A Delaware Sea Grant Technical Report

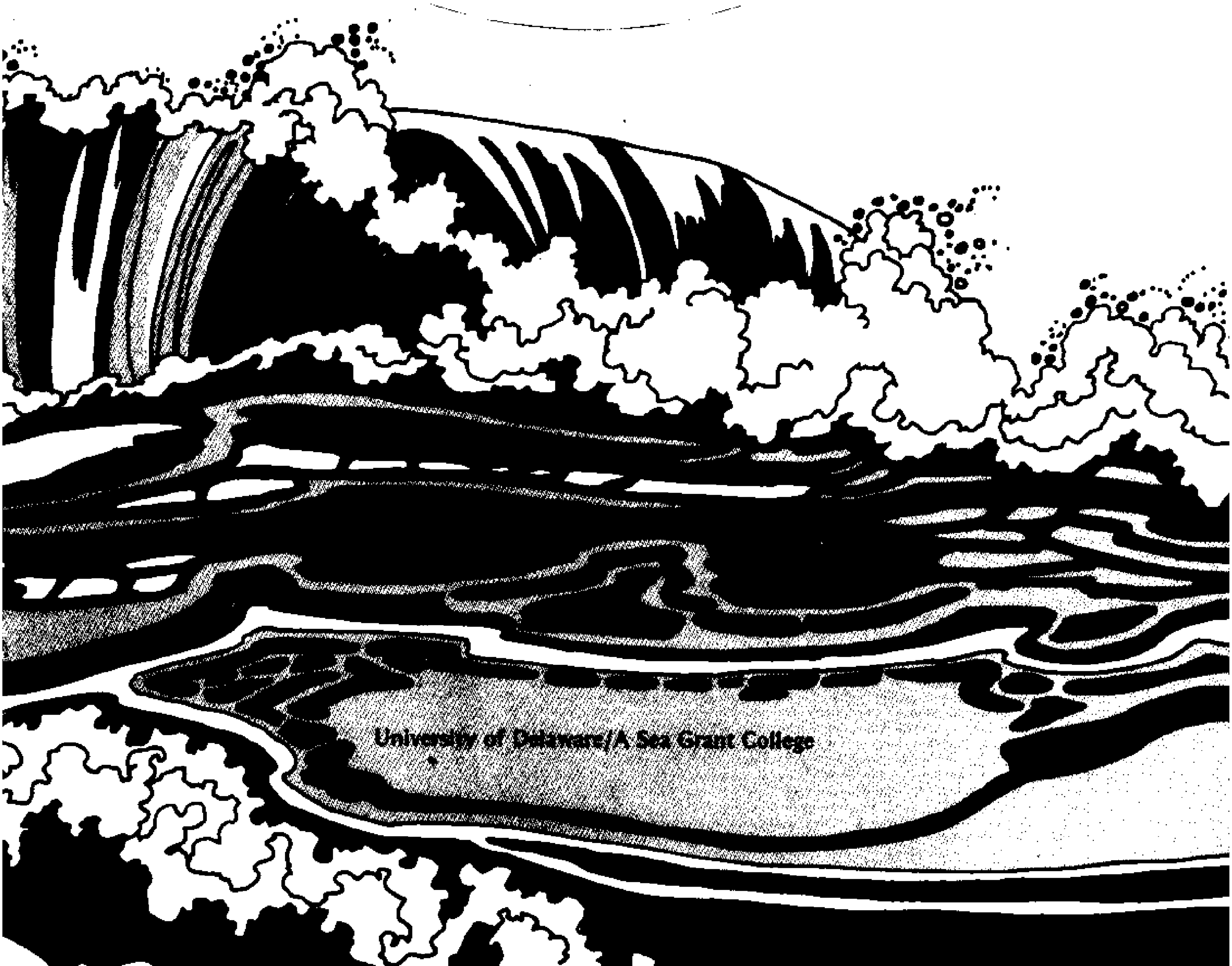
$6.00

INTERNAL SEDIMENTARY STRUCTURES, VERTICAL STRATIGRAPHIC SEQUENCES, AND GRAIN-SIZE PARAMETER VARIATIONS IN A TRANSGRESSIVE COASTAL BARRIER COMPLEX: THE ATLANTIC COAST OF DELAWARE

by

Chacko J. John

DEL-SG-10-77



$6.00

INTERNAL SEDIMENTARY STRUCTURES, VERTICAL STRATIGRAPHIC SEQUENCES, AND GRAIN-SIZE PARAMETER VARIATIONS IN A TRANSGRESSIVE COASTAL BARRIER COMPLEX: THE ATLANTIC COAST OF DELAWARE

by

Chacko J. John

DEL-SG-10-77

1977
Published by
The Delaware Sea Grant College Program
College of Marine Studies
University of Delaware
Newark, Delaware
19711

ACKNOWLEDGEMENTS

I wish to express my gratitude to Dr. John C. Kraft, Professor and Chairman, Department of Geology, University of Delaware, for having originally suggested the problem and for providing drill core data and photographs. His valuable guidance, support, and encouragement throughout the course of this study is much appreciated. I would also like to extend my sincere thanks and appreciation to Dr. R. B. Biggs, Dr. A. M. Thompson, Dr. B. P. Glass, and Dr. J. W. Wehmiller for their help and useful suggestions during this investigation, as well as to Mr. F. J. Swaye for the help he gave before he left the University in September, 1976.

Appreciation is extended to the Shell Development Company, Houston, Texas, for generously providing data for 20 drill cores resulting from their work in the area during 1964. These data include results of sediment analyses and electrical logs for 20 cores, 22 radiocarbon dates, and photographs of 13 cores. Thanks are also due to the U. S. Army Corps of Engineers and Richardson Associates, Newark, Delaware, for providing topographic maps of the barrier in addition to lagoonal and Rehoboth area core data. All these data were obtained through Dr. John C. Kraft. Gratitude is expressed to the Delaware Geological Survey for providing well logs Pj32-1-'59, Ni45-2-'61, and Ni35-5-'74, used in this study. The aerial photographic mosaic (Figure 14) was constructed from photographs obtained from the U. S. Department of Agriculture, Salt Lake City, Utah (formerly, Asheville, North Carolina).

Funds and facilities for the major portion of this work were provided by the Department of Geology, University of Delaware. Drilling data provided by Dr. John C. Kraft was partly supported by the University of Delaware, Office of Naval Research, Geography Programs, and NOAA Office of Sea Grant, Department of Commerce. The Society of Sigma Xi provided a small grant in aid of research.

The author gratefully acknowledges permission by the following to reproduce the diagrams mentioned below: American Geological Institute for Figure JC-II-1, from "The New Concepts of Continental Margin Sedimentation", edited by D. J. Stanley, 1969. This figure is from Lecture No. 2: "Shore zone sand bodies: barriers, cheniers, and beach ridges", by J. R. Curray (Figure 5 in this study); The American Association of Petroleum Geologists for Figure 3, from "Recognition of barrier environments", by

D. K. Davies, F. G. Ethridge, and R. R. Berg: American Association of Petroleum Geologists Bulletin, v. 55, No. 4, 1971, p. 550-565 (Figure 13 in this study); Edward Arnold (Publishers) Ltd., London, for Figure 3.9 (after Gierloff-Emden), from "Introduction to Marine Geology and Geomorphology", by C. A. M. King, 1974 (Figure 1 in this study).

Sediment analyses data accumulated over the past ten years from student projects in the course "Recent Sedimentary Environments of Coastal Delaware", taught by Dr. John C. Kraft at the Cape Henlopen laboratory of the College of Marine Studies, University of Delaware, have been selectively used in this investigation. Appreciation is also extended to all my student colleagues who helped with the drilling work, and to Roslyn Foner, who helped with editing and production of this book.

****

Editor's Note: The manuscript was typed and prepared entirely by the author, including the drafted figures.

PREFACE

The University of Delaware Department of Geology has been conducting a program of study of coastal processes and coastal sedimentary environmental relationships for the past ten years. Over the past three to four year period, we have been placing increasing emphasis upon the study of the washover process along the transgressing barrier coastline of Delaware. Studies of the washover process are extremely important in that it is by this process that the majority of destruction during coastal storms occurs. In addition, the washover process is an inherent part of normal geological processes which lead to the build-up and migration of transsive barrier systems. The University of Delaware Sea Grant Program has been particularly active in supporting these studies. Several projects are under way regarding the nature of the surficial washover process and its interface with other coastal sedimentary environments. However, to understand fully the nature of the washover processes on barrier island coasts, one must also examine the historical-geological perspective. In the Delaware coast, the barriers began forming in their present position from 2500 to 3750 years ago. Thus a study of the internal structure of the washover sedimentary deposits is extremely useful in understanding the washover mechanism and the importance of the process in a long-term continuum.

