fig. 33) are excluded. Of significance in the figure are the surface sands resting disconformably on a relatively flat mud deposit that is interpreted as Holocene in age, thus ruling out a pre-Holocene age for the shoals. Kraft (1971) suggested that because offshore ridges are alined with onshore Pleistocene beach ridges that intersect the present coastline at a small acute angle, they are genetically related. Several areas in this hypothesis that are disputable, as discussed by Field (1976), become clear when shoal characteristics of both shoals and dunes are examined. Equally important is the consideration of the difficulty in finding an example (ancient or modern) of an unconsolidated sand body, regardless of how or where formed, surviving the passage of a transgressing surf zone. This last constraint is a strong one and one that has argued for various theories of barrier island origin other than overstepping; it is also one to contend with in considering a Holocene barrier island origin of shoals.

Direct and indirect evidence accumulated in this study strongly suggests that linear shoals have evolved, and are evolving, in the submarine environment of the shoreface and Inner Continental Shelf. That they are related in some respect to the adjacent barrier island is clear from their distribution: the northern limit of the linear-shoal field coincides with the merging of the barrier spit to the headland coast; the southern limit is marked by the termination of the long barrier spit at southern Assateague Island. This relationship is probably genetic but it in no way substantiates a barrier origin of shoals. More likely and supportable is the concept of linear shoals forming and being maintained on the seaward side of the retreating barrier island.

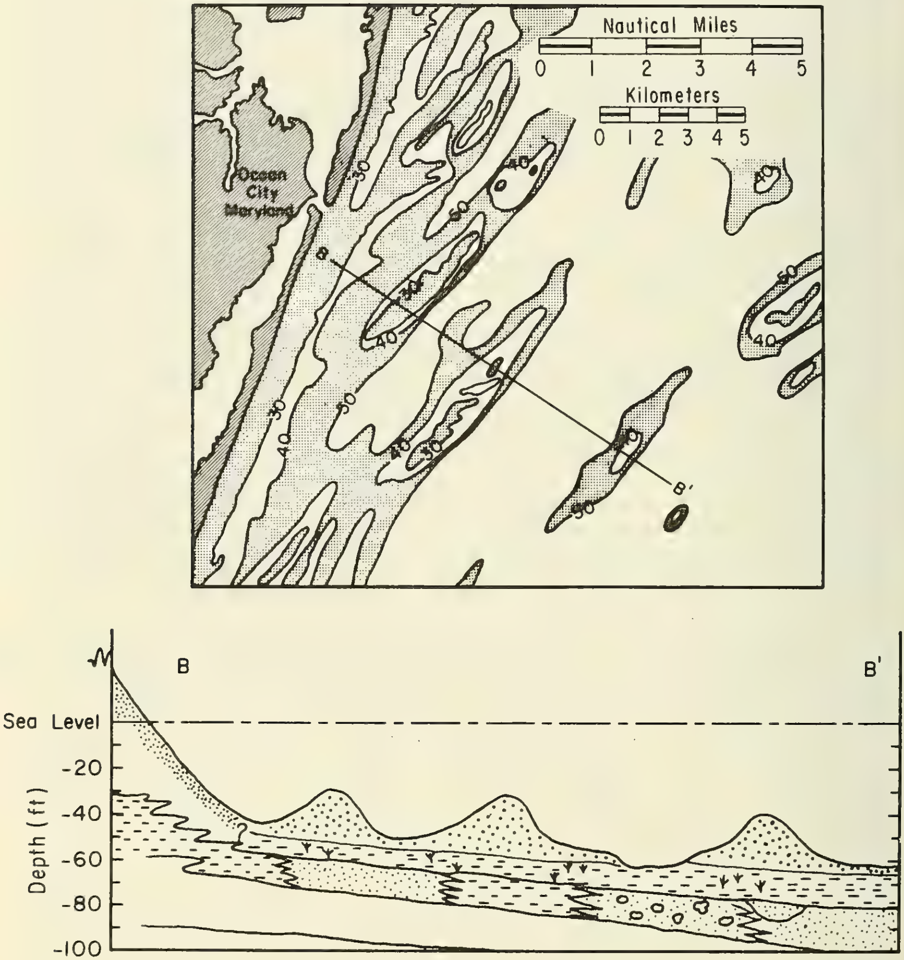


Figure 34. Plan view and representative cross-section profile of the Maryland inner shelf, constructed from seismic and sediment core data. Sediment units correspond to those designated in Figure 33.

The argument that it is difficult to maintain the integrity and identity of a relatively low relief (maximum 18 meters) sand body through a slow transgression of the surf zone across that body applies to Holocene barriers as well as to Pleistocene landforms. The often-noted occurrence of peat outcrops and tree stumps on the lower foreshore of many Atlantic coast barrier islands indicates that barrier sands once laid seaward and over these lagoonal or back-barrier deposits and have since been stripped off. Field (1974) reviewed the evidence for preservation of relict barrier deposits on the shelf and found that very little undisputable evidence existed. Although subtle indications of stillstands have been noted by some workers, no actual drowned barrier islands have been positively identified.

The lithostratigraphic character of the shelf in the vicinity of shoals provides no strong evidence for or against a drowned barrier island origin of shoals. The sequence of medium, well-sorted sands unconformably overlying lagoonal-estuarine muds is characteristic of both barriers and shoals. However, shallow-subsurface sediments of Ocean City and Assateague Island document the tendency for barrier island deposits not to be preserved in this area. Cross sections along and normal to the barrier (Field, 1976) show that barrier sands are not continuous units and are abruptly reworked in the shoreface area. If shoals mark former sites of the barrier island as it retreated or was overstepped during the Holocene transgression, an intermediate step should be evident. As shown by Field (1976), there is no evidence of such a transition; the barrier is truncated directly seaward of the active beach on the shoreface.

To briefly summarize, there is a distinct lack of evidence supporting the theory that linear shoals are remnants of overstepped barrier islands. This may be due in part to the fact that some of the criteria either were not examined or are similar to those that support a marine-origin hypothesis. Nevertheless, the data gathered in this study are extensive and varied; however, there are no clues to support this hypothesis. It is concluded that overstepping of barrier islands, which may have occurred in isolated situations, is not the principal origin of linear shoals on the inner shelf. The shoals are formed on the seaward side of the barrier, and are therefore a part of the dynamic sediment budget of the barrier, but as the shoreline retreats they become isolated shelf features.

The most striking characteristic of linear shoals is their abundance and distribution across the shelf from as far as 32 to 48 kilometers (20 to 30 miles) offshore to within 1 mile of the beach. Water depths over the crests range from less than 9 meters to more than 30 meters. This wide variation in location and depth suggests that formation was a continuous process, probably associated with sea level rise; it seems unlikely that shoals could have been formed only during a particular time or by a single event.

The marked similarity between all shoals in all major characteristics (shape, orientation, surface configuration, location with respect to coastal morphology, and internal structure and subsurface sediment relationships) strongly supports a single mode of formation for all shoals.

Swift, et al. (1971) and Duane, et al. (1972) hypothesized that shoals originate along the shoreface and as the shoreline retreats landward in adjustment to rising sea level, the shoals eventually become segmented and isolated on the inner shelf. Evidence gathered in this study supports that interpretation.

Because of their shallow depths and proximity to the littoral zone, shoals on the shoreface are the most active. They are more vulnerable to wave and current action, and a source of sediment is readily available from the eroding shoreface. Their internal configuration of clean, medium-grained sand unconformably overlying relict coastal deposits is similar to that of the isolated linear shoals of the inner shelf. Orientation with respect to the shoreline is similar for both shoreface shoals and isolated shoals; side slopes and surface configuration are also similar for both shoal types.

The mechanism causing initial formation of shoals is unknown, but probably some irregularity along the shoreline (ebb tidal delta, ancestral stream delta) forms the nucleus for further accretion by impounding of nearshore sediments. There does appear to be some association of shoreface shoals in the Delmarva coast with existing or historical inlets (Fig. 18) which may imply that tidal currents play a role in the initial development of a ridge. The shoreface of Ocean City and Assateague Island has many perturbations which may be incipient shoreface shoals, but such features are difficult to document.

Regardless of how they are first initiated, the process by which shoreface shoals subsequently evolve remains to be completely understood. Duane, et al. (1972) proposed that storm-generated coastal currents were the significant process responsible for the growth and development of shoreface shoals. According to them, "Wind-drift currents tend to develop speeds of one-twentieth to one-fiftieth that of surface and wind speeds, and a northeaster blowing at 40 knots per hour could generate a surface current of 1 or 2 knots (1.7 to 3.4 feet per second) which, during several days of downward momentum transfer, might extend some part of that velocity to the inner shelf floor."

Detailed studies of bathymetric changes, current measurements, and textural patterns on shoreface shoals (Moody, 1964; Swift, et al., 1971) suggest the effect of storm-generated, wave-drift currents on shoreface shoals is significant. Moody, for example, noted that large-scale migration of ridges off Bethany Beach, Delaware, occurred during the major storm of March 1962. The inferred transport along the bottom was at right angles to the direction of surface, wave-driven currents. Because of the Ekman effect, the subsurface flow is thought to be helical in nature, but this is an unproven assumption. The presumed helical flow in ridge troughs is thought to be generated by wind stress on a moving viscous medium that produces Langmuir-type circulation. As the cross-sectional area decreases toward the trough head, the competence of the bottom currents increases, thereby causing headward erosion of the trough and a net transport of material over the base of the shoal onto the crest and seaward flank. This situation presumably develops when the wave front is from the northeast, the dominant direction of storm waves. The effect of waves from the southeast would be to complement the ridge-building process, as the waves intersect the ridge at a small acute angle and move material northward along the seaward flank.

The development of a shoreface shoal into a shelf-isolated shoal can be visualized as an overall response to a relative rise in sea level and the concomitant retreat of the coastline. As a shoreface shoal begins to develop by accretion on the northern or distal end, it also begins to lengthen by headward erosion in the trough (Field, 1976). Continued accretion and trough erosion result in a long shoal with several ridges or arms. As the shoreline continues to recede, the shoal will eventually be segmented from the shoreface and isolated on the inner shelf as one or several individual shoals, depending on the final configuration of the shoal before segmentation.

Because linear shoals lie at depths varying from 10 meters to more than 30 meters, they are probably continuously modified by marine processes and the effect of these processes presumably differs for shoals of different depths. It is likely the crests of shoals, especially those shoals less than -15 or -18 meters MLW, must be very vulnerable to wave attack. Field (1976) reviewed the current literature on shelf transport and evaluated how wave-induced forces may modify shoals. The net effect of waves is limited to five possibilities: (a) shoals are unaffected; (b) shoals are built up; (c) shoals are destroyed; (d) shoals are driven landward; or (e) shoals are driven seaward. Data from seismic reflection profiling, detailed fathometer profiling and historical surveys, and lithostratigraphic evidence show that possibilities a, b, and c are unlikely, and that d and e are likely. All lines of evidence show that shoals migrate at various rates and in various directions. They can be visualized as active features that have a net component of migration that is small compared to its total movement in all directions.

VI. POTENTIAL SAND RESOURCES

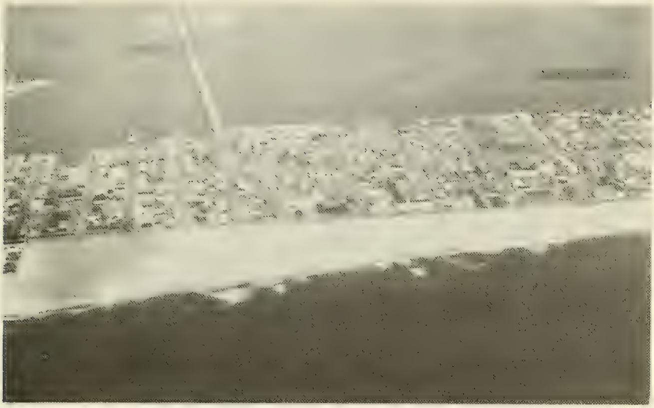
1. Depositional Patterns and Processes Along the Coast.

The origin of barrier islands has been, and remains, a controversial topic among geologists. Although many hybrid theories have been suggested, the three main hypotheses on barrier island origin are: (a) upbuilding of submarine bars; (b) segmentation of elongated spits, by inlets; and (c) submergence of mainland coastal ridges. Schwartz (1973) includes many of the original papers, as well as papers which compare and combine individual hypotheses.

The Maryland-Virginia barrier island chain has not received much attention relative to other east coast barriers, such as the Georgia sea islands (Hoyt, 1967) and the North Carolina Outer Banks (Pierce and Colqhoun, 1970). Kraft, Biggs, and Halsey (1973) hypothesized that the long barrier island or spit of Assateague Island formed by coalescing of smaller islands. They also concluded that the present-day barrier island coast did not originate at its present location but rather migrated from a former position at least 5 miles seaward on the shelf. The concept of barrier islands migrating from the shelf during the Holocene to their present position has been recently discussed in detail by Field and Duane (1976). They maintain that the inner shelf contains a sedimentary record which shows the presence of barrier island environments and that in view of this, many of the criteria developed to support hypotheses on barrier island origin are not appropriate. Field and Duane further emphasize that irrespective of its original mode of formation, a given barrier may evolve through one or a combination of processes, such as submergence, spit growth, and upward building.

a. Erosion and Deposition on the Beach and Shoreface. Wind waves that approach the shore at an angle produce longshore currents that may transport sediment along the coastline. Bethany Beach, Delaware, is a nodal point in the net littoral transport direction, such that sand is transported by littoral currents away from the locale. Approximately 145,000 cubic meters (190,000 cubic yards) of sand is transported annually along the coast between Bethany Beach and Indian River Inlet (Duane, et al., 1972). On the north side of Ocean City Inlet accretion rates of sand indicate 115,000 cubic meters (150,000 cubic yards) of material is annually transported southward. Historical profile data from the Ocean City-Assateague barrier islands, compiled by the U.S. Army Engineer District, Baltimore (1972), show an overall pattern of erosion of the coast. Major exceptions to the general trend of recession are the shoreline just north of Ocean City Inlet, just south of Indian River Inlet, the Fishing Hook spit area of Assateague, and the Cape Henlopen spit. Photos of these areas are shown in Figure 35, a to d. Between 1850 and 1929, the shoreline along the Ocean City-Fenwick Island coast receded at rates of 1.5 to 7.1 meters per year; since 1929 recession rates have varied considerably. The average retreat rate in Ocean City between 1850 and 1965 was about 0.61 meter (2 feet) per year north of 10th Street. South of 10th Street to the inlet accretion occurred rapidly after jetty construction (0.91 to 6.4 meters or 3 to 21 feet per year) and has slowed in recent years as sand filled in behind the jetty and began to bypass it. With the hurricane opening of the Ocean City Inlet in 1933, and jetty stabilization immediately thereafter, erosion increased on northern Assateague to rates of 10.7 meters per year. Along central and southern Assateague, accretion has occurred locally but the overall trend has been recession. Tree stumps and peat layers are periodically exposed on the beach face after erosive events. As shown by Gawne (1966) and U.S. Army Engineer District, Baltimore (1972), erosion is episodic and not continuous. Major erosion is often associated with major hurricanes or winter storms (northeasters). The hurricane of 1933 and the storm of March 1962 are two examples of storms which devastated the study area.