This report analyzes, probably in greater detail than anywhere else, the internal structure of a transgressive washover barrier. Because the author had available excellent drill core data, and the support necessary for these intensive studies, he was able to define the internal structure of washover barriers in considerable detail. Thus the reader can interpret more readily the significance of long-term intermittent washover events. This is valuable information for geologists studying barrier systems of this type and their facies interrelationships with other sedimentary environments. However, it is even more important to the developer, occupier, and builder in this area, and to geologists to use as models for recognition of transgressive sequences in the stratigraphic record. The information in this report should be of use for construction, coastal defense mechanisms, and coastal planning, in terms of the optimal utilization of our Delaware coastal zone.

John C. Kraft

John C. Kraft
Chairperson and Professor
Department of Geology
College of Arts & Science
and Professor of Marine
Geology, College of
Marine Studies

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE		PAGE

FIGURE PAGE

FIGURE | PAGE

FIGURE PAGE

FIGURE	PAGE

****

LIST OF TABLES

****

ABSTRACT

There is a vast volume of literature dealing with coastal barriers. Regressive barriers have been discussed more thoroughly than transgressive ones. Though it is presently more or less taken for granted that most barriers preserved in the stratigraphic record are regressive, a more detailed examination of the vertical sedimentary sequence may reveal thin transgressive sequences in what appears wholly as a regressive record. There is hardly any information available on the detailed internal organization of a transgressive coastal barrier complex which could serve as a model for recognition of similar sequences in the stratigraphic record. This study provides detailed information on the internal sedimentary structures, vertical stratigraphic sequences, and grain-size variations in a transgressive coastal barrier complex. A 27-km (16.8 miles) long stretch of a barrier complex on the Atlantic coast of Delaware, extending from Cape Henlopen in the north to Cottonpatch Hill in the south has been thoroughly investigated. This area lies on the northwest flank of the subsiding Baltimore Canyon Trough geosyncline of the Atlantic coastal plain-continental shelf. Thirty-two

transverse cross sections and one longitudinal cross section are presented showing the internal detail and stratigraphic sequences of this barrier complex. These sequences provide excellent illustrations of Walther's Law. Detailed sedimentary structures are presented, based on core photographs.

Four major variations of the coastal transgressive barrier complex found within the area of study include (1) the Cape Henlopen spit-beach-dune complex; (2) barrier against marsh; (3) beach against pre-Holocene (Pleistocene) highland; and (4) barrier-tidal delta-lagoon, which included a baymouth barrier and a tidal inlet section. Each of these variations has its own characteristic vertical sequences. Though this barrier complex is predominantly transgressive, a regressive situation exists at the Cape Henlopen spit, which is advancing rapidly into the deep waters of the Delaware Bay-Atlantic Ocean over marine-estuarine sediments. Sands of the barrier complex are medium to coarse grained, moderately well sorted, and negatively skewed. Sands at the spit are coarser than at other sections of the barrier complex. These sands are mostly derived by coastal erosion of the Atlantic shoreline, especially the highlands, and from offshore. Littoral transport carries sediment from south to north. Washovers are the dominant mechanism for landward barrier migration. Washovers and back-barrier marshes form part of the leading edge of the Holocene marine transgression along the Atlantic coast of Delaware as the barrier migrates landward and upward through space and time in response to coastal erosion and sea level rise.

Evidence from vertical stratigraphic sequences indicates that this barrier complex originated elsewhere further seaward and migrated to its present position. The greater thickness of transgressive sequence deposits in ancestral stream valleys crossing the barrier complex, compared to that at other sections of the barrier complex, gives it a better potential for preservation under a cover of marine sediments. Radiocarbon dates indicate that the present barrier sequence was formed within about the last 3,750 years. An important conclusion reached is that vertical sedimentary sequences of coarse sediments over fine sediments occur in both transgressive and regressive coastal environmental sequences. It follows that shapes of geophysical logs may be funnel-shaped, columnar-shaped, and/or possibly bell-shaped in an overall transgressive coastal environmental setting. Details presented in this study should aid identification of transgressive coastal barrier sequences in the stratigraphic record, and also in paleogeographic and paleoenvironmental reconstructions.

****

INTRODUCTION

GENERAL INFORMATION

Barrier complexes such as those found along the Eastern United States shoreline are significant features in many coastal regions of the world. The distribution of barrier and lagoon coasts around the world is shown in Figure 1. Though barrier complexes occur irrespective of climate or tidal conditions, they are best developed in lower latitudes and in areas of low to moderate tidal range (King, 1972). The best developed barrier complexes are in regions where the tidal range is less than two meters; barriers are rare where the tidal range exceeds three meters (Davies, 1973). Barriers are unequally distributed between continents. Cromwell (1971) made a survey of barrier coast distribution around the world and determined that 13.1 per cent (32,038 km) of the total world continental coastline of 243,775 km consisted of barrier coasts. Of this, North America has 10,765 km; Asia, 7,126 km; Africa, 5,984 km; South America, 3,302 km; Europe, 2,693 km; and Australia, 2,168 km. These results compare favourably with the ten to thirteen per cent proportion of barrier coasts to the worlds coastline as given by Leontyev (1965) and Zenkovich (1967).

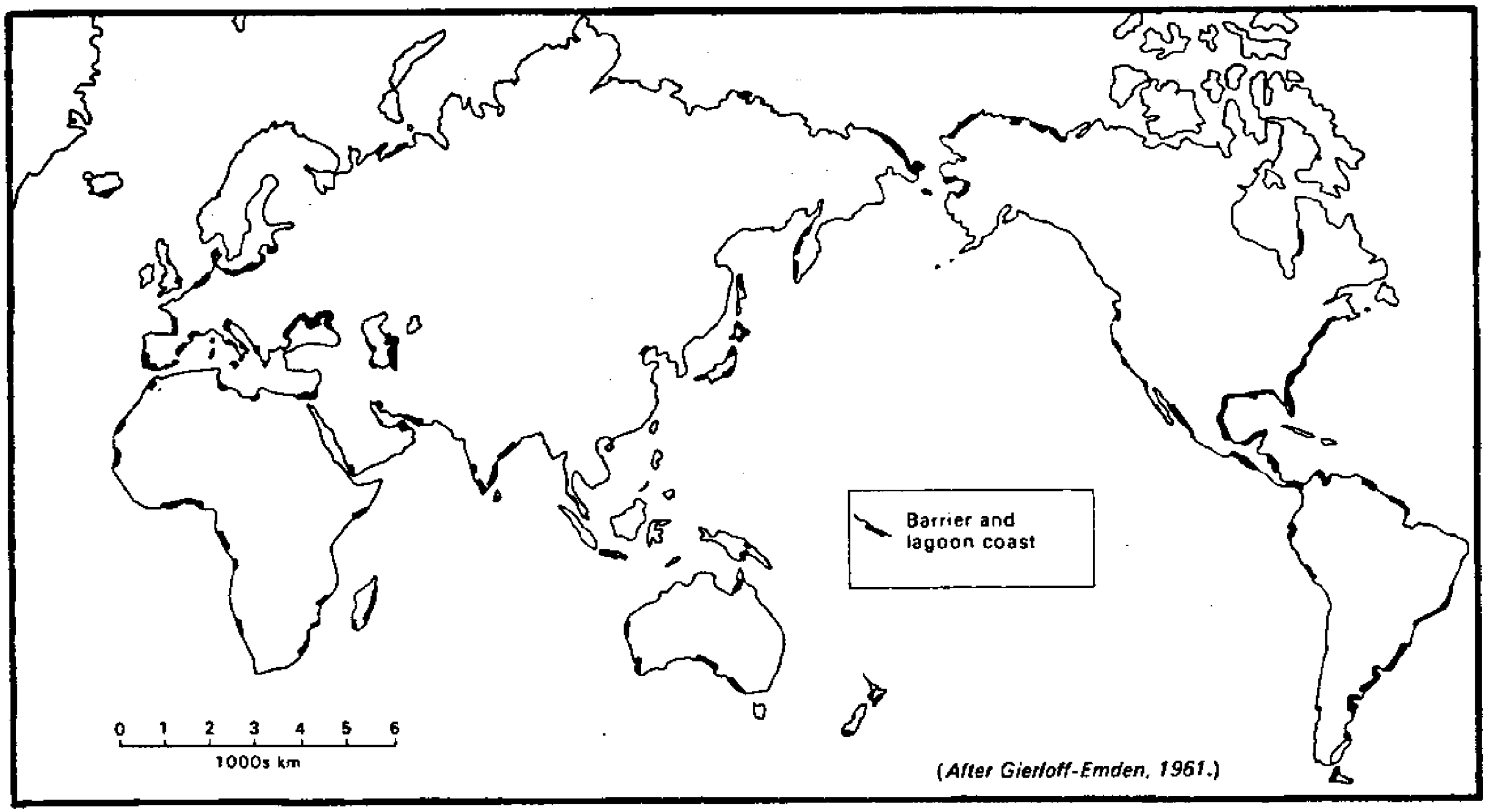


FIGURE 1. Map showing locations of barriers around the world. (From King, 1974, with permission of Edward Arnold, Publishers, London.)

For the purposes of this survey, Cromwell (1971) broadly defined a barrier-lagoon coast as including "all linear, detrital, topographic features along present coastlines which were less than 10 meters above sea level and which are impounding, or at one time have impounded, bodies of water between themselves and the mainland." An earlier survey by Berryhill, Dickinson, and Holmes (1969) had come up with different figures for barrier coast distribution around the world. This discrepancy was due to their using a more restrictive definition of barrier coasts (Cromwell, 1971). The interested reader is referred to King (1972) for a discussion on barriers from different parts of the world, and to Schwartz (1972, 1973) and Coates (1973) for a collection of significant papers on barriers and barrier-related features.

Barrier coastlines like the East and Gulf Coasts of the United States are situated between broad continental shelves and broad coastal plains. Usually, thick sections of Tertiary and Quaternary sediments are found in such areas which are subsiding continental margins. Hence this would suggest that subsiding geosynclinal type continental margins and thick sections of sediment are closely correlated with barrier coastlines (Shepard, 1960; Berryhill, Dickinson, and Holmes, 1969; Curray, 1969). An example of such an area is the Upper Delmarva and New Jersey area which is shown in

Figure 2. The barrier coastlines are distinctly seen as thin white strips bordering the Atlantic Ocean (right) and the Delaware Bay (top, middle). The entire drainage system of the area is also clearly seen in Figure 2.

AREA OF STUDY

The study area consists of a barrier complex situated on the Atlantic coast of Delaware. The location of the study area is indicated on the index map of the Atlantic coastal plain and continental shelf (Figure 3). It is adjacent to Delaware Bay (a drowned river valley system) and lies on the northwestern side of the subsiding Baltimore Canyon Trough geosyncline situated on the Atlantic coastal plain-continental shelf (Kraft, Sheridan, and Maisano, 1971). The area stretches from Cape Henlopen in the north to Cotton-patch Hill in the south. The total length of this coastal barrier complex is 27 km (16.8 miles). The eastern side is bounded by the Atlantic Ocean, and the limit of the study area on this side is approximately marked by the -18 ft. (-5.5 m) contour line. The western boundary extends slightly beyond the transgressive sands of the barrier complex. A block diagram of the study area is shown in Figure 4.

This barrier complex is characterized by the following component elements (Kraft, 1971a, 1971b):
(1) A spit system developed at Cape Henlopen. The Cape Henlopen spit includes a beachface, berm, a dune system,

FIGURE 2. High altitude (914 km) LANDSAT-I (ERTS-I) photograph of the Upper Delmarva Peninsula and New Jersey.

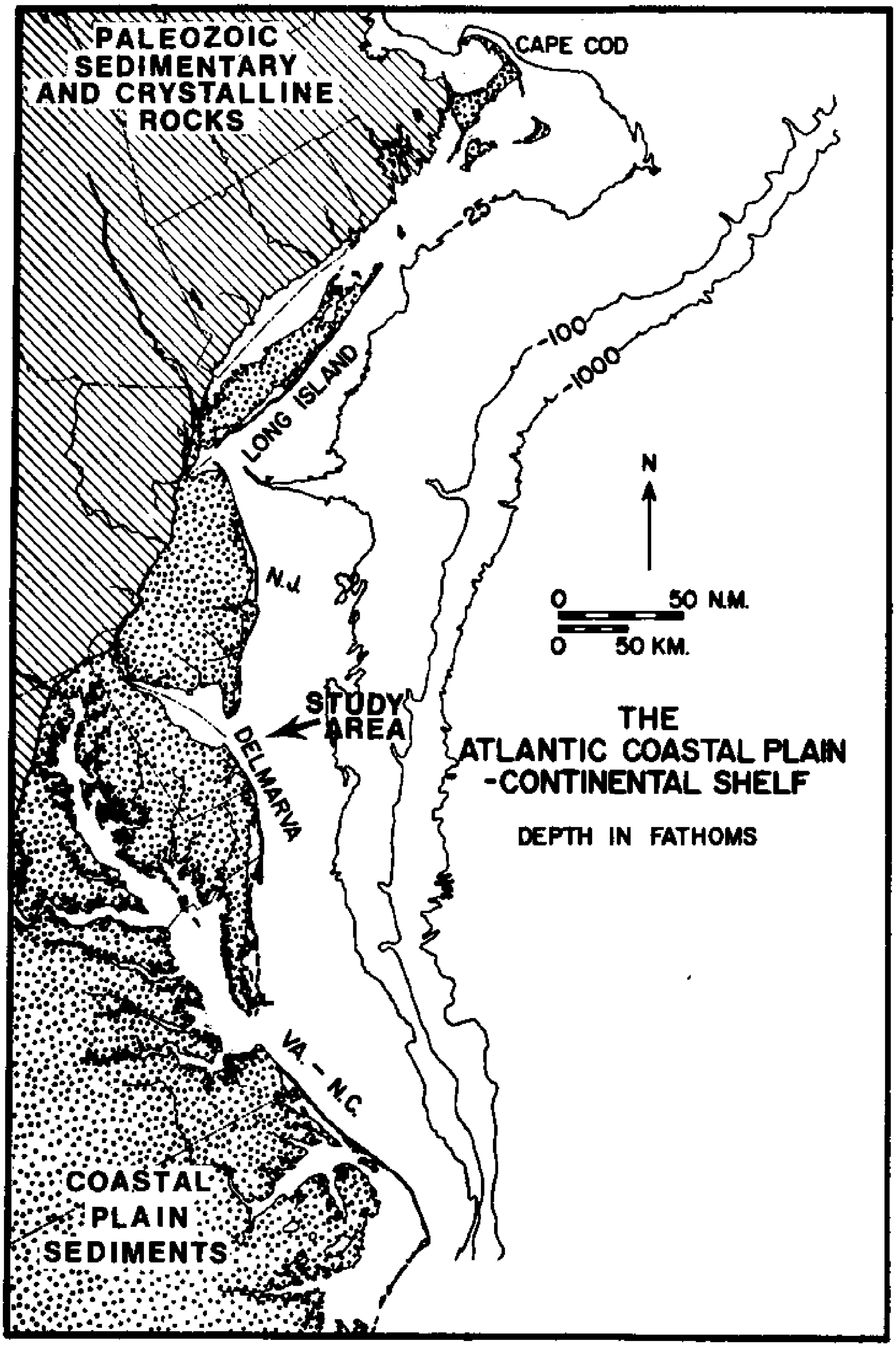


FIGURE 3. Index map to the Atlantic coastal plain-continental shelf (after Kraft and John, 1976), showing location of the study area.