If the long-term retreat rate averages about 0.61 meter per year (in many places this is a minimum rate), rough estimates of Holocene retreat rates can be made. At this rate the barrier islands could have



A Ocean City, Maryland, in the vicinity of the northern bridge.
Note accretion toward the south (left) due to the inlet jetty.

B Indian River Inlet, Delaware, looking north.
Note accretion on south side and erosion on north.

Figure 35. Photos showing areas that are major exceptions to the general trend of erosion, 28 May 1974.

C Cape Henlopen, Delaware, looking south.

D Fishing Hook spit, Virginia, at southern end of Assateague, looking south.

Figure 35. Photos showing areas that are major exceptions to the general trend of erosion, 28 May 1974.--Continued

migrated at least 3.2 kilometers inland from about 5,000 years B.P., given a steady sea level rise. Most sea level curves show a significant slowing in sea level advance at about 4,000 to 5,000 years ago (e.g., Curray, 1965; Milliman and Emery, 1968; Kraft, 1971), so the assumption can be made that recession rates were much greater before about 4,000 years B.P.

The concept of a continuously retrograding barrier island complex requires some consideration of the resulting sediment budget. Barrier island retreat results in erosion of both the shoreface and the beach (Swift, et al., 1972). Sandy sediments exhumed from the shoreface become a part of the retrograding coastal sands, which are either recycled in the barrier complex or lost to offshore deposition. Sediments recycled in the barrier island complex are not lost to the system, but simply deposited as washover fans, inlet fill, dunes, prograding spits, and local aggradation along the beach. The significance of these various considerations is that a large percentage of sediments eroded from a receding barrier island is required for maintenance of the barrier; the only external source of sediment is shoreface erosion, part of which aggrades on the sea floor (Bruun, 1962) and part of which may be transported onto the beach, as suggested by Pierce (1969) and Pilkey and Field (1972).

b. Depositional Patterns of the Barrier Island Complex. At the north and south end of the study area are large spits which have been steadily accreting since earliest historical surveys. Cape Henlopen is growing north and west into Delaware Bay (Fig. 35,C). Kraft and Caulk (1972) plotted past and present positions of the spit; the estimated rate of growth of the spit is on the order of 10 meters per year. At the southern end of Assateague Island littoral sediments are rapidly building the recurved Fishing Hook spit (Fig. 35,D). Results of successive surveys of the spit tip between 1902 and 1933 are shown in Figure 36. The tip of the spit migrated nearly 1,829 meters during the 25-year period, 1908 to 1933, for an average rate of about 73 meters per year. The barrier island coast of northern Delmarva, from Bethany Beach to Fishing Hook, is approximately 72 kilometers (40 nautical miles) long. Assuming a constant growth at the above rate, an adequate supply of sediment, and minimal interference from other budget variables, the whole of Fenwick Island, Ocean City, and Assateague Island conceivably could have been constructed by simple longshore transport in less than 1,000 years. This simplistic approach is unrealistic for many reasons, but it serves to point out the potentially significant role that longshore sediment movement might play in the evolution of the coast.

The process of retrogradation of the coast is accomplished primarily by the transfer of sediment from the front of the barrier to the middle and back side. Main mechanisms of transfer are by dune formation, inlet filling, trapping of windblown materials, filling of inlets by longshore transport, and washing of beach sands over the island to the back side. (See Fig. 18 for location of historical inlet sites along Ocean City and Assateague Islands.) Many other such inlets were probably formed and

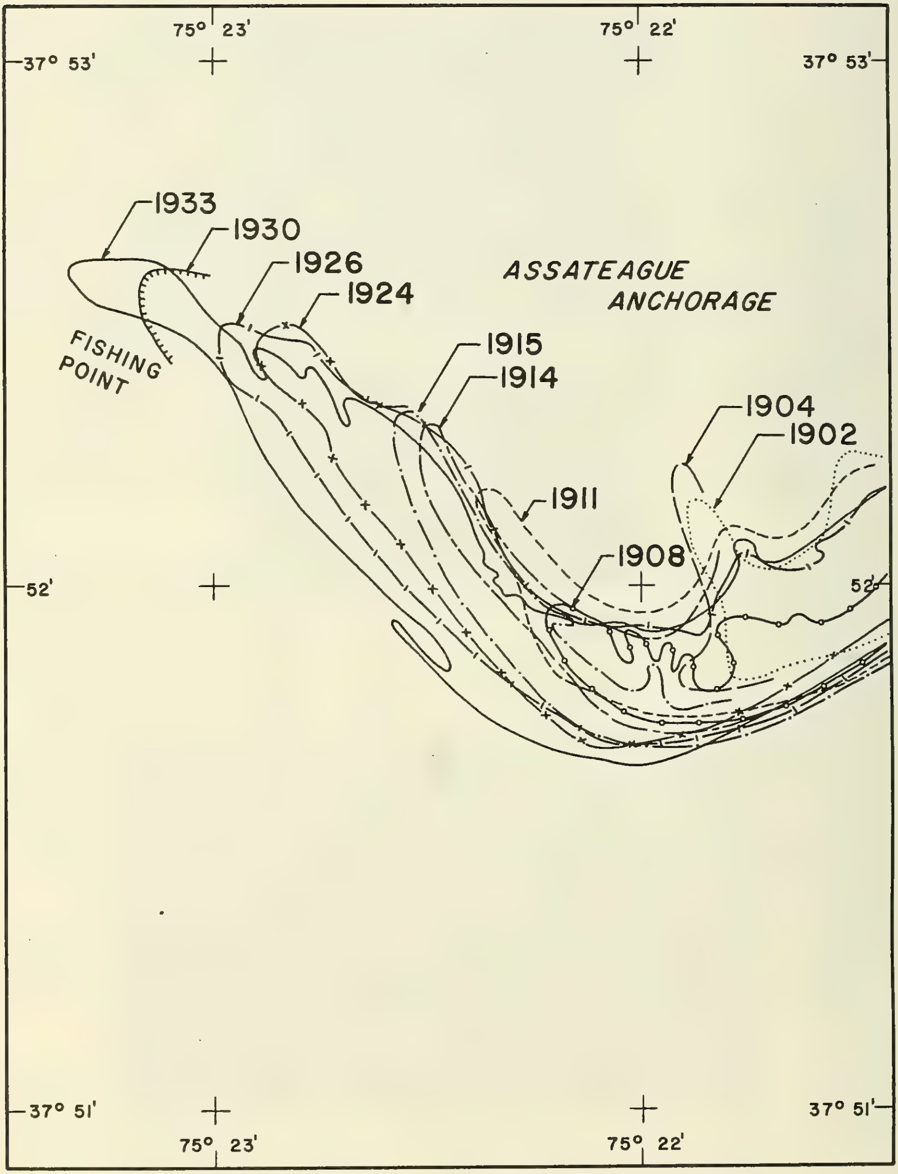


Figure 36. Time series of the growth of Fishing Hook spit, Assateague Island, 1902 to 1933 (from CERC unpublished shoreline change maps).

closed during prehistorical times. The net effect of the filling is to translate coarser sediments landward. Along Assateague there is sufficient evidence (beach ridge orientation, back-barrier and marsh configuration) indicating a significant role for inlet filling in barrier island evolution and also indicating that numerous inlets formerly existed, rather than a single inlet migrating for long distances along the coast (Harrison, 1972).

Transport of beach sands (overwash) through the dunes and across the island by storm-generated surge is a major mechanism of modification to barrier islands. As storms pile up water against the coast, the attendant storm breakers often breach the dunes and carry sand to the central and back side of the island, and often into the lagoon. The transport mechanics and resulting sedimentary record of overwash are discussed by Godfrey and Godfrey (1973) and Schwartz (1975). Overwash has been a major modifying process along the coastline of the study area. During the March 1962 storm most of the Maryland coast was completely submerged at one time or another (U.S. Army Engineer District, Baltimore, 1972). Washover on Assateague may occur as individual fans, a series of fans, or large coalesced fans. Characteristics of these features are discussed by Field (1976). The net effect of overwash is to place coarse and medium beach sands immediately over back-barrier fine sand and lagoonal muds. This is a key process in the landward translation of the barrier itself.

A series of geologic cross sections of the coast by Kraft, Biggs, and Halsey (1973) show that the modern barrier sands vary in thickness between 2.4 and 13.7 meters (8 and 45 feet); depth to Pleistocene between 6.1 and 12.2 meters below sea level. The cross sections also show the presence of certain units (e.g., lower Holocene sands) only at certain locations. Both Biggs (1970) and Weigle (1974) present subsurface geologic data for shore-normal transects from the mainland across the lagoon and onto the barrier. These sections show that dip is not uniformly east and that local reversals are common in dip of the Holocene-Pleistocene contact. No distinct vertical sedimentary sequence exists for the whole of the barrier island. Beneath Ocean City, sands overlie silt and clay, which overlie sandy silts over peat. The peat, traceable across the entire zone, lies at about -4.6 to -7.6 meters and has been sampled from several places, including the shoreface, and radiocarbon age-dated; the dates and pollen analysis both indicate at least a mid-Wisconsin age. Except for the northern part of the island, this peat horizon is generally absent beneath Assateague.

Correlation of onshore borehole data and seismic refraction data with offshore vibratory core and seismic reflection data across the Fox Hills level area on central Assateague Island is shown in Figure 37. Subsurface lithologies are generally correlative between boring and the offshore core. The sequence of clayey silt at -15.2 to -18.3 meters, underlain by fine and very fine sands, is particularly distinctive for the two seaward borings and the offshore core. The contact between the two coincides with a seismic reflection horizon beneath the shoreface. At greater subsurface depths (-22.2 to -25.3 meters or -73 to -83 feet), a layer of gravelly

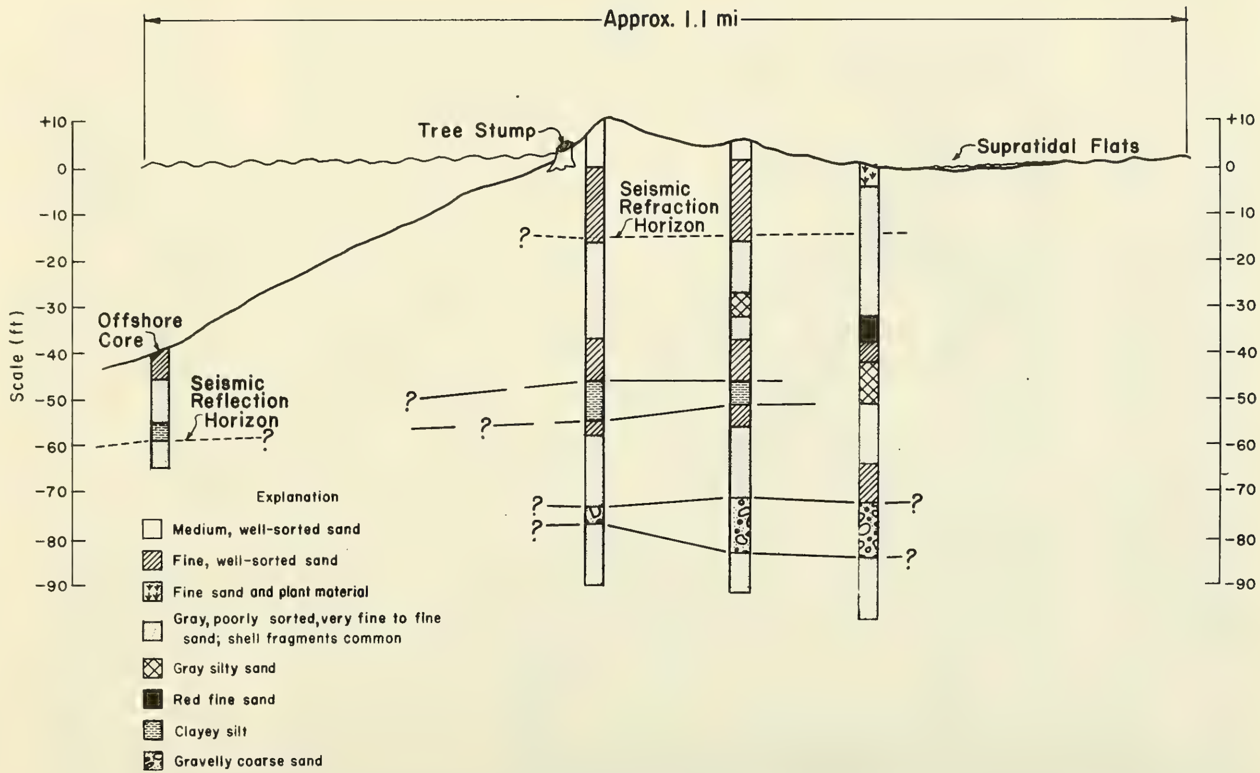


Figure 37. Geologic cross section across central Assateague in the vicinity of Fox Hills level, showing correlation of onshore seismic refraction and borehole data with offshore seismic reflection and core data.

coarse sand is present in all three borings. This layer correlates with the Pleistocene acquifer of Rasmussen and Slaughter (1955) and Weigle (1974) and probably marks the base of the Pleistocene. No peats were encountered in either the borings or the core; plant material recovered near the surface in the landwardmost boring is modern dune grass. Surface textures across the subaerial part of the barrier island show remarkable consistency. The central and back-barrier sands are all medium-sized overwash deposits and resemble the beach sands in all parameters. On the shoreface there is no evidence of these high-energy, medium-sized sands; sands dominant seaward of the surf zone are fine grained and well sorted.