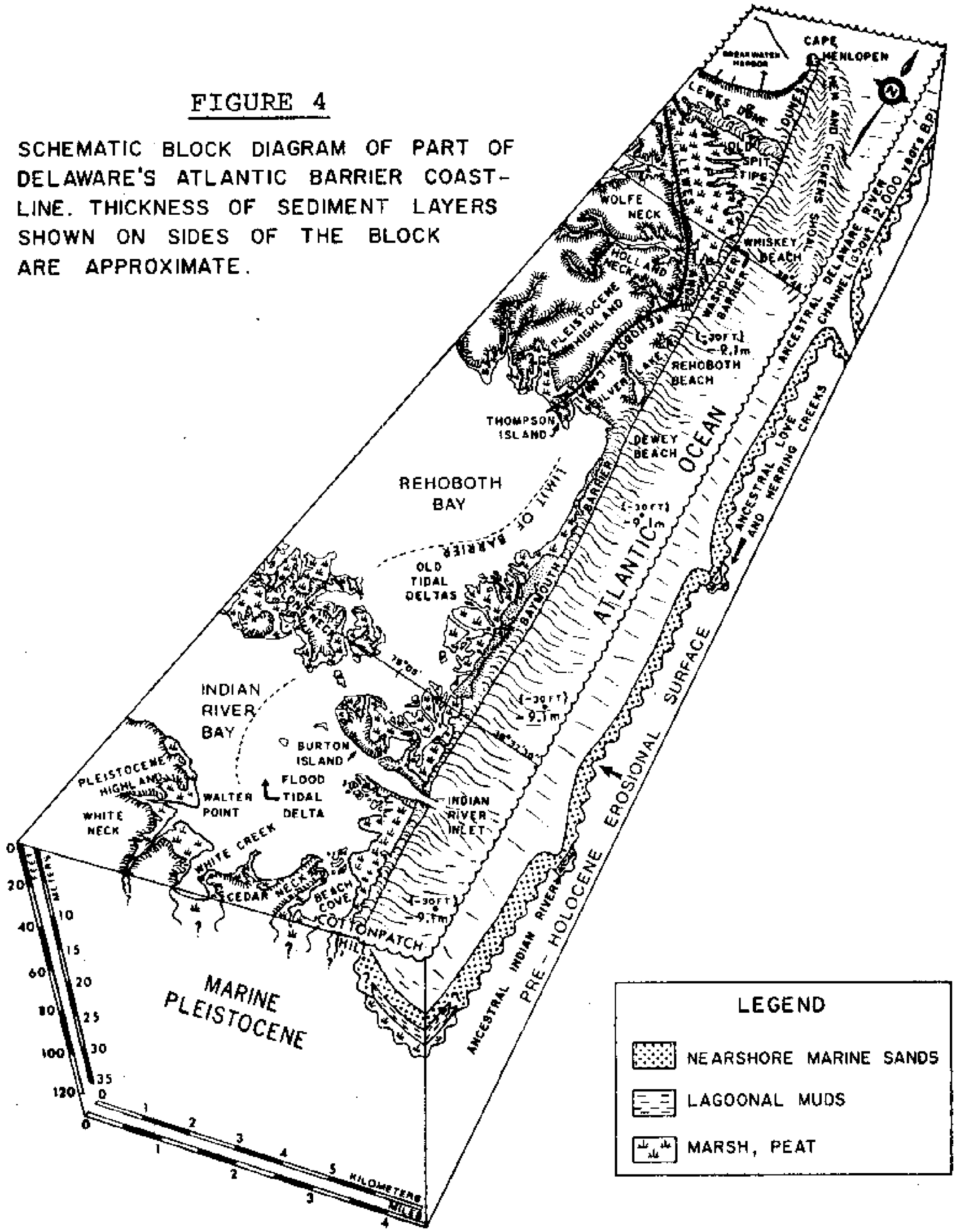


FIGURE 4

SCHEMATIC BLOCK DIAGRAM OF PART OF DELAWARE'S ATLANTIC BARRIER COASTLINE. THICKNESS OF SEDIMENT LAYERS SHOWN ON SIDES OF THE BLOCK ARE APPROXIMATE.

and a back-barrier tidal flat with giant sand waves and swash bars.

(2) A washover barrier at Whiskey Beach.

(3) A narrow beach abutting against the pre-Holocene (Pleistocene) highland at Rehoboth Beach and Cottonpatch Hill.

(4) A linear baymouth barrier extending from South Rehoboth (Dewey Beach) to the southern end of the study area, that is, up to Cottonpatch Hill. The continuity of this barrier is broken by the Indian River Inlet. Hence this linear barrier has also a tidal delta sequence. It is separated from the mainland by a lagoon system comprising Rehoboth Bay and Indian River Bay.

PURPOSE OF STUDY

Though this area has been studied in great detail, all the investigations so far have been mainly surficial in nature. The previous work dealt essentially with the coastal changes taking place at present, processes responsible for these changes, and the growth of the Cape Henlopen spit (Kraft, 1971a, 1971b). Geological literature abounds with studies on sedimentary structures, but so far there has been no detailed study done in this area, or in any other, on the internal sedimentary structure organization and stratigraphic sequences in a transgressive coastal barrier complex. There are hardly any three-dimensional data available as can be seen from the studies of Rittenhouse (1961), Potter (1967), and Pettijohn, Potter, and Siever (1972). The two investigations which come closest to this one, but on a regressive barrier, are those of Bernard, LeBlanc, and Major (1962), and Davies, Ethridge, and Berg (1971), on the Galveston barrier, Texas. These studies will be discussed in some detail later in this report. Hence the main purposes of this investigation are as follows:

(1) To accumulate detailed information regarding types and distribution of sedimentary structures in a transgressive coastal barrier complex.

(2) To investigate the detailed stratigraphic-environmental sequences and their variations in different areas of the coastal transgressive barrier complex.

(3) To determine the feasibility of distinguishing various sub-environments of the barrier (beachface, berm, dunes, washover) on the basis of sedimentary structures and variations in grain-size parameters.

A study of this nature will provide a greater understanding of modern coastal barrier sedimentation. Ancient buried barriers are potential traps for concentration of petroleum as emphasized by Bass (1934). In view of this, a greater understanding of present-day barrier complexes and their internal features should be of great use to petroleum geologists and others, especially in identifying paleoenvironments.

TERMINOLOGY

The study of constructional coastal features like barriers has in the past suffered from terminological difficulties. In general, however, it appears at present that emerged features are referred to as "barrier islands", "barrier beaches", "barriers", and "spits"; submerged features have been termed "bars" (Shepard, 1952, Price, 1951). Shepard (1952) defined a barrier beach as "a single elongate sand ridge rising slightly above the high tide level and extending generally parallel with the coast, but separated from it by a lagoon." Leontyev and Nikiforov (1965) quote Zenkovich (1957) as giving the following definition of a barrier beach: "... long narrow strips of detritus raised above sea level and extending at some distance from the original land parallel to the general trend of the coast." Curray (1969) defined the terms "beach", "barrier", and "barrier complex" as follows:

> A beach is a sedimentary deposit, generally of sand or gravel, formed principally by wave action along the shore of a body of water.
>
> A barrier is a sedimentary complex, generally of sand and gravel separating an open body of water such as the sea or ocean floor from an enclosed or partially enclosed body of water such as the lagoon.

> A barrier complex may commonly consist of a shoreface, a beach, dunes, sand flat or barrier flat and a lagoon beach. A barrier may form a barrier island, barrier spit, or bay barrier depending on whether it is in the form of an island, is attached to the mainland at one end, or is attached at both ends.

A diagrammatic representation of these terms as given by Curray (1969) is shown in Figure 5. Curray's definitions have been adopted in this report.

METHODS OF INVESTIGATION

As this is essentially a study of subsurface geology, this work is based on cores taken along the length of the barrier complex in connection with coastal geologic work and course work conducted by the Department of Geology, University of Delaware during the last decade under the guidance of Dr. John C. Kraft. A truck-mounted auger drilling rig owned and operated by the University of Delaware-Water Resources Center, was used for obtaining the auger cores. The Shell Development Company, Houston, Texas, provided photographs for 13 cores, and lithologic, sedimentologic, and electric log data, and 22 radiocarbon dates for 20 rotary drill cores taken by them in 1964 in this area. The U. S. Army Corps of Engineers and Richardson Associates, Newark, Delaware, provided information on lagoonal and Rehoboth highland cores.

Stratigraphic cross sections provide most

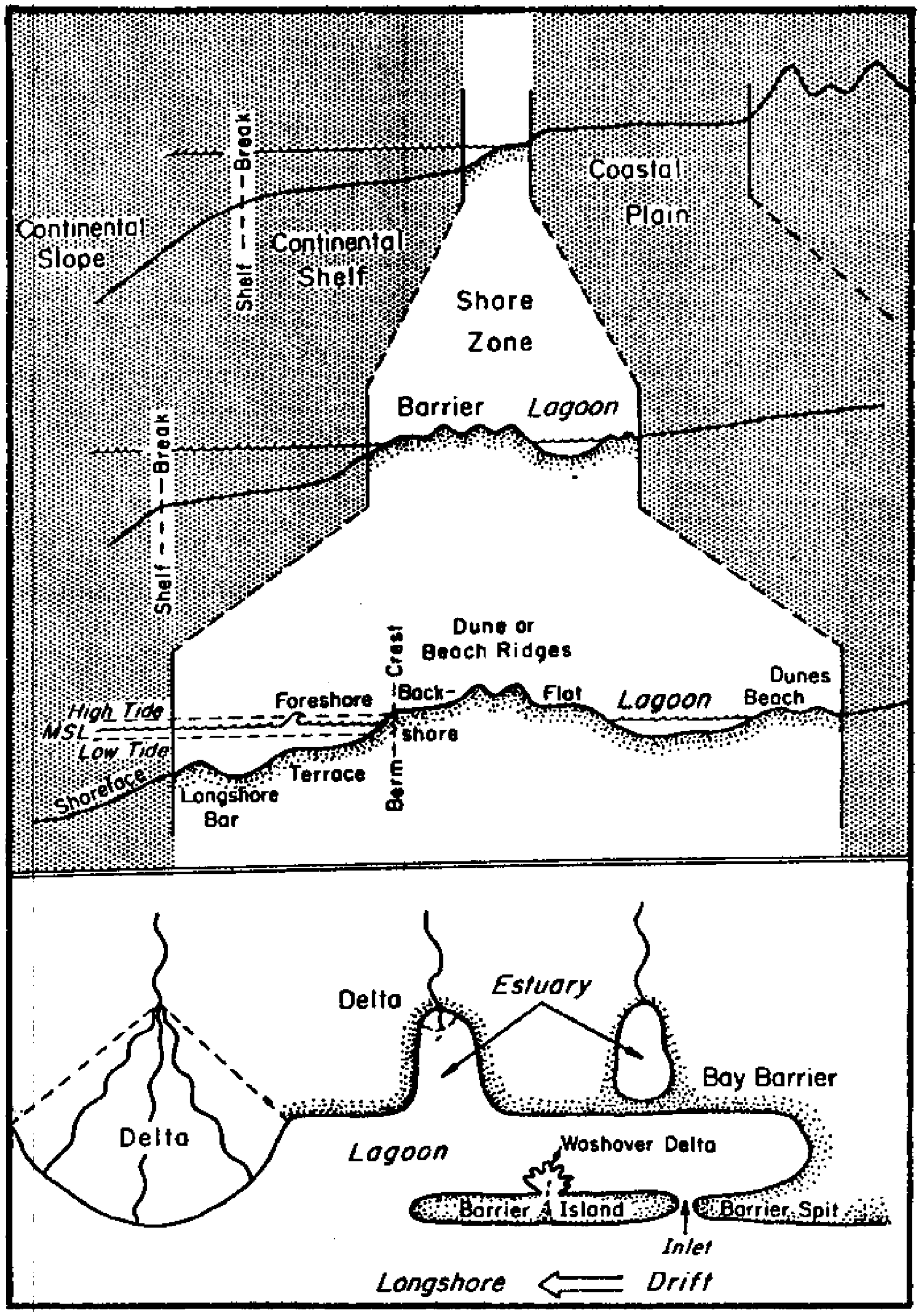


FIGURE 5. Diagrammatic illustration of the shore zone with some of its component parts, and coastal terminology. (From Curray, 1969, with permission of the American Geological Institute.)

information regarding internal organization of a sand body. 32 sub-parallel cross sections at right angles to the length of the barrier complex, and 1 longitudinal cross section parallel to the barrier were drawn. Detailed topographic maps with a contour interval of 2 ft. (0.6 m), provided by the U. S. Army Corps of Engineers and Richardson Associates, Newark, Delaware, and Soils maps were used in the construction of these 33 cross sections.

Sediment grain-size data accumulated over the previous years, mainly as a result of course work conducted by Dr. John C. Kraft in "Recent Sedimentary Environments of the Delaware Coast", were used selectively in addition to such work done by the author. The initial visual field descriptions of the cores have been verified and corrected by sediment-size analyses wherever possible. The grain-size scale used in this study is given as Appendix I. Analysis of sand core samples were done using the U. S. Standard sieve nest at full phi unit intervals, and the Rotap shaker in accordance with standard procedures described by Folk (1968) and Royse (1970). Silt and clay percentages in the sediment sample were determined by standard wet sieving and pipette analysis as described by Guy (1969). Cumulative curves were then plotted from raw sediment grain-size data thus obtained, thereby indicating grain-size diameters and respective percentages.

Grain-size parameter data provided by the Shell Development Company were based on the work of Trask (1932) and Inman (1952), and these have been used in this study. Inman parameters are used by the U. S. Army Coastal Engineering Research Center (1973) in their work. The presently more commonly used grain-size parameters were suggested by Folk and Ward (1957) and Folk (1968) and are referred to as "Folk parameters". Since the results obtained by using Folk parameter formulae are not significantly different from those obtained by using Inman formulae, as far as this study is concerned, it does not warrant re-calculation of existing Inman parameter data according to Folk's system. The parameters compared in this study are the median (Md_{ϕ}), Trask's coefficient of sorting (S_o), graphic standard deviation (σ_G), and graphic skewness (Sk_G). A short discussion of each of these parameters is given below.

<u>Median (Md_{ϕ})</u>: The value of the Inman phi median is given by the 50<u>th</u>. percentile on the cumulative size frequency curve. Half of the given sample by weight will have a coarser grain size than this value, and the other half will be finer.

<u>Trask's coefficient of sorting (S_o)</u>: This parameter is defined as the square root of the ratio of the first and third quartiles, as suggested by Trask (1932). Millimeter

values are used.

$$S_o = \sqrt{\frac{Mm\ 25}{Mm\ 75}}$$

When the value of the coefficient so calculated is unity, the sediment is considered to be perfectly sorted. Well sorted sediments have a value of less than 2.5, normally sorted sediments have a value of about 3.0, and poorly sorted sediments have values greater than 4.5 (Royse, 1970). Pettijohn (1957) considered these verbal limits to be very high.

Graphic standard deviation (σ_G): The Inman graphic standard deviation is similar to Trask's coefficient of sorting in that it is an index of the degree of sorting, but is given in phi units. Its value gives a measure of the limits to which the sample spreads from the mean.

$$\sigma_G = \frac{\phi 84 - \phi 16}{2}$$

Though Folk (1968) used a modified formula $\left(\frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6} \right)$ in order to cover a greater portion of the cumulative curve than given by Inman's formula, his suggested verbal limits for sorting are equally applicable to Inman parameter values in this study, and are given below:

Under .35ø, very well sorted

.35ø - .50ø, well sorted

.50ø - .71ø, moderately well sorted

.71ø - 1.0ø, moderately sorted

1.0ø - 2.0ø, poorly sorted

2.0ø - 4.0ø, very poorly sorted

over 4.0ø, extremely poorly sorted (Folk, 1968)

Folk (1968) has found that dune and beach sand sorting values in Texas generally range from .25ø to .35ø.

Graphic skewness (Sk_G): The Inman graphic skewness represents a function of the displacement of mean grain size (given by the average of the ø16 and ø84 points) from the median grain size. It is geometrically independant of sorting, and is a measure of the symmetry of the grain-size curve.

$$Sk_G = \frac{\phi 16 - \phi 84 - 2\phi 50}{\phi 84 - \phi 16}$$

The absolute limits of skewness ranges from +1.00 to -1.00. Perfectly symmetrical curves have $Sk_G = .00$. A negative skewness value is obtained if the sediment sample has an excess of coarse material; an excess of fine material in the sample will give a positive skewness value. Verbal limits of skewness set by Folk (1968) using the formula $\frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$ in order to cover a greater portion of the cumulative curve are as follows:

+1.0 to +.30, strongly finely skewed

+.30 to +.10, fine skewed

+.10 to -.10, nearly symmetrical

-.10 to -.30, coarse skewed

-.30 to -1.0, strongly coarse skewed (Folk, 1968)
The above verbal limits have been adopted for Inman graphic skewness values used in this investigation.

Detailed sedimentary structures of the barrier complex as seen in the cores were drawn using photographs of 13 rotary drill cores provided by the Shell Development Company. An ordinary reading lens with a diameter of 8.9 cm (3½ inches) was used to study structural details seen in the photographs, and these were reproduced by line drawings.

****

REVIEW OF RELATED CONCEPTS

CHARACTERISTICS OF BARRIERS

Barriers, according to Shepard (1960) are characterized by the following features:

> (1) An outlying belt of sand separated from the mainland by a shallow body of water, (2) a much greater length than width, and (3) a straight seaward margin in contrast to a lobate, crenulate or cuspate lagoonal shoreline. The typical barrier has three major divisions: (1) an outer beach with a broad berm, (2) a belt of dunes, and (3) an inner flat or marsh. The dune belt may include a series of low ridges, commonly 5 to 20 feet high, which are not easily differentiated from beach ridges, or the dunes may consist of a broadly encroaching belt.