In summary, the barrier spit is evolving by several different processes, each of which varies in importance according to the specific location. Spit building, washover deposition, and inlet filling are all locally important in redistributing sediments eroded from the beach and shoreface. Sediments aggrading on the shoreface probably do not exceed in volume those eroded from the shoreface as the submarine part of the barrier island translates landward. A variation in subsurface lithology along the coast is the rule rather than the exception. This is because each segment of the coast has experienced a different history. The location of fluvial, estuarine, and tidal channels has a strong bearing on each segment. Secondly, as the barrier retreats it intersects older landforms lying at different orientations and different altitudes, hence some sections of the barrier have a shallow subsurface "core" of Pleistocene sediments, and other segments do not. This is a characteristic of barrier islands in general (Field and Duane, 1976), and has been demonstrated for numerous coastlines; two well-documented examples are the Georgia sea island coast (Hoyt and Hails, 1967) and the North Carolina Outer Banks (Pierce and Colqhoun, 1970).

2. Requirements for Beach Restoration and Characteristics of Beach Sands.

The conditions of erosion along the northern Delmarva coast, discussed previously, led the U.S. Army Engineer District, Baltimore, to design a plan of improvement for the shoreline. That plan called for construction of groins along the Maryland coast and addition of large quantities of sand for beach erosion control and hurricane protection (U.S. Army Engineer District, Baltimore, 1972). Similar plans are being designed for the Delaware coast by the U.S. Army Engineer District, Philadelphia.

Original designs for the Maryland shoreline called for extensive beach restoration along much of the coast. A summary of the requirements are shown in Table 6. More than 9.2 million cubic meters (12 million cubic yards) would be required for initial construction with an additional 60.4 million cubic meters (79 million cubic yards) needed for maintenance over a 50-year timespan, if the entire project is implemented. If only the Fenwick Island and Ocean City improvements are made, the fill required for initial construction will be about 3.4 million cubic meters (4.4 million cubic yards), with an additional 3.5 million cubic meters (4.6 million cubic yards) required for 50 years of maintenance.

Table 6. Fill requirements for the Maryland coast (U.S. Army Engineer District, Baltimore, 1972).

Location	Initial fill ($\times10^6$ yd^3)	Nourishment ($\times10^6$ yd^3) Annual	50-yr period
Fenwich Island	3.1262	0.0913	4.5650
Ocean City	1.3115		
Assateague	5.4843	1.4885	74.4250
North Beach	0.9729		
Fox Level	0.6542		
Pope Bay	0.8544		
Tom's Cove	0.1558		
Totals	12.5593	1.5798	78.9900
Total sand requirement for complete project: 91,550,000 yd^3.			

Textural characteristics of beach sand at Ocean City and Assateague as reported by the U.S. Army Engineer District, Baltimore (1972), are shown in Table 7. Of 36 samples collected between the dune and the low water line along Ocean City, most are within the fine- and medium-size classification of sand. The actual range of median sizes is 2.56 to 0.79 phi (0.17 to 0.58 millimeter); the average median size is 1.69 phi (0.31 millimeter), which is about the middle of the medium-size classification (1 to 2 phi). Seventy-six samples were collected from the beaches of Assateague Island. These sands tend to be slightly coarser than those from Ocean City, having an average median diameter of 1.56 phi (0.34 millimeter). Beach sands from this region are durable quartz and feldspar grains with minor amounts of accessory heavy minerals. Calcium carbonate content and content of easily abraded or crumbled grains, such as clasts of peat or clay, glauconite grains, foram tests, etc., are limited to a few percent.

3. Resource Assessment of Inner Shelf Sand Deposits.

a. Textural Characteristics of Offshore Sands. Although most of the entire inner shelf off northern Delmarva is mantled by fine to coarse sands, the linear shoals provide the best potential source of beach sand in terms of size, sorting, thickness, and ease in locating. The impact of local relief on the three-dimensional shape of the surface sand body is illustrated by the thickness map of medium- to coarse-size, clean sands (Fig. 38). This figure, constructed using the results of a visual inspection of core samples collected at 1-foot intervals, groups the sediment thicknesses in four classes. Cores collected from the crests of large shoals generally show sand thicknesses greater than 3.7 meters or at least between 1.8 and 3.7 meters. Sand thicknesses between 0.9 and 1.8 meters are restricted to flanks of shoals, or in some cases, between shoals.

Table 7. Textural characteristics of beach samples at Ocean City and Assateague.

	Samples (No.)	Median grain size				Coefficient of sorting	
		Range		Average			
		(phi)	(mm)	(phi)	(mm)	(phi)	(mm)
Ocean City							
Dune	9	1.60 to 2.56	0.33 to 0.17	1.84	0.28	-0.12 to -0.41	-1.33 to -1.09
Berm	9	1.56 to 2.56	0.34 to 0.17	1.84	0.28	-0.58 to -0.08	-1.49 to -1.06
High water	9	0.79 to 2.47	0.58 to 0.18	1.51	0.35	-0.74 to -0.08	-1.67 to -1.06
Low water	9	1.03 to 2.47	0.49 to 0.18	1.64	0.32	-0.53 to -0.08	-1.44 to -1.06
All samples	36			1.69	0.31		
Assateague							
Dune	18	1.18 to 1.89	0.44 to 0.27	1.64	0.32	-1.13 to -0.20	-2.19 to -1.15
Berm	18	1.06 to 2.12	0.48 to 0.23	1.56	0.34	-0.98 to -0.21	-1.97 to -1.16
High water	20	0.49 to 2.12	0.71 to 0.23	1.43	0.37	-0.63 to -0.18	-1.55 to -1.13
Low water	20	1.06 to 2.06	0.48 to 0.24	1.64	0.32	-0.70 to -0.24	-1.63 to -1.18
All samples	76			1.56	0.34		

Source: U.S. Army Engineer District, Baltimore (1972).

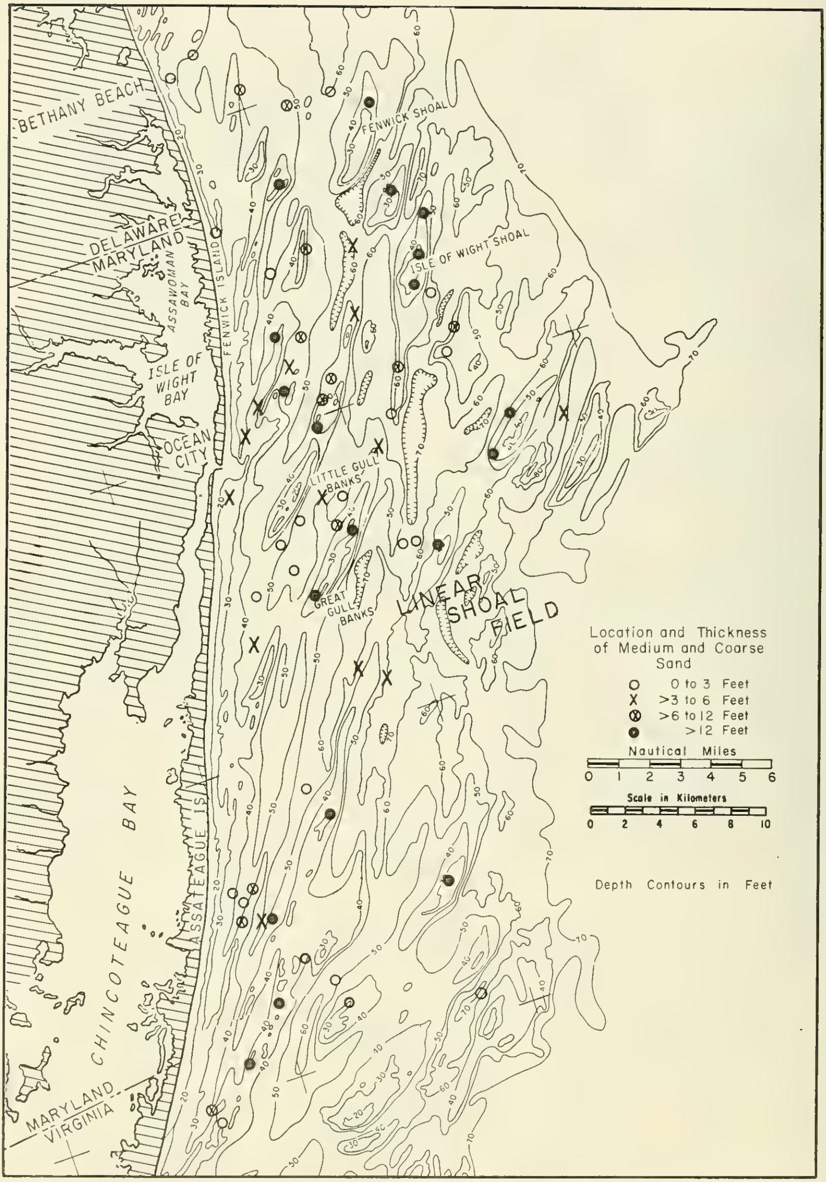


Figure 38. Map showing location and thickness of medium and coarse (modal size) sand in relation to sea floor topography.

Those areas with less than 1 meter of medium-sized sand are restricted to depressions and flats between shoals. Thus, the shape of the surface sand body depends on the shape of the sea floor. It can be visualized as a thin (rarely exceeding 6 meters) and locally discontinuous body having a nearly flat lower surface and an undulatory upper surface.

The description of the surface sand deposit as medium to coarse grained reflects megascopic and microscopic identification of the modal size. Actual mean sizes, determined by sieve and fall velocity (RSA) techniques, tend to be slightly finer. This is due in part to the exclusion of very coarse sand and gravel from the settling-tube measurements and in part to the influence of the fine tail of the grain-size distribution, which is not detected in visual estimates. Figure 39 is a plot of the mean grain size versus sorting for 160 samples from the upper 1 meter of the surface sand body. The majority of samples are type I sands; some type II fine sands are also included. Only 5 percent of the samples have phi means in the coarse sand class, compared to 57 percent in the medium sand class and 38 percent in the fine sand class. Using the classification scheme of Friedman (1962), the majority of sands are moderately well sorted (44 percent) and well sorted (29 percent); about 22 percent are moderately sorted. Only 4 percent are very well sorted and 1 percent is poorly sorted. One significant aspect of Figure 39 is the apparent lack of trend between sorting and mean size. There appears to be no improvement in sorting associated with a decrease in mean grain size, as might be expected.

b. Location and Estimated Volume of Potential Borrow Sites. The Delmarva linear shoals form a well-defined field extending from Bethany Beach, Delaware, to Chincoteague, Virginia, and bounded on the northeast by the Delaware shelf valley (see Sec. II). Each of the individual shoals composing the field is a potential borrow site and each has been arbitrarily assigned a letter for convenience in discussion of their characteristics (Fig. 40). Those shoals, which have several extensions such as shoal A, or that are made up of several topographic highs, such as shoal C, are designated by a single letter with a number designating each extension or high area. A summary of shape characteristics of the shoals, taken from Field (1976), is given in Table 8.

Table 8. Extreme and typical values for size, shape, and orientation of shoals.

	Extreme low values	Extreme high values	Typical values
Relief (ft)	10	40	20 to 30
Length (nmi)	2	10	4.5 to 7.5
Width (nmi)	0.5	1.5	0.75 to 1.25
Shape factor (length-width)	2.5	11	3.5 to 7.0
Azimuth (°)	13°	61°	25° to 50° avg. = 39.5°
Angle of intersect with coast (°)	1°	35°	5° to 30° avg. = 17.5°
Side slopes (°)	0.2°	7.0°	0.75° to 2.0°

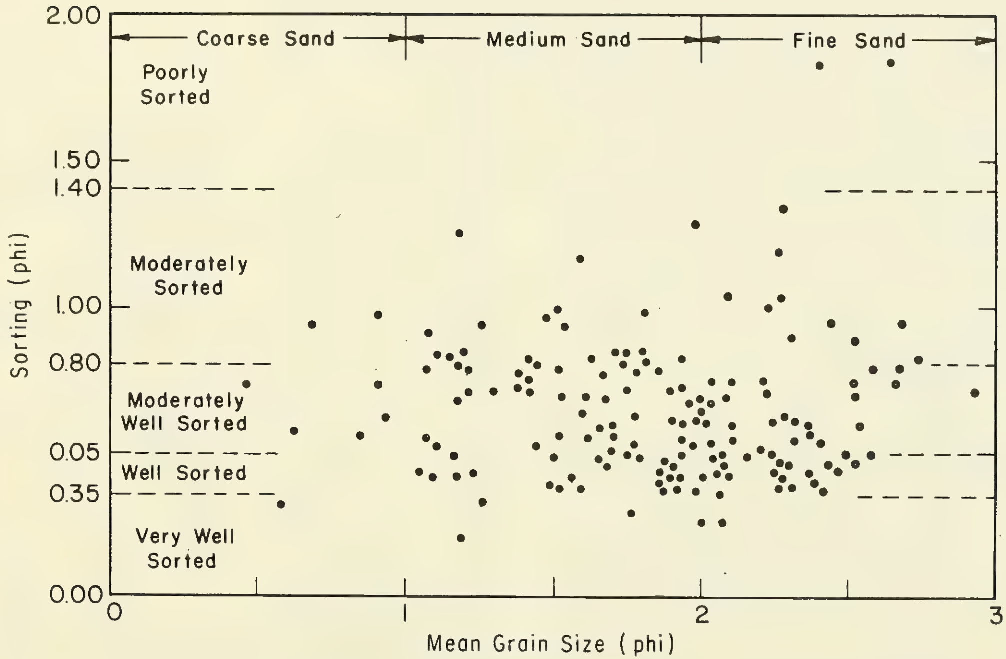


Figure 39. Scatter diagram of mean grain size versus sorting for 160 sand samples collected from the upper 1 meter of the shelf floor. The sorting classification is from Friedman (1962).