Berryhill, Dickinson, and Holmes (1969) state that the length to width ratio of barrier islands is usually greater then 10:1 and they are generally less than 18.3 m (60 ft.) in thickness. Shepard (1960) found that the sand barriers of the Northern Gulf Coast have a width of several kilometers and thicknesses from about 6 to 8 m (20 to 60 ft.)

Shepard (1960) stated that larger barriers had at least four facies: (a) beaches, (b) dune belts, (c) barrier flats or marshes, and (d) inlets. Sediment characteristics and structures of each of these facies are distinctive. A somewhat similar set of morphologic units was observed by Berryhill, Dickinson, and Holmes (1969) at Padre Island, Texas. Shepard (1960) found Gulf Coast beach sands to have lower grain roundness than the dune sands. Calcareous aggregates were found in some cases in barrier flats and marshes. The latter environments also had a higher silt content than sediments from the other barrier environments. The inlets were characterized by mixed Bay and open Gulf organic remains and intermediate sand content.

SOURCE OF SAND FOR BARRIERS

It is generally believed that the major sources of sand for barrier complexes are the continental shelf, eroding coastal highlands, and rivers. Shepard (1960) has observed that when shelf sands are covered by mud, the barriers have been continually eroded. Necessary prerequisites for barrier formation according to Zenkovich (1962, 1964) and Leontyev and Nikiforov (1965) are (a) abundant reserves of unconsolidated material; (b) a gently sloping nearshore bottom which is above the profile of equilibrium for the prevailing hydrodynamic conditions; and (c) movement normal to the coast of material derived from the sea floor. Under these conditions, a recession of relative sea level causes barrier formation, whereas a rise in relative sea level causes barrier erosion. Leontyev and Nikiforov (1965) do not consider longshore transport as a major factor for sand supply and barrier formation. The barrier complex of the study area obtains a major portion of its sediments by erosion of previously deposited sediments, in the landward direction.

Pierce (1969) studied the sediment budget for a 100-km (62.2 miles) stretch of barrier coastline in the Southeastern United States and concluded that the major source of sand here was the continental shelf, or outcrops of poorly consolidated Tertiary rocks thinly covered by Holocene sediments. Studies by Zenkovich (1964, 1969, 1971) along the coastline of the Soviet Union reveal evidence for abundant sediment delivery from the sea bottom to the shore. Investigations conducted on the East Gippsland barrier coast of Australia by Bird (1961, 1969, 1971) have determined that the bulk of sand for these barriers has been eroded or collected from the sea floor and transported shorewards. Other sources of sediment supply for the East Gippsland barriers are longshore drift, erosion of adjacent parts of the coast, and fluvial sediment; locally in some desert parts the sand is blown from land into the sea and then transported to the coast. Bird (1971) states that "the concept of landward sweeping of sea floor sediments during the post glacial marine transgression helps to explain many aspects of Australian beach and barrier formations." Shepard (1973) expressed similar views on the subject, and added that in some tropical areas the sand was mostly derived from the remains of marine organisms, and in other areas glacial outwash could be a major source of sand. The barrier island off Rhode Island is formed of reworked glacial sediments (Dillon, 1970). Henry and Hoyt (1968) determined that sand for the Georgia coastal barriers was mainly derived from offshore during the Holocene transgression. Fischer (1961) found that sand for the beaches on the Atlantic coast of New Jersey was partly derived from the sea floor, and partly from the coastal highlands towards the north. Barrier beaches in the Southern Gulf of St. Lawrence are mostly supplied with sand from offshore areas (Owens, 1974). Further proof for the continental shelf being the major source of sand to barrier beaches comes from the mineral assemblage studies in beach sands of New Jersey by McMaster (1954), the Northwest Gulf of Mexico by van Andel and Poole (1960), and the South Atlantic coast (Georgia Bight) by Giles and Pilkey (1965). Detrital phosphate analysis in the sands of the Georgia and Carolina coasts by Pevear and Pilkey (1966) support the same conclusion, as no phosphate was found in nearby river sands but only in the shelf and nearshore sands.

However, longshore drift is the major sand source for the barriers of North and South Holland as revealed by van Straaten's (1965) investigation. Kwon (1969) studied the source of barrier sediments of the Northern Gulf Coast and found the rivers to be the major supplier of sediments. Next in importance was the erosion of coastal Pleistocene highland deposits, and to some extent the large estuaries in the area. Littoral transport was the main factor in transporting sand from the source to initiate or maintain barrier development in this region. Longshore drift is responsible for formation of parts of the barrier chain along the Virginia-North Carolina "Outer Banks" coastline (Fisher, 1967). A short discussion on sources of sand for barriers is provided by Swift (1969). Schuberth (1970) and Yasso and Hartman (1975) have pointed out that coastal erosion of the Montauk headlands has provided most of the sand for the barrier complex on the southern shore of Long Island, New York.

From the above review of research work on the subject, it seems that the major source of sand supply to barriers still remains a much debated question. Both the continental shelf as well as coastal erosion combined with longshore drift appear to be major sources, one predominating over the other locally in different places and conditions. Sand for the barrier complex of this study area is believed to come from (a) erosion of earlier Holocene and pre-Holocene ridges exposed on the inner shelf sea floor as the Holocene transgression proceeds landward (Sheridan, Dill, and Kraft, 1974); (b) continuing coastal erosion by waves of present barrier lithosomes as evidenced by the marsh outcrops in the surf zone (Kraft, 1971a, 1971b); eroded material is delivered to the barrier complex by littoral transport, tidal currents, waves, and storm overwash; (c) erosion of abutting Pleistocene highlands, like that at Rehoboth Beach (Kraft, 1971a, 1971b); (d) fluvial sources, that is, sediment brought into the lagoons and bays by rivers and streams from inland areas; also some amount of sediment from Delaware Bay by tidal action; and (e) eolian sand blown in from inland dunes during periods of high offshore winds.

ORIGIN OF BARRIERS

The origin of barriers is one of the most controversial topics in coastal geomorphology today and the question still remains unresolved. Hoyt's (1967a) discussion provides a good introduction to the subject, and also sets forth four conditions that any theory of barrier origin must satisfy. These are (Hoyt, 1967a):

> (1) The absence of open marine or shallow neritic sediments and fauna landward of the barrier; (2) the ability of barrier island systems to reform after they have been terminated by an emergence; (3) the absence of a worldwide, higher than present sea level during the Holocene; and (4) development and maintenance of a barrier system during a slow rise in sea level.

The three different explanations given for barrier origin are (a) building up of submerged offshore bars above water level; (b) inlets cut through spits; and (c) submergence of pre-existing coastal beach or dune ridges (Schwartz, 1971).

The earliest ideas on the subject were those of de Beaumont (1845), Gilbert (1885), and McGee (1890). De Beaumont believed that waves excavated the sea floor and piled up the sand so produced into an offshore ridge, which was later built above sea level to become a barrier. Gilbert (1885) was of the view that longshore transport carried sediments and deposited them as a spit along the shore. Later, gaps were cut through such extended spits by storm waves, producing barrier islands. McGee (1890) proposed that partial submergence of former beach ridges due to sea level rise along a gently sloping coastal plain caused barrier development with lagoons on the landward side due to associated flooding. Merrill (1890) expressed views similar to those of de Beaumont, but was uncertain regarding the process which brought the submarine bars above water level, and considered continental elevation as a possible cause. De Beaumont's theory was also applied by Davis (1896) in his study of the Cape Cod shoreline.

The pros and cons of these three original hypotheses of barrier formation were discussed until Johnson's (1919) classic work ended the controversy temporarily. Johnson (1919) rejected McGee's (1890) theory on the ground that it implied formation of bars at the edge of the mainland, and discussed the theories of de Beaumont and Gilbert. Johnson analyzed actual offshore profiles across barriers, and after comparing it with the hypothetical profiles of de Beaumont and Gilbert concluded that his evidence favoured de Beaumont's theory. Zenkovich (1967) commenting on de Beaumont's theory stated that "on the basis of modern information this view may be regarded as correct." However, Zenkovich (1957, 1967) was not entirely convinced of the correctness of Johnson's (1919) profile analysis, but thought that it did however suggest that the de Beaumont - Johnson idea was true in most cases. Price (1963b) has observed the emergence of offshore bars produced by very high storm tides when conditions returned to normal. Fisher (1973) re-examined and discussed Johnson's (1919) and other profiles with the latest available data. He found that offshore profiles of barrier and non-barrier areas were not significantly different. Fisher also believed that barriers developed on shorelines of submergence, and not on shorelines of emergence as proposed by de Beaumont and Johnson.