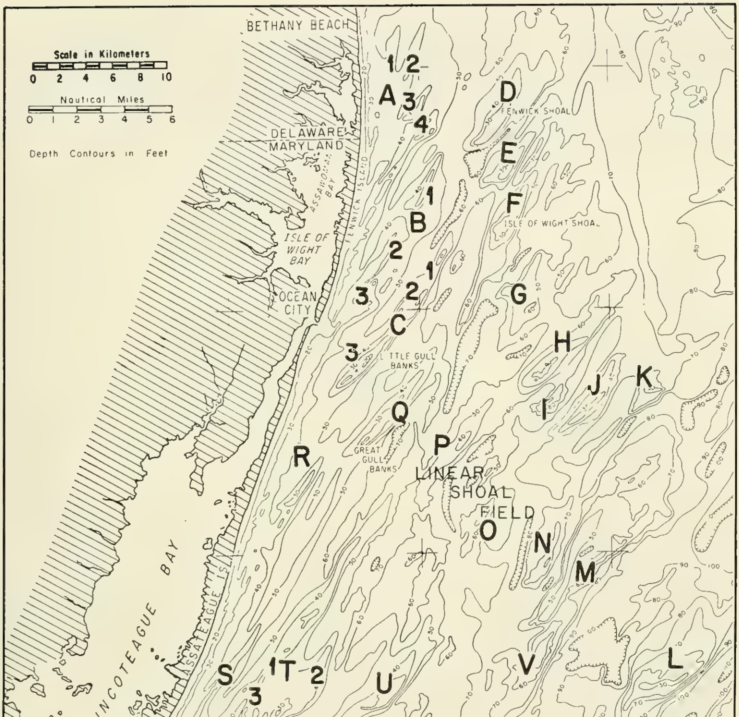


Figure 40. Base map of the shoal field of the northern Delmarva inner shelf indicating potential borrow sites (designated by letter). Borrow sites (shoals) with more than one ridge have numerical subscripts. Contours are compiled from charted depths on NOS chart 1220, scale 1:80,000. Shaded areas are depths shoaler than 40 feet (12.2 meters).

Although seismic data and sediment samples were not collected from each of the borrow areas identified in Figure 40, all are presumed to be suitable for sand borrow, based on the characteristics of those surveyed. The estimated volumes of sand in each shoal are as shown in Table 9. Calculations of volume.were made as follows:

$$V = \frac{1}{6} h \ (A_0 + 4 \ A_1 + A_2)$$

where

V = volume (in cubic yards)

h = height, thickness of the deposit (in yards)

A_0 = surface area of the top (in square yards)

A_1 = surface area of the midsection, taken at 1/2 h (in square yards)

A_2 = surface area of the base of the deposit (in square yards)

Area measurements were made with an engineering planimeter from a 1:80,000 scale chart. The top of the deposit was taken as the shoalest closed contour and is given in Table 9. The base of the deposit was taken as the deepest enclosing contour; in cases where the deepest contour paralleled the shoal only part way, it was extrapolated the remainder of the way. Shoreface shoals were measured by truncating contours at the base of the shoal where it merges with the shoreface.

It is estimated that approximately 2.2 billion cubic yards of sand suitable for use in beach restoration is present in 39 separate shoal borrow sites on the inner shelf off northern Delmarva (Table 9). This figure represents a minimum value since no effort was made to assess the volumes of sand in nonshoaled sea floor areas.

Not all of the shoals designated as potential borrow sites were sampled, as indicated in Table 9. Size characteristics of samples from shoal areas are given in Figures 41 and 42 and in Appendix B. If sand volumes are tabulated only for those shoals that were sampled, there is more than 765 million cubic meters (1 billion cubic yards) of suitable material. This is over an order of magnitude greater than the amount required for construction and 50 years of maintenance for the entire Maryland seashore.

c. Vertical Textural Patterns of Shoals. The mean grain size of core samples, determined by sieve analysis and settling-tube analysis (and corrected to sieve equivalents) were grouped by individual linear shoals (Fig. 41) and by shoreface and shoreface shoals (Fig. 42) to observe vertical-size trends. Both sets of data generally show an abrupt decrease in size of cored sands from 0.03 meter (-1 foot) up to the core

Table 9. Estimated sand volumes of potential offshore shoal borrow sites.

Shoal	Depth to top (ft)	Depth to base (ft)	Height of borrow deposit (ft)	Estimated volume of suitable material ($\times 10^6$ yd^3)	Samples obtained
A-1, -2, -3	30	40	10	40.40	Core 2
A-4	30	40	10	14.88	Core 12
B-1	30	50	20	31.78	Core 29
B-2, -3	30	50	20	110.09	Cores 30, 57
C-1	30	50	20	15.30	Core 21
C-2	30	50	20	38.63	Cores 54, 55, 56
C-3	20	50	30	74.93	Core 50
D	30	50	20	80.68	Core 6
E	30	50	20	31.07	Core 11
F	30	50	20	56.46	Cores 4, 15
G	40	60	20	75.96	Cores 22, 23
H	40	60	20	51.98	Cores 17, 18
I	70	80	10	3.04	None
J	30	50	20	51.74	None
K	50	70	20	30.83	None
L	50	70	20	87.41	None
M	50	60	10	63.13	None
N	50	70	20	35.19	None
O	50	60	10	10.18	None
P	40	50	10	13.82	Core 47
Q	30	50	20	108.38	Cores 44, 48, 49, 53
R	30	40	10	14.12	Cores 39, 40
S	30	40	10	7.75	Core 64
T	20	40	20	92.14	Cores 62, 71, 74, 77
U	30	50	20	89.78	Core 72
V	50	60	10	15.34	None
W	30	50	20	32.13	None
X	30	50	20	61.19	Core 58
Y	20	40	20	67.57	None
Z	20	40	20	33.90	Core 73
AA	50	70	20	19.49	None
AB, AC	60	90	30	139.90	None
AD	50	60	10	13.82	None
AE	40	60	20	65.09	None
AF	40	60	20	20.55	None
AG	30	50	20	31.07	None
AH	20	50	30	137.87	None
AI	30	40	10	27.19	None
Hen and Chicken shoal	20	50	30	225.00	None

Total volume: 2,119,760,000 cubic yards.

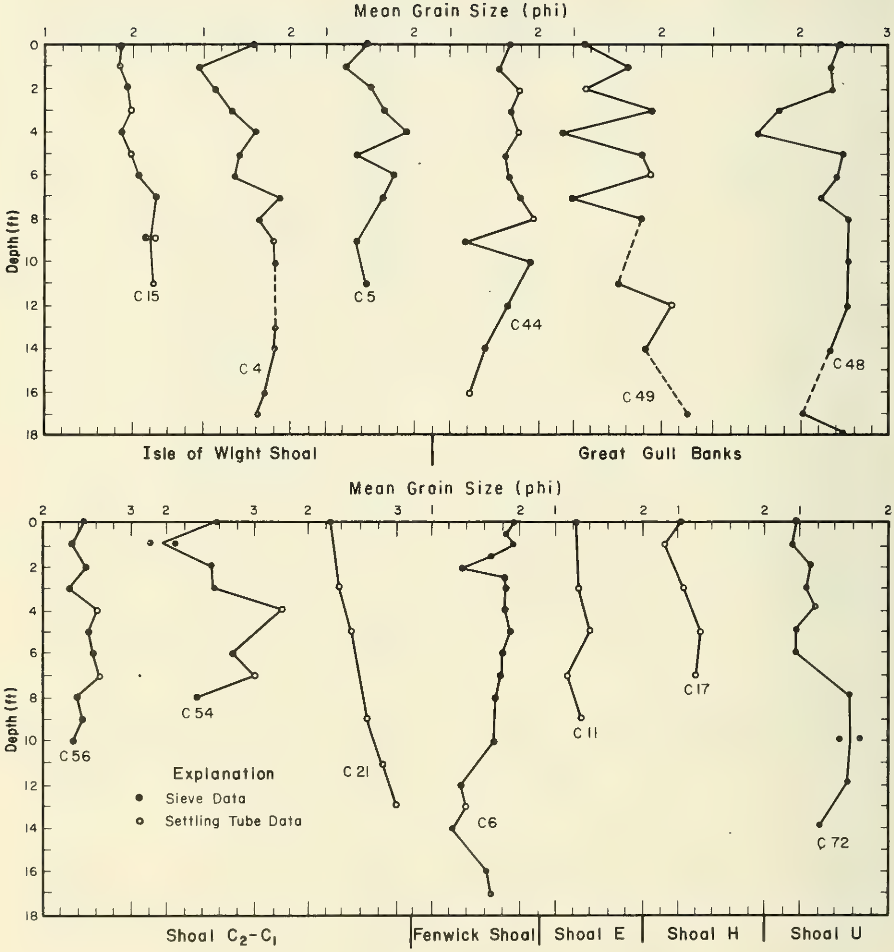


Figure 41. Mean grain size versus depth below sea floor for selected cores form offshore linear shoals. Data points separated by intervals of 3 feet (1 meter) or more are connected by dotted lines. Settling tube data were corrected to sieve equivalents using an empirically derived formula (see App. B).

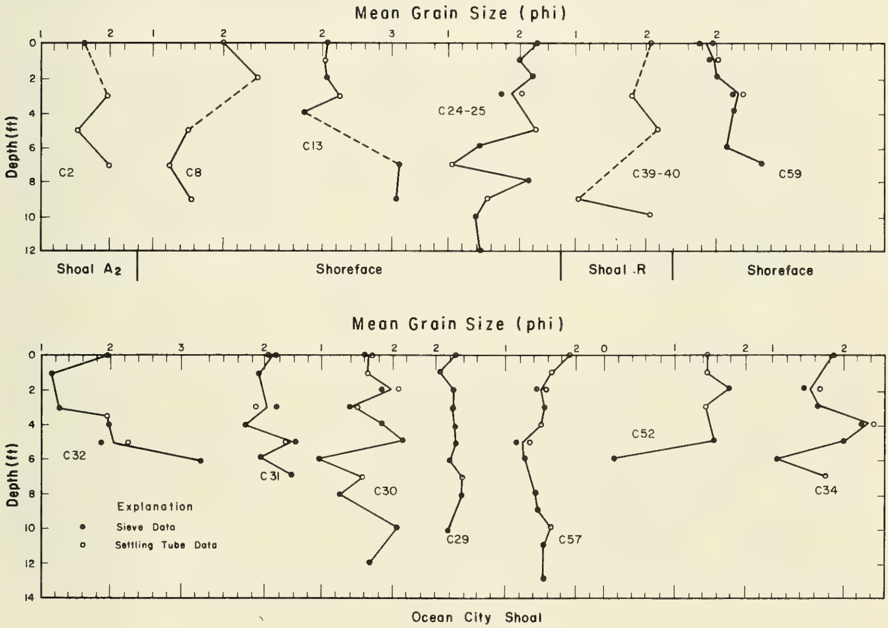


Figure 42. Mean grain size versus depth below sea floor for selected cores collected from the shoreface and shoreface shoals. Data points separated by intervals of 3 feet (1 meter) or more are connected by dotted lines. Settling tube data were corrected to sieve equivalents using an empirically derived formula (see App. B).

top. Thirteen (62 percent) of the 21 cores for which samples from the top and 0.3-meter levels were analyzed show this size decrease characteristic. In comparison, seven (33 percent) show no change in grain-size slope and only one (5 percent) becomes coarser upward from 0.3 meter. This pattern is probably an artifact of the coring technique. Surface sediments are high in water content and during extrusion of the core liner from the barrel, the core is held horizontally. This results in some mixing of the uppermost sediments and grains are probably size-fractionated due to differential settling rates.

Vertical textural trends of the shoal are somewhat enigmatic in that trends of adjacent cores sometimes correlate. Of the three cores (15, 4, and 5) collected along the axis of Isle of Wight shoal, 15 and 4 have an overall upward coarsening trend. The two cores differ from each other, however, in that core 15 is significantly finer grained than core 4 at every level. Cores 4 and 5 appear to be closely related in overall size and trend with a distinct coarsening from -1.2 to -0.3 meter (-4 to -1 foot) which may represent a single depositional "event." The alternatives are that the trend is coincidental or that the trend is a characteristic result of depositional processes on the shoal crests.

Size trends from cores 44, 49, and 48 on Great Gull Banks (Fig. 41) bear little resemblance to each other, with only one exception. A coarse layer or event occurs at about -1.2 meters in cores 49 and 48. This layer does not appear in core 44, and the level (-2.7 meters) of the one coarse layer in that core was not sampled in the other two cores. The three cores (56, 54, and 21) collected from shoal C_2-C_1 (north of Little Gull Banks) also show vertical size trends that appear independent of one another. Core 56 remains essentially constant in mean grain size; core 21 distinctly and consistently coarsens upward to -0.3 meter. Generally, the three cores contain finer sands than other cores collected from offshore linear shoals (Fig. 41). Single cores taken from offshore shoals also show variations as a group in vertical size trends. Core 17 shows subtle upward coarsening; core 6 shows subtle upward fining; and cores 11 and 72 exhibit no distinct trends. Core 6, from Fenwick shoal, was sampled at 0.5-meter intervals down to 1 meter and at 0.3-meter intervals down to -2.4 meters. Examination of mean grain-size data (Fig. 41) shows that the increased sampling density had little influence on the shape of the curve, although in other cores a close sample spacing may be necessary to delineate true trends.

Some cores from the shoreface and shoreface-shoal transects (Fig. 42) were not sufficiently sampled to evaluate the size trends. Of the six individual cores (Fig. 42, top), only cores 13 and 59, which are both distinctly finer grained than the rest, show an overall upward-coarsening trend. Cores 24, 25, 39, and 40 display upward-fining trends. For the most part, the intracore variations in mean grain size are larger than those between cores and often exceed one whole phi class. Comparison of textural trends in four cores collected along the axis of Ocean City shoal (Fig. 42, lower) show little similarity in mean grain size or trend, with the exception of a fine layer or event in cores 32, 31, and 30 at the

-1.5-meter level. Cores 31 and 29 are finer than the other cores and only core 32 shows a marked trend (upward coarsening). Core 29, which was obtained from a small detached shoal at the northern end of Ocean City shoal, has an unusual lack of variation in mean grain size. Vertical size trends in cores 57, 52, and 34, collected along one of the ridges or arms of Ocean City shoal, are essentially dissimilar, with two exceptions. Cores 52 and 34 both contain a coarse layer or event at -1.8 meters, and from that level to the surface, all three cores show a subtle upward-fining trend.

Despite the diverse nature of these mean size versus depth curves, some generalizations can be made about their characteristics and trends. Two-thirds of the cores are dominantly medium sand; the rest are fine sand. About one-third show a distinct upward coarsening, one-third show a subtle upward-fining trend, and one-third no apparent trend at all. The coarsening trends are usually more obvious than the fining trends. At least one, core 54, shows a coarsening trend overlying a fining trend. Cores collected along transects of individual shoals can occasionally be correlated on the basis of a single fine or coarse layer or event. No other textural patterns occur along shoal transects. Finer sands occur at both the southern and northern end of shoals, as do cores showing the least or most variation in mean grain size within a shoal.

An examination of the grain size from only the upper part of the cores shows a pattern of upward increase in grain size to be more apparent than for the whole core (Fig. 41). Considering only the upper (exclusive of the disturbed surface sample) trend or slope of data points, 7 of the 13 cores show definite upward coarsening, compared to only 2 which show upward fining; 4 of the cores have no distinct pattern. Samples from the shoreface and shoreface shoals, however, do not display this pattern. Of the 13 cores (Fig. 42), 4 do not have sufficient data for evaluation. Only two cores each show upward fining and upward coarsening and five cores show no distinct vertical trend in grain size.

VII. SUMMARY

The northern Delmarva Inner Continental Shelf has a complex bathymetric configuration largely shaped by Holocene and modern marginal marine (fluvial, estuarine, coastal, shallow shelf) processes. The morphology of the region is dominated by the large shelf valley of the ancestral Delaware River and estuary and a linear-shoal field composed of individual shelf and shoreface shoals and bracketed by a large shoal-retreat massif off Cape May, New Jersey, and a small one off Chincoteague, Virginia. The controlling influence in forming these major morphologic elements was the Holocene eustatic sea level rise.

Shallow subsurface strata consist of gently dipping Neogene sedimentary beds that conform to the gentle dip gradient (1 on 8,000) and direction (east and southeast) of the Atlantic Coastal Plain and that display no evidence of tectonic deformation (folding or faulting). Eleven major acoustic surfaces, some of which are correlative with stratigraphic and hydrologic units on land, are present within the upper 122 meters of the shelf subbottom. The presumed Tertiary-Quaternary unconformity is defined by a strong acoustic reflector; near the shore it lies at about 31 meters below MLW and it drops over 61 meters, 12.9 kilometers (8 miles) offshore.

Buried channels are common to the sea floor of the entire region, and in some instances are present in underlying Tertiary strata. In the Delaware Bay entrance, there are numerous buried channels, most of which reach more than 46 meters below sea level; many of these channels do not coincide with present or historical Delaware channels. Seismic reflection data indicate that at least some of the channels filled laterally from both the New Jersey and Delaware shelves. On the Maryland inner shelf, numerous small channels, many of which are alined with one another with existing onshore drainage, or with historical inlet sites, lie within 12.6 kilometers (7 nautical miles) of the coast. These channels display a linear relationship between maximum thalweg depth and distance from shore that is applicable in engineering studies.

The upper 6.1 meters of the inner shelf sampled by cores consists of terrigenous sands and silts derived from the adjacent Coastal Plain and Piedmont provinces. Four major sediment types are recognized--three are subarkosic arenites varying only in a modal grain size and sorting, and the fourth is a slightly sandy mud. A fifth category comprises those sediments that rarely occur throughout the region, such as peats and iron-stained gravels. Based on fauna, lithology, and stratigraphic position, the environments of deposition represented on the shallow shelf are determined to be modern marine, back barrier, lagoonal, and fluvial. Gray-brown, fine to coarse, well-sorted quartz sand is the dominant lithology on the surface. It decreases in relative abundance with depth. Increases in sand thickness occur locally in shoal areas and correspond directly with topographic relief. The sand overlies poorly sorted, fine sands and muds remnant from Holocene back-barrier and lagoonal deposition which are periodically exposed and eroded on the sea floor.

The marked similarities in geometry and sediment relationships of all linear shoals on the shelf show them to be genetically related. They are typically 6.1 to 9.1 meters high, 6.4 to 12.9 kilometers (4 to 8 miles) long by about 1.6 kilometers (1 mile) wide, oriented north-northeast, and strike an angle of 5° to 30° with the coast. Side slopes are about 1° to 2°, and seaward slopes tend to be steeper than landward ones, except along the shoreface. Individual shoals commonly display a progressive south-to-north change in shape from a well-defined, relatively narrow, single-crested form to a broader, multicrested or furrowed shape. This axial trend is inherited from the shoreface origin of these shoals where growth and bifuraction of these features always occur at the northern end. Shoal sand unconformably overlies truncated Holocene lagoonal muds, or in some cases, older, relict, coastal deposits. Coarser constituents of the mud unit are incorporated into the base of migrating shoals.

The linear shoals of the northern Delmarva shelf have a potential for use as a sand source for beach restoration projects. Shoal sands are fine to coarse sizes, are well sorted to moderately sorted, and reach a thickness of up to 10 meters. Most shoals contain between 15.3 to 53.5 million cubic meters (20 to 70 million cubic yards) of sand, and it is conservatively estimated that combined, the shoals contain approximately 1.7 billion cubic meters (2.2 billion cubic yards) of material that is suitable for nourishment of eroding beaches.

LITERATURE CITED

ALLEN, R.H., "A Glossary of Coastal Engineering Terms," MP 2-72, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., Apr. 1972.

AMERICAN GEOLOGICAL INSTITUTE, *Dictionary of Geological Terms,* Doubleday and Co., Inc., Garden City, N.J., 1962.

BIGGS, R.B., "The Origin and Geological History of Assateague Island, Maryland, and Virginia," No. 446, *Assateague Ecological Studies,* Natural Resources Institute, University of Maryland, College Park, Md., 1970, pp. 9-41.

BRUUN, P., "Sea Level Rise as a Cause of Shore Erosion," *Journal of the Waterways and Harbors Division,* Vol. 88, No. 1, Feb. 1962, pp. 117-130.

BUMPUS, D.F., and LAUZIER, L.M., "Surface Circulation on the Continental Shelf of Eastern North America Between Newfoundland and Florida," *Serial Atlas of the Marine Environment,* Folio 7, American Geographical Society, New York, 1965.

CALDWELL, J.M., "Coastal Processes and Beach Erosion," *Journal of the Society of Civil Engineers,* Vol. 53, 1966, pp. 142-157.

CURRAY, J.R., "Sediments and History of Holocene Transgression, Continental Shelf, Northwest Gulf of Mexico," *Recent Sediments, Northwest Gulf of Mexico,* F.P. Shepherd, et al., eds., American Association of Petroleum Geologists, Tulsa, Okla., 1960, pp. 221-288.

CURRAY, J.R., "Late Quaternary History, Continental Shelves of the United States," *The Quaternary of the United States,* Wright and Frey, eds., Princeton University Press, Princeton, N.J., 1965, pp. 723-736.

CUSHING, E.M., KANTROWITZ, I.H., and TAYLOR, K.R., "Water Resources of the Delmarva Peninsula," Professional paper 822, U.S. Geological Survey, Reston, Va., 1973.

DAVIS, D.K., ETHRIDGE, F.G., and BERG, R.R., "Recognition of Barrier Environments," *The American Association of Petroleum Geologists Bulletin,* Vol. 55, No. 4, Apr. 1971, pp. 550-565.

DENNY, C.S., "Sand Dunes on the Lower Delmarva Peninsula, Maryland, and Delaware," *Proceedings of the Geological Society of America, Northeastern Section,* 1974, pp. 18-19.

DUANE, D.B., et al., "Linear Shoals on the Atlantic Inner Continental Shelf, Florida to Long Island," *Shelf Sediment Transport: Process and Pattern,* Swift, Duane, and Pilkey, eds., Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pa., 1972, pp. 447-499.

EDSALL, T.D., "Sands of the Continental Shelf Near Maryland," unpublished Master's Thesis, Rutgers University, New Brunswick, N.J., 1955.

EMERY, K.O., "Atlantic Continental Shelf and Slope of the United States - Geologic Background," Paper 529-A, U.S. Geological Survey, Washington, D.C., 1966.

EMERY, K.O., "Relict Sediments on Continental Shelves of the World," *The American Association of Petroleum Geologists Bulletin*, Vol. 52, No. 3, Mar. 1968, pp. 445-464.

FIELD, M.E., "Buried Strandline Deposits on the Central Florida Inner Continental Shelf," *The Geological Society of America Bulletin*, Vol. 85, No. 1, Jan. 1974, pp. 57-60.

FIELD, M.E., "Quaternary Evolution and Sedimentary Record of a Coastal Plain Shelf: Central Delmarva Peninsula, Mid-Atlantic Bight, USA," unpublished Ph.D. Dissertation, George Washington University, Washington, D.C., 1976.

FIELD, M.E., and DUANE, D.B., "Regional Geology of the U.S. Atlantic Inner Shelf Applied to Coastal Zone Planning," Abstract, Annual Meeting, Geological Society of America, Vol. 5, No. 7, Oct. 1972.

FIELD, M.E., and DUANE, D.B., "Geomorphology and Sediments of the Inner Continental Shelf, Cape Canaveral, Florida," TM-42, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., Jan. 1974.

FIELD, M.E., and DUANE, D.B., "Post-Pleistocene History of the Inner Continental Shelf: Significance to Barrier Island Origin," *The Geological Society of America Bulletin*, Vol. 87, No. 5, May 1976, pp. 691-702.

FISCHER, A.G., "Stratigraphic Record of Transgressing Seas in Light of Sedimentation on Atlantic Coast of New Jersey," *The American Association of Petroleum Geologists Bulletin*, Vol. 45, No. 10, Oct. 1961, pp. 1656-1666.

FISHER, J.J., "Barrier Island Formation: Discussion," *The Geological Society of America Bulletin*, Vol. 79, No. 10, Oct. 1968, pp. 1421-1426.

FRIEDMAN, G.M., "On Sorting, Sorting Coefficients, and Log Normality of the Grain Size Distribution of Sand Stones," *Journal of Geology*, Vol. 70, No. 6, Nov. 1962, pp. 737-756.

GAWNE, E.C., "Shore Changes on Fenwick and Assateague Islands, Maryland and Virginia," unpublished Master's Thesis, University of Illinois, Urbana, Ill., 1966.

GODFREY, P.J., and GODFREY, M.M., "Comparison of Ecological and Geomorphic Interactions Between Altered and Unaltered Barrier Island Systems in North Carolina," *Coastal Geomorphology Publications in Geomorphology*, D. Coates, ed., State University of New York, Binghamton, New York, 1973, pp. 239-258.

HALL, J.V., "Artificially Nourished and Constructed Beaches," TM-29, U.S. Army, Corps of Engineers, Beach Erosion Board, Washington, D.C., Dec. 1952.

HAMBLIN, W.K., "Internal Structures of Homogeneous Sandstones," *The Kansas Geological Survey Bulletin*, Vol. 175, No. 1, 1965, pp. 569-582.

HARRISON, S.C., "The Sediments and Sedimentary Processes of the Holocene Tidal Flat Complex, Delmarva Peninsula, Virginia," TR-112, Coastal Studies Institute, Louisiana State University, Baton Rouge, La., Apr. 1972.

HARRISON, W., and NORCROSS, J.J., "Circulation of Shelf Waters off the Chesapeake Bight," Professional Paper 3, Environmental Science Services Administration, Washington, D.C., July 1967.

HICKS, S., "Vertical Crustal Movements From Sea Level Measurements Along the East Coast of the United States," *Journal of Geophysical Research*, Vol. 77, No. 30, Oct. 1972, pp. 5930-5934.

HOBSON, R.D., "Review of Design Elements for Beach-Fill Evaluation," TP 77-6, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., June 1977.

HOYT, J.H., "Barrier Island Formation," *The Geological Society of America Bulletin*, Vol. 79, No. 10, Oct. 1967, pp. 1427-1432.

HOYT, J.H., and HAILS, J.R., "Pleistocene Shoreline Sediments in Coastal Georgia: Deposition and Modification," *Science*, Vol. 155, No. 3769, Mar. 1967, pp. 1541-1543.

HYNE, N.J., and GOODELL, H.G., "Origin of the Sediments and Submarine Geomorphology of the Inner Continental Shelf off Choctawhatchee Bay, Florida," *Marine Geology*, Vol. 5, May 1967, pp. 299-313.

JAMES, W.R., "Beach Fill Stability and Borrow Material Texture," *Proceedings of the 14th International Coastal Engineering Conference*, American Society of Civil Engineers, Vol. 2, No. 14, 1974, pp. 1334-1349.

JORDON, G.F., "Large Submarine Sand Waves," *Science*, Vol. 136, No. 3519, June 1962, pp. 839-848.

JORDON, R.R., and ADAMS, J.K., "Early Tertiary Bentonite from the Subsurface of Central Delaware," *The Geological Society of America Bulletin*, Vol. 73, No. 3, Mar. 1962, pp. 395-398.

KRAFT, J.C., "Sedimentary Environment Facies Patterns and Geologic History of a Holocene Marine Transgression," *The Geological Society of America Bulletin*, Vol. 82, No. 8, Aug. 1971, pp. 2131-2158.

KRAFT, J.C., and CAULK, R.I., *The Evolution of Lewes Harbor*, TR-10, College of Marine Studies, University of Delaware, Newark, Del., Nov. 1972.