At the time Johnson (1919) put forward his ideas on the origin of barriers he did not have any data from borings through barriers. Virtually all such subsequently available drilling data favor the submergence idea, combined with an upward growth of barriers during the late Holocene sea level rise. Results of investigations on the Texas barrier coastline by Shepard and Moore (1955a, 1955b), LeBlanc and Hodgson (1959), Fisk (1959), Rusnak (1960); on the Georgia coast by Hoyt and Hails (1967); on the Dutch coast by van Straaten (1965), and elsewhere in the world, provide evidence against barrier development from submarine bars.

Shepard (1963) attributed barrier formation to a slowing down of the rate of sea level rise after the climatic optimum. This view is also supported by Jelgersma (1961) for barrier development on the coast of Holland. Leontyev and Nikiforov (1966) and Leontyev (1969) state that submarine barrier bars formed when the oceans were at their highest level (3-5 m higher than present) during the Flandrean transgression (5000-6000 years ago). Later, recession of relative sea level caused emergence of these barrier bars above the surface. However, this view is not compatible with Hoyt's (1967a) conditions for barrier formation outlined earlier. Other investigators (Price, 1963b; Zenkovich, 1969) have also suggested that world-wide barrier formation was caused either by the Holocene transgression as a whole, or by the Flandrean high sea level stand. Hoyt, Henry, and Weimer (1962) relate the development of the Georgia coastal barriers to the complex history of late Quaternary sea level fluctuations. Curray (1964, 1969) linked formation of barriers to the eustatic rise of sea level at the end of the Pleistocene glaciation, and estimated that barriers grew upward during transgressions. The latter point is also supported by Hoyt (1967a, 1968b). Once formed the barriers are subject to seaward and lagoonal growth (Shepard, 1973). Seaward growth of barriers is documented by Psuty's (1965, 1966) studies on the beach-berm ridges of Tabasco in Mexico. Barrier extension on the lagoonal side takes place by overwash sediment deposition during storms, tidal delta formation, and wind deposition in marshes on the lagoon side (Shepard, 1973).

Fisher (1967) was convinced from his study of the Virginia-North Carolina (Outer Banks) barrier coastline that barriers developed along a shoreline of submergence. He observed that the Middle Atlantic barrier coastline of the United States consisted of five coastal compartments (1) North Carolina-Virginia coast; (2) Delmarva coast; (3) New Jersey coast; (4) Long Island coast; and (5) Cape Cod coast. These compartments are separated from each other by the estuaries of Chesapeake Bay, Delaware Bay, New York Harbor, and Block Island Sound (Swift, 1969). Within these five compartments, regarded by Fisher (1967) as classic examples of barrier formation by distally prograding spits, there are four distinct units. "They are

(1) an updrift spit or cuspate foreland; (2) a slightly convex seaward headland; (3) a slightly concave-convex barrier island unit; and (4) one or more strongly concave units of barrier islands" (Fisher, 1967). However, Hoyt and Henry (1967) were doubtful whether the relict beach ridges which Fisher (1967) had used as evidence for distal progradation of the Carolina Banks, were deposited as spit tips or as sides of migrating inlets.

Hoyt (1967a) started a flood of controversy on the origin of barriers when he proposed a modified version of McGee's (1890) theory. He stated that barriers were formed by gradual submergence of pre-existing coastal beach-dune ridges, with a lagoon forming when the lower land area behind such ridges was flooded. Hoyt (1967a) considered the emerged offshore bar theory and the spit progradation theory invalid because of the following two reasons:

(a) Field observations and wave tank experiments by other researchers (Evans, 1942; McKee and Sterrett, 1961; Leontyev and Nikiforov, 1966) showed that offshore bars do not grow above water level. Also, there are no present day examples of bars becoming barriers in different stages of development anywhere in the world.

(b) Drilling data seldom reveal open marine sediments and organisms on the landward side of barriers, as would be expected if barriers developed from bars.

However, Hoyt (1967a) does agree that barriers may sometimes be formed from spits by their later truncation during storms by waves, and also that minor short-lived barriers could form from submerged bars, as was observed by Price (1963b). Another case of a short-lived barrier being formed exclusively from wave processes and water level changes on Gull's Reef on the Polish Baltic coast has been documented by Rudowski and Tobolewski (1974).

Cooke (1968) criticized Hoyt's (1967a) theory by stating that barriers could form without a change in sea level and cited Hatteras Banks, Sapelo Island, and Padre Island on the Texas coastline as examples. Fisher (1968) thought that Hoyt's theory suggested that a stable shoreline was necessary for dune formation. In his reply to Cooke's (1968) criticism, Hoyt (1968a) disagreed with Cooke's suggested mode of formation of the barriers he cited as examples. With regard to Fisher's (1968) argument, Hoyt (1968c) stated that dune ridges can be observed to form very rapidly under present conditions. In both cases Hoyt stressed the importance of the absence of marine sediments and fauna on the landward side of barriers. Otvos (1970a) claimed that Hoyt's (1967a) submergence theory for barrier origin would require special conditions that never existed in the last 3,500-5,000 years, when most of the Gulf Coast barriers were formed. Otvos (1970a, 1970b) favored an emerged offshore bar origin, and landward migration of barriers parallel, perpendicular, or oblique to the main shoreline. He believed that nearshore low salinities and coastal marshes accounted for the landward absence of marine organisms and ocean sediments, respectively. Inland migration of barriers was also stressed by Stapor (1973). Hoyt (1970) disagreed with Otvos on the origin of barriers he cited as examples to support his case, doubted the growth of salt marshes on open coasts, and again returned to his main argument regarding the lack of marine sediments and organisms landward of the barrier. Dillon (1970) provides an example of a barrier off Rhode Island being formed by reworked glacial sediments at a lower sea level stand, and migration landward as the sea transgressed.

Colquhoun, Pierce, and Schwartz (1968), and Pierce and Colquhoun (1970) proposed a theory which appears to incorporate all the main criteria of other investigators discussed above. From their field and laboratory studies they defined two types of barriers: (1) a primary barrier, formed by submergence of primary coastal ridges during the marine transgression; this barrier is bounded by back-barrier sediments overlying a former land surface on the landward side, and migrates landward with rise in sea level; and (2) a secondary barrier, formed by the upward building of offshore bars, or by breaching of spits. This secondary barrier is developed after the primary, is underlain by continental shelf sediments, and is seaward of the primary barrier. The secondary barrier was formed during a stationary sea level, or a slow recession of relative sea level. In other investigations by Colquhoun (1965, 1969b), evidence from terrace complexes is given to support primary and secondary barrier formation. Pierce and Colquhoun (1970) state thet "along present shorelines, no primary barrier exists in an unmodified form, nor do secondary barriers exist as originally formed." In later discussions between Cooke (1971), Hails (1971), and Pierce and Colquhoun (1971a, 1971b), there were no differences in the major principles involved, though there was disagreement on conclusions based on similar observations.

Many investigators recognized more than one mode of origin for barriers (Shepard, 1963, 1973; Zenkovich, 1959, 1967; Bird, 1969; Langford-Smith, 1969; King, 1972) and provided supporting evidence to prove it. Schwartz (1971) therefore proposed multiple causality and suggested the following classification:

(I) Primary
  1. Engulfment of beach ridges

(II) Secondary
  1. Breached spits
  2. Emergent offshore bars
     a. Sea level rise
     b. Sea level fall

(III) Composite
  (Combination of two or more of the above)

The latest views on the origin of barriers are those of Swift (1975), and Field and Duane (1976). Swift (1975) states as follows (from abstract):

> Thus the "origin" of most barriers is that they have retreated in from the position of their immediate predecessors. Barrier genesis, in the classic sense of large scale, coastwise spit progradation or mainland-beach detachment, could only have occurred at Late Wisconsin low-stand, when the sense of sea-level displacement was reversed. The relative roles of coastwise spit progradation and mainland-beach detachment depends on coastal relief and slope, with steep, rugged coasts favoring progradation at the expense of mainland-beach detachment. Since most major barrier systems form on flat coastal plains, it would appear that mainland-beach detachment is the more important mode of barrier formation.