KRAFT, J.C., BIGGS, R.B., and HALSEY, S.D., "Morphology and Vertical Sedimentary Sequence Models in Holocene Transgressive Barrier Systems," *Coastal Geomorphology: Publications in Geomorphology*, D. Coates, ed., State University of New York, Binghamton, New York, 1973, pp. 321-354.

KRUMBEIN, W.C., and JAMES, W.R., "A Lognormal Size Distribution Model for Estimating Stability of Beach Fill Material," TM-16, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Washington, D.C., Nov. 1965.

KRUMBEIN, W.C., and SLOSS, L.L., *Stratigraphy and Sedimentation*, W.H. Freeman and Co., San Francisco, Calif., 1963.

LEOPOLD, L.B., WOLMAN, M.G., and MILLER, J.P., *Fluvial Processes in Geomorphology*, W.H. Freeman and Co., San Francisco, Calif., 1964.

MAURIELLO, L.J., "Experimental Use of Self-Unloading Hopper Dredge for Rehabilitation of an Ocean Beach," *Proceedings of the First World Dredging Conference*, World Dredging Association, Vol. 67, 1967, pp. 367-395.

McCLENNEN, C.E., "New Jersey Continental Shelf Near Bottom Current Meter Records and Recent Sediment Activity," *Journal of Sedimentary Petrology*, Vol. 43, No. 2, June 1973, pp. 371-380.

McMASTER, R.L., and GARRISON, L.E., "A Submerged Holocene Shoreline Near Block Island, Rhode Island," *Journal of Geology*, Vol. 75, No. 3, May 1967, pp. 335-339.

MEADE, R.H., "Landward Transport of Bottom Sediments in Estuaries of the Atlantic Coastal Plain," *Journal of Sedimentary Petrology*, Vol. 39, No. 1, Mar. 1969, pp. 222-234.

MEISBURGER, E.P., "Geomorphology and Sediments of the Chesapeake Bay Entrance," TM-38, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., June 1972.

MEISBURGER, E.P., and DUANE, D.B., "Shallow Structural Characteristics of Florida Atlantic Shelf as Revealed by Seismic Reflection Profiles," *Transactions of the Gulf Coast Association of Geological Societies*, Vol. XIX, 1969, pp. 207-215 (also CERC Reprint 1-70, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Washington, D.C., NTIS AD 702 003).

MEISBURGER, E.P., and FIELD, M.E., "Geomorphology, Shallow Structure, and Sediments of the Florida Inner Continental Shelf, Cape Canaveral to Georgia," TM-54, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., July 1975.

MILLER, H.J., TIREY, G.B., and MECARINI, G., "Mechanics of Marine Mineral Exploration," *Proceedings of the Underwater Technology Conference*, American Society of Mechanical Engineers, 1967.

MILLIMAN, J.D., "Atlantic Continental Shelf and Slope of the United States: Petrology of the Sand Fraction of Sediments, Northern New Jersey to Southern Florida," Professional Paper 529-J, U.S. Geological Survey, Reston, Va., Mar. 1972.

MILLIMAN, J.D., and EMERY, K.O., "Sea Levels During the Past 35,000 Years," *Science*, Vol. 162, No. 3858, Dec. 1968, pp. 1121-1123.

MILLIMAN, J.D., PILKEY, O.H., and ROSS, D.A., "Sediments of the Continental Margin off the Eastern United States," *The Geological Society of America Bulletin*, Vol. 83, No. 5, May 1972, pp. 1315-1334.

MINARD, J.P., et al., "Cretaceous-Tertiary Boundary in New Jersey, Delaware, and Eastern Maryland," *The U.S. Geological Survey Bulletin*, No. 1274-H, 1969, pp. H1-H33.

MIXON, R.B., et al., "Geologic Framework of the Southernmost Delmarva Peninsula, Accamack and Northampton Counties, Virginia," *Proceedings of the Geological Society of America Meeting*, Northeastern Section, 1974, pp. 56-57.

MOODY, D.W., "Coastal Morphology and Processes in Relation to the Development of Submarine Sand Ridges off Bethany Beach, Delaware," unpublished Ph.D. Dissertation, John Hopkins University, Baltimore, Md., 1964.

MOORE, D.G., and PALMER, H.P., "Offshore Seismic Reflection Surveys," *Civil Engineering in the Oceans*, American Society of Civil Engineering, 1968, pp. 780-806.

NEIHEISEL, J., "Source of Detrital Heavy Minerals in Estuaries of the Atlantic Coastal Plain," unpublished Ph.D. Dissertation, Georgia Institute of Technology, Atlanta, Ga., 1973.

OWENS, J.P., and DENNY, C.S., "Provisional Stratigraphic Sequence in the Maryland-Delaware Parts of the Lower Delmarva Peninsula," *Proceedings of the Geological Society of America Meeting*, Northeastern Section, Vol. 6, No. 1, 1974, pp. 61-62.

PETTIJOHN, F.J., POTTER, P.E., and SIEVER, R., *Sand and Sandstone*, Springer-Verlag, Berlin, New York, 1972.

PIERCE, J.W., "Sediment Budget Along a Barrier Island Chain," *Sedimentary Geology*, Vol. 3, Sept. 1969, pp. 5-16.

PIERCE, J.W., and COLQHOUN, D.J., "Holocene Evolution of a Portion of the North Carolina Coast," *The Geological Society of America Bulletin*, Vol. 81, Dec. 1970, pp. 3697-3714.

PILKEY, O.H., and FIELD, M.E., "Onshore Transportation of Continental Shelf Sediments, Southeastern United States," *Shelf Sediment Transport: Process and Pattern*, Swift, Duane, and Pilkey, eds., Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pa., 1972, pp. 429-446.

RASMUSSEN, W.C., and SLAUGHTER, T.H., "The Water Resources of Somerset, Wicomico, and Worcester Counties," Bull. 16, Department of Geology, Mines and Water Resources, State of Maryland, Baltimore, Md., 1955.

RESIO, D.T., and HAYDEN, B.P., "An Integrated Model of Storm Generated Waves," Technical Report No. 8, Department of Environmental Sciences, University of Virginia, Charlottesville, Va., Dec. 1973.

SANDERS, J.F., "North-South Trending Submarine Ridge Composed of Coarse Sand off False Cape, Va.," Abstract, Annual Meeting, *American Association of Petroleum Geologists*, 1962.

SCHOPF, T.J.M., "Atlantic Continental Shelf and Slope of the United States, Nineteenth Century Exploration," Professional Paper 529-F, U.S. Geological Survey, Washington, D.C., 1968.

SCHWARTZ, M.L., *Barrier Islands*, Benchmark Papers in Geology, Dowden, Hutchinson and Ross, Inc., Vol. 9, Stroudsburg, Pa., 1973.

SCHWARTZ, R.K., "Nature and Genesis of Some Storm Washover Deposits," TM-61, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., Dec. 1975.

SHEPARD, F.P., *Submarine Geology*, Harper and Row, New York, 1963.

SHEPARD, F.P., and COHEE, G.V. "Continental Shelf Sediments off the Mid-Atlantic States," *The Geological Society of America Bulletin*, Vol. 47, No. 3, Mar. 1936, pp. 441-457.

SHERIDAN, R.E., DILL, C.E., and KRAFT, J.C., "Holocene Sedimentary Environment of the Atlantic Inner Shelf off Delaware," *The Geological Society of America Bulletin*, Vol. 8, Aug. 1974, pp. 1319-1328.

SINNOTT, A., and TIBBITTS, G.C., Jr., "Records of Selected Wells on the Eastern Shore Peninsula, Virginia," Mineral Resources Circular No. 3, Virginia Division of Geology and Mineral Resources, Charlottesville, Va., 1955.

SMITH, J.D., "Geomorphology of a Sand Ridge," *Journal of Geology*, Vol. 77, No. 1, Jan. 1969, pp. 39-55.

STAHL, L., KOZAN, J., and SWIFT, D., "Anatomy of a Shoreface Ridge on the New Jersey Shelf: Implications for the Genesis of the Shelf Surficial Sand Sheet," *Geology*, Vol. 2, No. 3, Mar. 1974, pp. 117-120.

SWIFT, D.J.P., "Quaternary Shelves and the Return to Grade," *Marine Geology*, Vol. 8, Aug. 1970, pp. 5-30.

SWIFT, D.J.P., "Delaware Shelf Valley: Estuary Retreat Path, Not Drowned River Valley," *The Geological Society of America Bulletin*, Vol. 84, No. 8, Aug. 1973, pp. 2743-2748.

SWIFT, D.J.P., and SEARS, P., "Estuarine and Littoral Patterns in the Surficial Sand Sheet, Central and Southern Atlantic Shelf of North America," *Estuary and Shelf Sedimentation: A Symposium*, G.P. Allen, ed., University of Bordeauz, Talence, France, 1974.

SWIFT, D.J.P., STANLEY, D.J., and CURRAY, J.R., "Relict Sediments on Continental Shelves: A Reconsideration," *Journal of Geology*, Vol. 79, No. 3, May 1971, pp. 322-346.

SWIFT, D.J.P., et al., "Textural Differentiation on the Shoreface During Erosional Retreat of an Unconsolidated Coast, Cape Henry to Cape Hatteras, Western North Atlantic Shelf," *Sedimentology*, Vol. 16, No. 3/4, June 1971, pp. 221-250.

SWIFT, D.J.P., et al., "Holocene Evolution of the Shelf Surface, Central and Southern Atlantic Shelf of North America," *Shelf Sediment Transport: Process and Pattern*, Swift, Duane, and Pilkey, eds., Dowden, Hutchinson, and Ross, Inc., Stroudsburg, Pa., 1972, pp. 499-575.

TRUITT, R.V., "Highwinds...High Tides,," Educational Series No. 77, Natural Resources Institute, University of Maryland, College Park, Md., 1967.

TRUMBULL, J.V., "Atlantic Continental Shelf and Slope of the United States: Sand Size Fraction of Bottom Sediments, New Jersey to Nova Scotia," Professional Paper 529-K, U.S. Geological Survey, Reston, Va., 1972.

UCHUPI, E., "Atlantic Continental Shelf and Slope of the United States - Physiography," Professional Paper 529-C, U.S. Geological Survey, Washington, D.C., 1968.

U.S. ARMY, CORPS OF ENGINEERS, COASTAL ENGINEERING RESEARCH CENTER, *Shore Protection Manual*, 3d ed., Vols, I, II, and III, Stock No. 008-022-00113-1, U.S. Government Printing Office, Washington, D.C., 1977, 1,262 pp.

U.S. ARMY ENGINEER DISTRICT, BALTIMORE, "Survey Report on Beach Erosion Control and Hurricane Protection, Atlantic Coast of Maryland and Assateague Island, Virginia," Baltimore, Md., Feb. 1972.

U.S. ARMY ENGINEER DISTRICT, PHILADELPHIA, "Delaware Coast from Kitts Hummock to Fenwick Island, Beach Erosion Control Study," App. A-H, Philadelphia, Pa., 1956.

VEATCH, A.C., and SMITH, P.A., "Atlantic Submarine Valleys of the United States and the Congo Submarine Valley," Special Paper 7, The Geological Society of America, New York, Sept. 1939.

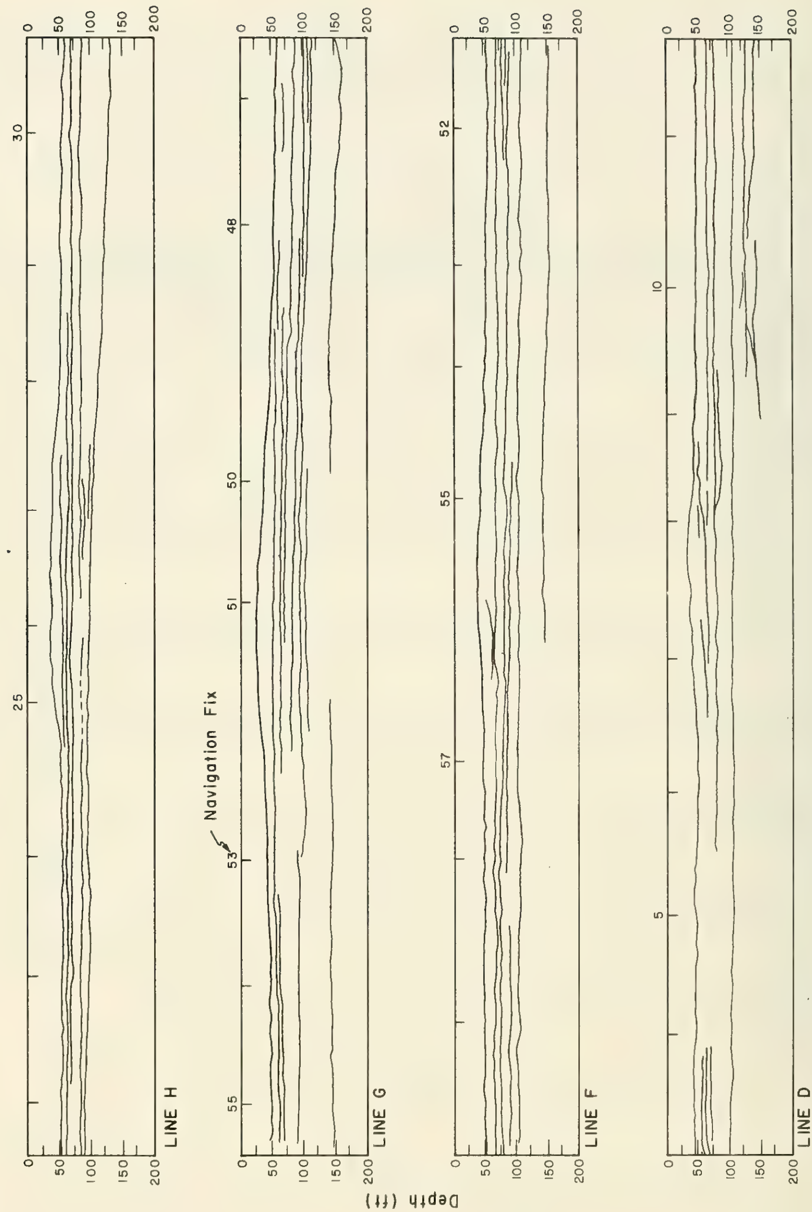
WEIGLE, J.M., "Availability of Fresh Water in Northeastern Worcester County, Maryland," No. 24, *Maryland Geological Survey Report of Investigations*, 1974.

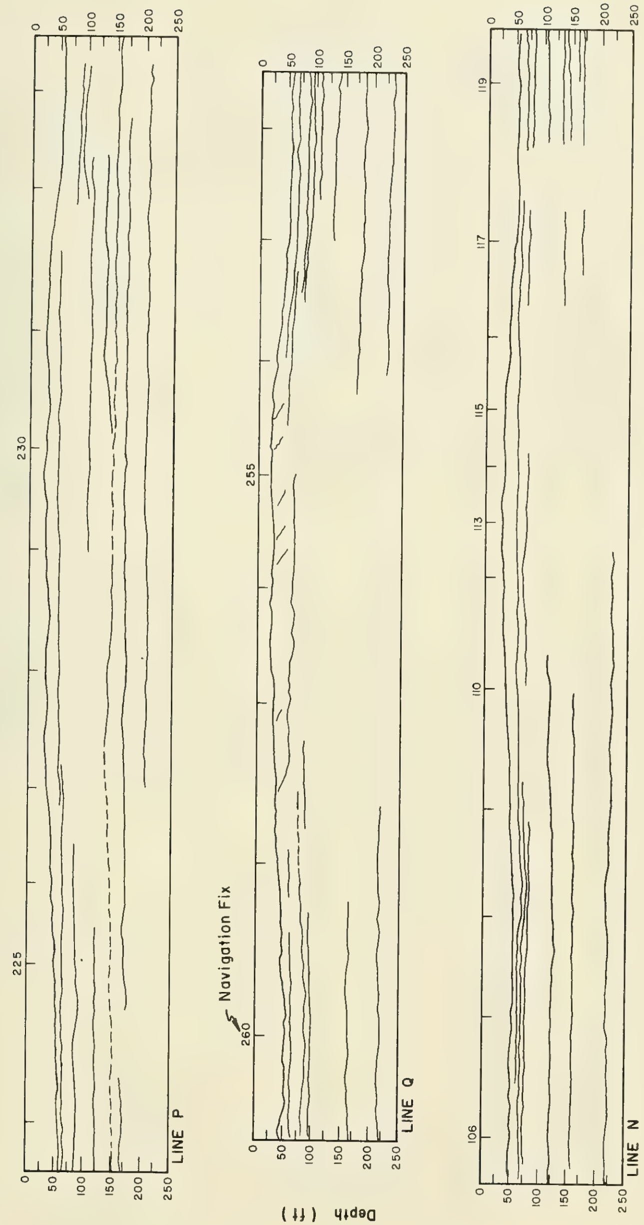
WILLIAMS, S.J., and DUANE, D.B., "Regional Shelf Studies - A Guide to Engineering Design," *Preprints of Eighth Annual Conference and Exposition Marine Technology Society*, U.S. Army Coastal Engineering Research Center, Washington, D.C., 1972, pp. 227-236.

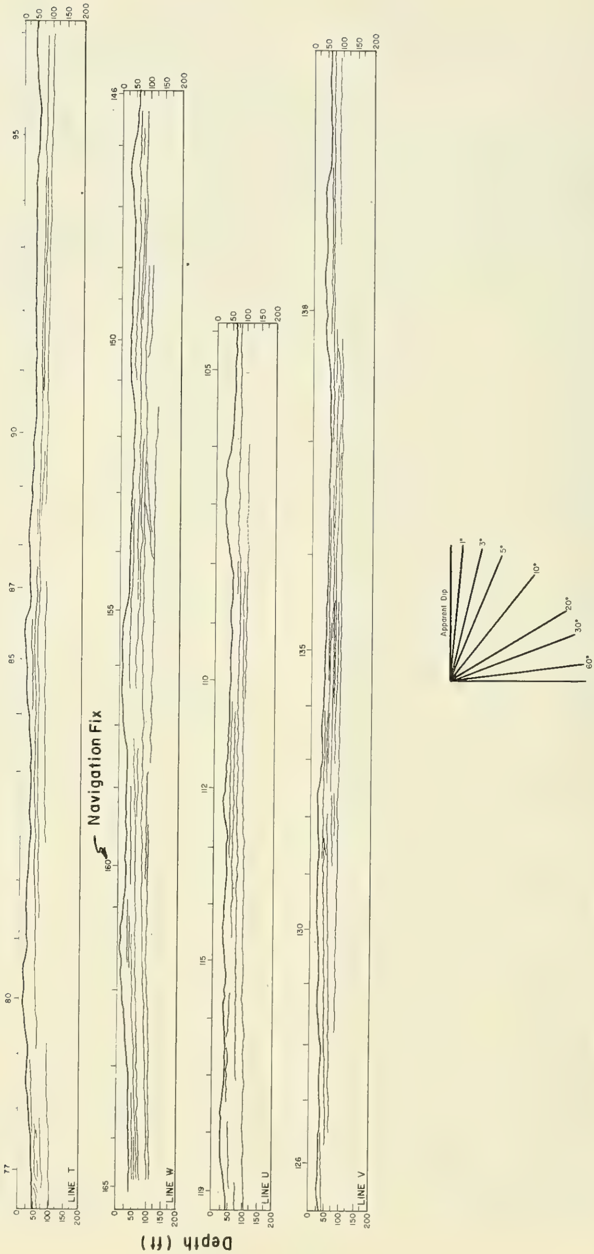
APPENDIX A

SEISMIC REFLECTION PROFILES

This appendix contains interpreted seismic reflection profiles across the inner shelf off Maryland. Seismic reflection data were collected in the spring of 1974. Locations of tracklines are shown in Figure 4.


LINE H
LINE G
LINE F
LINE D
Navigation Fix
Depth (ft)
0
50
100
150
200
30
25
48
50
51
53
55
52
55
57
10
5


LINE P
LINE Q
LINE N
Navigation Fix
Depth (ft)
0 50 100 150 200 250
225
230
255
260
106
110
113
115
117
119


LINE T
LINE W
LINE U
LINE V
Navigation Fix
Depth (ft)
Apparent Dip
1°
3°
5°
10°
20°
30°
60°

APPENDIX B

RESULTS OF GRAIN-SIZE ANALYSIS

This appendix provides a list of mean grain size and sorting for samples analyzed by sieving and settling-tube techniques. Sieve data (Table B-1) were obtained by sieving samples at 0.5-phi intervals for periods of 20 to 30 minutes. Raw weights were used to calculate mean grain size and sorting by use of the method of moments.

Settling-tube data (Table B-2) were obtained by analyzing samples on the CERC Rapid Sediment Analyzer (RSA). The RSA method records at the top and bottom of a 1-meter-long (3-inch-diameter) plastic tube as grains settle through the water column through use of two pressure transducers. Pressure data are digitized and converted to equivalent size data of spherical quartz grains, and mean grain size and sorting are computed by the method of moments. Through comparison of the results of samples analyzed by both the RSA and sieving techniques, empirical relationships were developed for converting data obtained on the RSA to its sieve equivalent. These expressions, given below, were used to convert RSA means and sorting values to their sieve equivalents as shown in Table B-2.

$$\text{Mean:} \quad \bar{\phi}_{Sieve} = 0.1876 + 1.0735\ \bar{\phi}_{RSA}$$

$$\text{Sorting:} \quad S_{\phi_{Sieve}} = -0.146 + 1.453\ S_{\phi_{RSA}}$$

Conversion between phi units and millimeters for grain diameters is possible using the Wenworth grain-size scale (Table B-3). The techniques are discussed in the Shore Protection Manual (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977).

Table B-1. Sieve mean grain size and sorting values for selected core samples.

Core	Sediment depth (ft)	Mean (phi)	Std. dev. (phi)
4	0	1.58	0.52
	-1	0.95	0.95
	-2	1.11	0.83
	-3	1.34	0.47
	-4	1.61	0.46
	-5	1.46	0.57
	-6	1.40	0.59
	-7	1.91	0.44
	-8	1.68	0.40
	-10	1.85	0.55
	-14	1.84	0.55
	-16	1.73	0.58
5	-2	1.50	0.47
	-4	1.90	0.54
	-6	1.74	0.60
5A	0	1.47	0.70
	-1	1.20	0.83
	-3	1.66	0.68
	-5	1.33	0.87
	-7	1.64	0.50
	-9	1.32	1.01
	-11	1.48	1.14

Core	Sediment depth (ft)	Mean (phi)	Std. dev. (phi)
6C	0	1.93	0.50
	-0.5	1.87	0.46
	-1	1.93	0.43
	-1.5	1.70	0.56
	-2	1.35	0.90
	-2.5	1.86	0.47
	-3	1.86	0.53
	-4	1.84	0.47
	-5	1.90	0.58
	-6	1.81	0.55
	-7	1.80	0.49
	-8	1.73	0.76
	-10	1.75	0.81
	-12	1.34	0.57
	-14	1.29	0.60
	-16	1.63	0.63
13	0	2.09	0.41
	-2	2.06	0.48
	-4	1.72	1.31
	-7	3.09	0.95
	-9	3.07	0.96
15	0	1.86	0.41
	-2	1.92	0.43
	-4	1.77	0.58
	-6	2.08	0.61
	-7	2.27	0.70
	-9	2.16	0.74
	-11	2.22	0.65

Core	Sediment depth (ft)	Mean (phi)	Std. dev. (phi)
24	-1	2.00	0.62
	-2	2.20	0.50
	-3	1.77	0.85
	-6	1.45	1.34
	-7	0.18	1.59
	-8	2.11	0.67
	-10	1.38	1.10
	-12	1.43	0.85
28	0	1.56	0.66
	-1	1.61	0.63
	-2	2.10	0.59
	-4	2.09	0.65
	-6	1.36	1.86
	-10	0.19	1.13
29	-1	2.09	0.49
	-2	2.27	0.42
	-3	2.27	0.41
	-4	2.32	0.47
	-5	2.33	0.53
	-6	2.26	0.55
	-8	2.41	0.51
	-10	2.25	0.75
30	0	1.60	0.57
	-2	1.83	0.48
	-3	1.40	0.70
	-4	1.82	0.59
	-4	1.39	0.80
	-5	2.10	0.56
	-6	0.96	0.98
	-8	1.28	0.80
	-10	2.07	0.58
	-12	1.65	0.86

Table B-1. Sieve mean grain size and sorting values for selected core samples.--Continued

Core	Sediment depth (ft)	Mean (phi)	Std. dev. (phi)
31	0	2.06	0.42
	-1	1.90	0.45
	-3	2.12	0.51
	-4	1.69	0.84
	-5	2.41	0.81
	-6	1.89	1.18
	-7	2.33	1.56
32	-1	1.18	0.81
	-3	1.28	0.92
	-4	1.96	0.54
	-5	1.76	0.52
	-6	3.29	0.66
34	-2	1.46	0.92
	-3	1.63	0.81
	-4	2.36	0.53
	-5	1.99	0.74
	-6	1.07	1.12
44	0	1.68	0.91
	-1	1.54	0.69
	-3	1.69	0.67
	-5	1.59	0.79
	-6	1.65	0.51
	-7	1.77	0.49
	-9	1.19	0.92
	-10	1.90	0.52
	-12	1.64	0.64
	-14	1.40	0.78

Core	Sediment depth (ft)	Mean (phi)	Std. dev. (phi)
48	-1	2.35	0.40
	-2	2.37	0.40
	-3	1.74	0.84
	-4	1.51	1.17
	-5	2.50	0.42
	-6	2.43	0.50
	-8	2.54	0.49
	-12	2.51	0.47
	-14	2.35	0.57
	-17	2.03	1.05
	-18	2.50	0.57
49	-1	1.61	0.68
	-3	1.90	0.71
	-4	0.89	0.80
	-5	1.78	0.75
	-7	0.99	1.21
	-8	1.79	0.60
	-11	1.50	0.70
	-14	1.79	0.78
	-17	2.26	0.63
52	-2	1.76	0.84
	-5	1.53	0.66
	-5	2.48	0.51
	-6	0.19	1.49
54	-1	2.10	0.73
	-2	2.51	0.73
	-3	2.53	0.87
	-6	2.77	0.70
	-8	2.37	1.02

Core	Sediment depth (ft)	Mean (phi)	Std. dev. (phi)
56	-1	2.32	0.53
	-2	2.50	0.47
	-3	2.31	0.61
	-5	2.52	0.33
	-6	2.56	0.42
	-8	2.39	0.57
	-9	2.45	0.47
	-10	2.35	0.52
57	-2	1.43	0.52
	-3	1.56	0.42
	-5	1.18	0.49
	-6	1.25	0.43
	-8	1.41	0.49
	-9	1.45	0.44
	-11	1.52	0.47
	-13	1.52	0.58
69	0	1.80	0.89
	-1	1.93	0.81
	-2	2.00	0.67
	-3	2.23	0.67
	-4	2.22	0.76
	-6	2.12	0.90
	-7	2.65	0.44
72	0	0.50	0.95
	-1	0.91	0.96
	-3	1.09	0.54
	-5	0.97	0.73
	-6	0.94	0.72
	-8	1.55	0.53
	-10	1.46	0.46
	-12	1.55	0.44
	-14	1.22	0.53

Table B-2. RSA mean grain size and sorting values for selected core samples, converted to sieve equivalents.

Core	Sediment depth (ft)	Mean (phi)	Std. dev. (phi)
1	0	1.90	0.60
	-3	1.42	0.70
	-5	1.39	0.76
	-9	1.42	0.70
2	0	1.65	0.58
	-3	1.97	0.67
	-5	1.51	0.57
	-7	1.96	0.57
3	-1	1.26	0.93
	-3	1.71	0.84
	-7	2.46	0.57
4	0	1.76	0.28
	-1	1.08	0.78
	-3	1.44	0.51
	-5	1.63	0.38
	-9	1.81	0.44
	-13	1.85	0.33
	-17	1.67	0.55
5A	0	1.64	0.55
	-3	1.79	0.48
	-7	1.72	0.44
	-11	1.71	0.64
6C	0	1.96	0.44
	-3	1.93	0.41
	-5	1.95	0.45
	-13	1.39	0.51
	-17	1.70	0.44

Core	Sediment depth (ft)	Mean (phi)	Std. dev. (phi)
7	0	1.37	0.71
	-5	2.78	1.37
	-9	1.27	0.62
8A	0	2.00	0.52
	-2	2.46	0.44
	-5	1.51	0.64
	-7	1.25	0.83
	-9	1.59	1.32
	0	0.89	0.76
	-1	2.23	0.70
10	0	2.09	0.41
	-3	2.08	0.42
	-5	1.47	0.84
	-7	1.21	0.89
11	0	1.23	0.42
	-3	1.26	0.33
	-5	1.41	0.45
	-7	1.19	0.54
	-9	1.31	0.52
12	-1	1.09	0.90
	-3	1.18	0.67
	-5	1.25	0.35
	-9	1.06	0.74
13	-1	2.04	0.52
	-3	2.27	0.39
14	0	2.29	1.34
	-1	2.23	0.99
	-3	2.65	1.84

Core	Sediment depth (ft)	Mean (phi)	Std. dev. (phi)
15	0	1.86	0.41
	-1	1.85	0.44
	-3	1.99	0.38
	-5	2.03	0.49
	-9	2.26	0.46
16	0	1.16	0.49
17	0	1.05	0.44
	-1	0.85	0.55
	-3	1.09	0.42
	-5	1.26	0.67
	-7	1.20	0.83
18B	0	0.58	0.32
	-2	1.18	0.20
	-4	0.45	0.38
	-6	0.37	0.55
	-7	0.70	0.32
	-9	0.65	0.70
	-10	0.85	1.00
20	0	2.07	0.25
	-1	1.98	1.26
21	0	2.25	0.42
	-3	2.36	0.58
	-5	2.50	0.55
	-9	2.69	0.28
	-11	2.85	0.30
	-13	3.01	0.68
22	0	0.62	0.57
	-2	0.92	0.74
	-4	0.97	0.90

Core	Sediment depth (ft)	Mean (phi)	Std. dev. (phi)
23	0	2.11	0.54
	-2	2.40	0.51
	-5	2.51	0.39
24-25	0	2.24	0.60
	-3	2.01	0.65
	-5	2.29	0.41
	-7	1.03	1.00
	-9	1.57	0.76
28	0	1.70	0.55
	-3	2.69	0.94
	-5	2.43	0.48
29	0	2.30	0.38
	-2	2.28	0.41
	-4	2.29	0.33
	-7	2.44	0.49
30	0	1.70	0.52
	-1	1.63	0.49
	-2	2.08	1.03
	-3	1.52	0.55
	-7	1.57	0.86
31A	0	2.00	0.42
	-3	1.86	0.38
	-5	2.31	0.49
32	0	1.94	0.49
	-3	1.96	0.52
	-5	2.28	0.70
33	0	2.26	1.18
	-2	1.59	1.16

Table B-2. RSA mean grain size and sorting values for selected core samples, converted to sieve equivalents.--Continued

Core	Sediment depth (ft)	Mean (phi)	Std. dev. (phi)
34	0	1.85	0.77
	-2	1.67	0.76
	-4	2.44	0.41
	-7	1.73	0.89
36	0	1.81	0.81
39-40	0	2.09	0.68
	-3	1.81	0.49
	-5	2.18	0.52
	-9	1.04	1.15
	-10	2.07	0.48
41	0	2.03	0.74
	-3	0.68	0.94
	-4	2.62	0.58
42	0	1.94	0.54
	-4	1.94	0.64
43	0	2.21	0.73
	-1	2.54	0.58
	-4	3.20	0.90
44	0	1.77	0.61
	-2	1.76	0.58
	-4	1.73	0.67
	-8	1.95	0.39
	-16	1.23	0.60
45	-4	2.51	0.45
	-8	0.77	1.06
46	0	1.52	0.78
	-1	2.31	0.89

Core	Sediment depth (ft)	Mean (phi)	Std. dev. (phi)
47	0	1.77	0.58
	-2	1.77	0.52
48	0	2.42	0.36
	-1	2.39	0.36
	-7	2.23	0.57
	-10	2.48	0.32
49	0	1.15	0.81
	-2	1.18	0.42
	-6	1.89	0.70
	-12	2.13	0.57
50	0	2.51	0.74
	-1	2.58	0.78
51	0	2.94	0.70
	-1	1.49	0.38
	-3	1.40	0.74
	-5	1.84	0.42
52	0	1.45	0.80
	-1	1.49	0.96
	-3	1.43	0.80
53	0	1.30	0.70
	-1	1.21	0.78
	-4	1.65	0.76
54	0	2.56	0.48
	-1	1.81	0.97
	-4	3.32	0.03
	-7	3.00	0.44

Core	Sediment depth (ft)	Mean (phi)	Std. dev. (phi)
55	-1	2.67	0.77
	-7	2.89	1.42
56	0	2.46	0.44
	-4	2.53	0.41
	-7	2.66	0.44
57A	0	1.92	0.38
	-1	1.67	0.46
	-2	1.52	0.38
	-4	1.50	
	-5	1.35	0.36
	-10	1.61	0.52
58	-1	2.26	0.36
	-4	2.41	0.38
	-7	2.24	0.54
	-8	2.32	0.48
	-15	2.71	0.44
	-16	2.55	0.58
60	-1	1.51	0.99
	-4	2.35	0.41
	-13	0.79	0.41
62	0	1.68	0.46
	-1	1.59	0.36
	-4	1.68	0.45
	-10	1.69	0.71
63	0	2.74	0.81
	-2	2.40	1.82
	-3	2.26	1.02
	-4	1.49	1.05

Core	Sediment depth (ft)	Mean (phi)	Std. dev. (phi)
65	0	1.54	0.93
	-2	1.98	0.62
68	0	1.75	0.71
	-2	2.24	0.49
	-5	1.84	0.89
69	0	1.94	0.71
	-1	2.00	0.64
	-3	2.36	0.58
71	0	2.29	0.61
	-2	2.16	0.49
	-4	2.50	0.41
	-7	2.17	0.57
	-15	2.57	0.65
72	0	0.94	0.61
	-2	1.10	0.52
	-4	1.14	0.45
	-10	1.67	0.28
73	0	1.19	1.25
	-1	2.43	0.93
74	0	0.46	0.74
	-1	1.22	0.70
	-4	1.48	0.73
	-7	1.11	0.68
	-13	0.94	0.68
77	0	2.06	0.35
	-1	1.91	0.60
	-4	2.07	0.42
	-7	1.97	0.44

Table B-3. Grain-size scales--soil classification (modified from U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977).

Unified Soils Classification	ASTM Mesh	mm Size	Phi Value	Wentworth Classification
COBBLE				BOULDER
		256.0	-8.0	
COBBLE				COBBLE
		76.0	-6.25	
COARSE GRAVEL				COBBLE
		64.0	-6.0	
COARSE GRAVEL				PEBBLE
		19.0	-4.25	
FINE GRAVEL				PEBBLE
	4	4.76	-2.25	
SAND coarse				PEBBLE
	5	4.0	-2.0	
SAND coarse				GRAVEL
	10	2.0	-1.0	
SAND medium				SAND very coarse
	18	1.0	0.0	
SAND medium				SAND coarse
	25	0.5	1.0	
SAND medium				SAND medium
	40	0.42	1.25	
SAND fine				SAND medium
	60	0.25	2.0	
SAND fine				SAND fine
	120	0.125	3.0	
SAND fine				SAND very fine
	200	0.074	3.75	
SILT				SAND very fine
	230	0.062	4.0	
SILT				SILT
		0.0039	8.0	
CLAY				CLAY
		0.0024	12.0	
CLAY				COLLOID

Field, Michael E.

Sediments, shallow subbottom structure, and sand resources of the inner continental shelf, central Delmarva Peninsula / by Michael E. Field. – Ft. Belvoir, Va. : U.S. Coastal Engineering Research Center ; Springfield, Va. : available from National Technical Information Service, 1979.

122 p. : ill. ; 27 cm. – (Technical paper – U.S. Coastal Engineering Research Center ; no. 79-2)

Bibliography : p. 106-112.

A data base of high-resolution seismic reflection, bathymetric, and side-scan sonar profilings was obtained in 1970 and 1974, along with 71 vibratory cores and 3 onshore borings, to assess sand resource potential for beach restoration and to establish the Quaternary evolutionary framework of the northern Delmarva inner shelf.

1. Continental shelf – Delmarva Peninsula. 2. Geomorphology – Delmarva Peninsula. 3. Seismic reflection. 4. Beach nourishment. I. Title. II. Series: U.S. Coastal Engineering Research Center. Technical paper no. 79-2.

TC203 .U581tp no. 79-2 627

Field, Michael E.

Sediments, shallow subbottom structure, and sand resources of the inner continental shelf, central Delmarva Peninsula / by Michael E. Field. – Ft. Belvoir, Va. : U.S. Coastal Engineering Research Center ; Springfield, Va. : available from National Technical Information Service, 1979.

122 p. : ill. ; 27 cm. – (Technical paper – U.S. Coastal Engineering Research Center ; no. 79-2)

Bibliography : p. 106-112.

A data base of high-resolution seismic reflection, bathymetric, and side-scan sonar profilings was obtained in 1970 and 1974, along with 71 vibratory cores and 3 onshore borings, to assess sand resource potential for beach restoration and to establish the Quaternary evolutionary framework of the northern Delmarva inner shelf.

1. Continental shelf – Delmarva Peninsula. 2. Geomorphology – Delmarva Peninsula. 3. Seismic reflection. 4. Beach nourishment. I. Title. II. Series: U.S. Coastal Engineering Research Center. Technical paper no. 79-2.

TC203 .U581tp no. 79-2 627

Field, Michael E.

Sediments, shallow subbottom structure, and sand resources of the inner continental shelf, central Delmarva Peninsula / by Michael E. Field. – Ft. Belvoir, Va. : U.S. Coastal Engineering Research Center ; Springfield, Va. : available from National Technical Information Service, 1979.

122 p. : ill. ; 27 cm. – (Technical paper – U.S. Coastal Engineering Research Center ; no. 79-2)

Bibliography : p. 106-112.

A data base of high-resolution seismic reflection, bathymetric, and side-scan sonar profilings was obtained in 1970 and 1974, along with 71 vibratory cores and 3 onshore borings, to assess sand resource potential for beach restoration and to establish the Quaternary evolutionary framework of the northern Delmarva inner shelf.

1. Continental shelf – Delmarva Peninsula. 2. Geomorphology – Delmarva Peninsula. 3. Seismic reflection. 4. Beach nourishment. I. Title. II. Series: U.S. Coastal Engineering Research Center. Technical paper no. 79-2.

TC203 .U581tp no. 79-2 627

Field, Michael E.

Sediments, shallow subbottom structure, and sand resources of the inner continental shelf, central Delmarva Peninsula / by Michael E. Field. – Ft. Belvoir, Va. : U.S. Coastal Engineering Research Center ; Springfield, Va. : available from National Technical Information Service, 1979.

122 p. : ill. ; 27 cm. – (Technical paper – U.S. Coastal Engineering Research Center ; no. 79-2)

Bibliography : p. 106-112.

A data base of high-resolution seismic reflection, bathymetric, and side-scan sonar profilings was obtained in 1970 and 1974, along with 71 vibratory cores and 3 onshore borings, to assess sand resource potential for beach restoration and to establish the Quaternary evolutionary framework of the northern Delmarva inner shelf.

1. Continental shelf – Delmarva Peninsula. 2. Geomorphology – Delmarva Peninsula. 3. Seismic reflection. 4. Beach nourishment. I. Title. II. Series: U.S. Coastal Engineering Research Center. Technical paper no. 79-2.

TC203 .U581tp no. 79-2 627

Field, Michael E.
Sediments, shallow subbottom structure, and sand resources of the inner continental shelf, central Delmarva Peninsula / by Michael E. Field. – Ft. Belvoir, Va. : U.S. Coastal Engineering Research Center ; Springfield, Va. : available from National Technical Information Service, 1979.
122 p. : ill. ; 27 cm. – (Technical paper – U.S. Coastal Engineering Research Center ; no. 79-2)
Bibliography : p. 106-112.
A data base of high-resolution seismic reflection, bathymetric, and side-scan sonar profilings was obtained in 1970 and 1974, along with 71 vibratory cores and 3 onshore borings, to assess sand resource potential for beach restoration and to establish the Quaternary evolutionary framework of the northern Delmarva inner shelf.
1. Continental shelf – Delmarva Peninsula. 2. Geomorphology – Delmarva Peninsula. 3. Seismic reflection. 4. Beach nourishment. I. Title. II. Series: U.S. Coastal Engineering Research Center. Technical paper no. 79-2.
TC203 .U581tp no. 79-2 627

Field, Michael E.
Sediments, shallow subbottom structure, and sand resources of the inner continental shelf, central Delmarva Peninsula / by Michael E. Field. – Ft. Belvoir, Va. : U.S. Coastal Engineering Research Center ; Springfield, Va. : available from National Technical Information Service, 1979.
122 p. : ill. ; 27 cm. – (Technical paper – U.S. Coastal Engineering Research Center ; no. 79-2)
Bibliography : p. 106-112.
A data base of high-resolution seismic reflection, bathymetric, and side-scan sonar profilings was obtained in 1970 and 1974, along with 71 vibratory cores and 3 onshore borings, to assess sand resource potential for beach restoration and to establish the Quaternary evolutionary framework of the northern Delmarva inner shelf.
1. Continental shelf – Delmarva Peninsula. 2. Geomorphology – Delmarva Peninsula. 3. Seismic reflection. 4. Beach nourishment. I. Title. II. Series: U.S. Coastal Engineering Research Center. Technical paper no. 79-2.
TC203 .U581tp no. 79-2 627