Commenting on Swift's (1975) theory, Hayes and Kana (1976) write " ... so according to this idea, barrier islands originated by some mysterious process at a lower stand of sea level and migrated over the drowning coastal plains as sea level rose." Field and Duane (1976) found evidence from the Quaternary stratigraphic record of the Atlantic inner shelf for the former existence of barrier islands on the shelf. They state that this evidence goes against the earlier idea that lack of marine sediments under lagoons implies barrier origin by coastal ridge submergence. Field and Duane (1976) contend that if barriers formed from spits, the evidence would be seaward of the present shoreline. They are of the view that the onset of the Holocene transgression was responsible for extensive formation of barriers, which later migrated regularly and irregularly, in time and space, towards the present shoreline.

TRANSGRESSIONS AND REGRESSIONS

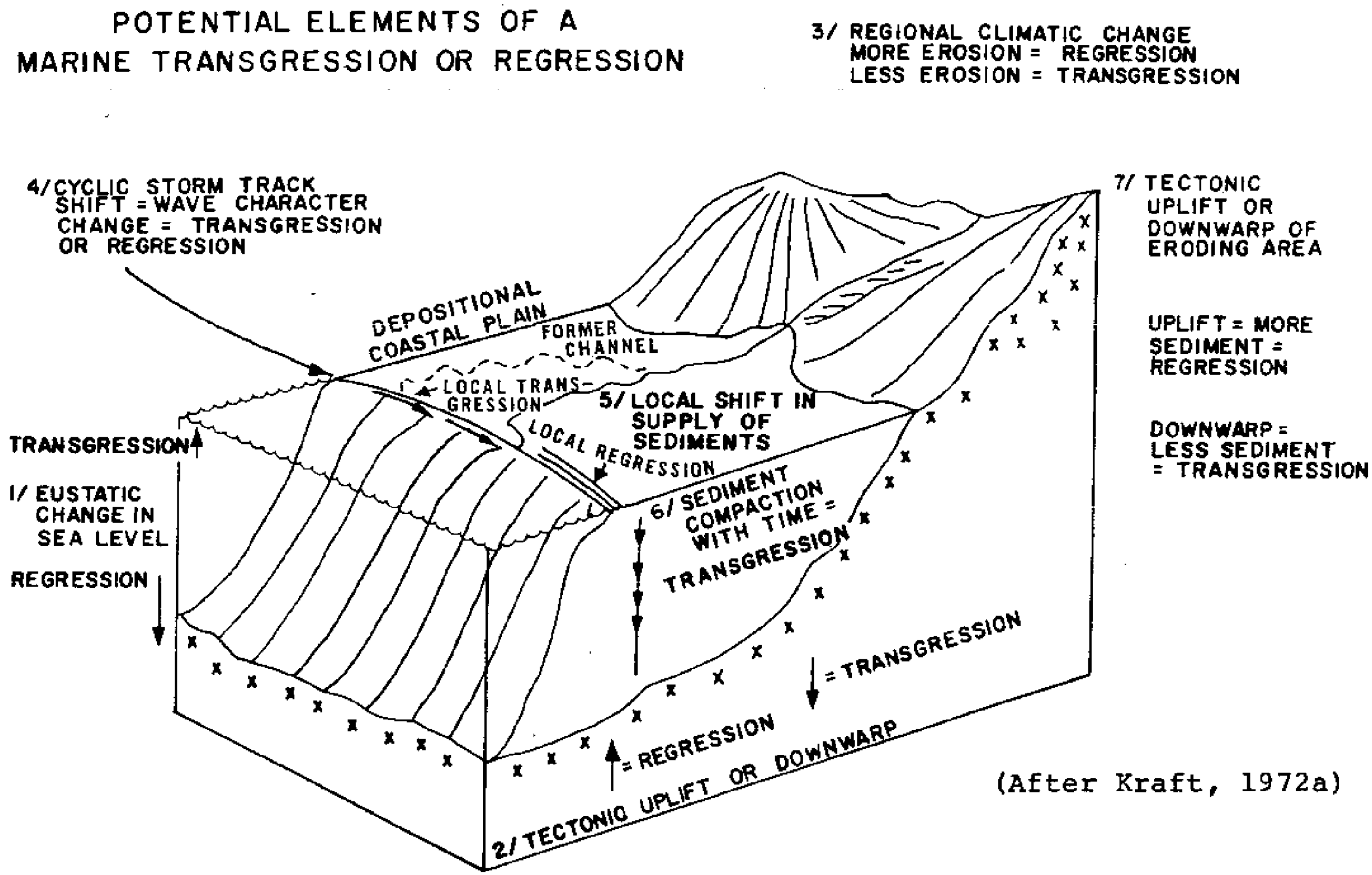
The development, migration, and patterns of sedimentation of barrier complexes are greatly influenced by the history of sea level changes. Shoreline features are a function of dynamic processes, for when sea level is fluctuating such features cannot be static. Landward migration of barriers (transgression) occurs with rising sea level, and seaward migration (regression) takes place with falling sea level. Curray (1964) elucidated the concepts of transgression and regression, and suggested that relative sea level rise and rate of net deposition were the two main controlling factors for these processes. However, Blatt, Middleton, and Murray (1972) stated that transgression or regression was mainly controlled by the balance between sediment supply and movement and not by a rise or fall in sea level. The effects of deposition or erosion could reverse the processes of transgression and regression. A rising sea level and a very high rate of deposition can cause the shoreline to prograde seaward, as in the case of a delta. Similarly, when rapid erosion is combined with a slowly falling sea level, it could produce a net transgression of the shoreline, instead of regression. Rapid erosion and rapid relative sea level rise will cause maximum transgression, while rapid sedimentation together with a rapidly falling relative sea level will cause maximum regression (Curray, 1964). Gill (1967) stated that "mobility of sea level is matched by mobility in shoreline structures." Sea level changes can be brought about by tectonic causes, or as a result of eustatic changes in sea level. The latter can take place either due to a volume change in the ocean basins (tectonic control), or of water in the oceans (glacial control). Curray (1964) believed that though distinguishing between the effects of tectonics and eustatic changes was not possible, tectonic effects were more common. He also suggested that Quaternary sea level changes were eustatically controlled and modified by local tectonics.

The potential elements of a marine transgression or regression as visualized by Kraft (1972a) are shown in Figure 6. This figure illustrates seven variables affecting coastal stability in a sedimentary continental shelf-coastal plain setting. As observed in this diagram, a simple transgression or regression could be triggered by an extremely complex set of events.

The overall eustatic rise of sea level during the past 10,000 years (Fairbridge, 1961) has caused erosion of barriers around the world (Leontyev, 1965). In many coastal areas, sea level has risen approximately 15 cm (6 inches) per hundred years during the past 6,000 years, according to the studies conducted by Donn and Shaw (1963).

FIGURE 6

POTENTIAL ELEMENTS OF A MARINE TRANSGRESSION OR REGRESSION



(After Kraft, 1972a)

However, at various coastal regions around the world, sea level changes have occurred at different rates and directions during this time (Hoyt, 1972). Wanless (1976) gives the following account of what happens when sea level fluctuates:

> During rapid sea level rise, coastal environments must (1) play catch-up sedimentation, (2) rapidly migrate landward (transgress), grow upward, or be overridden by the rising sea, and (3) constantly change in pattern in response to changing topographic-bathymetric setting. With slow sea-level rise or a steady state and sufficient sediment nourishment, coast constructing environments may maintain a stationary position or even expand seaward (regress), and intracoastal holes will tend to fill in toward equilibrium condition. With insufficient nourishment, mobile constructional coasts may migrate landward or dissipate.

Transgressions and regressions were classified by Curray (1964) into depositional and erosional types, based on the rate of net deposition relative to rise and fall of sea level. A number of Quaternary examples of transgression have been discussed by Curray (1964). When a high depositional rate is combined with slow subsidence it results in a "depositional regression", and this is the most common type preserved in the geological record. Substantial evidence for the Holocene transgression is provided by the surface and near-surface sediments of the continental shelves, beaches, lagoons, and bays, and hence most of the cited modern examples are of transgressions. As these transgressive deposits overlie the late Wisconsin regressive sediments, it is only by deep drill cores or chance sampling in rarely exposed areas that the latter can be studied (Curray, 1964). Hence the apparent paucity of such examples. Hoyt (1968b) stated that "the Quaternary barrier systems differ from those of older periods in that they have not been transgressed and buried by later sediments." Thompson (1937) found that beach deposits were preserved mainly in regressive sequences; he suggested that the destruction of marginal deposits during transgression was mainly determined by shoreface geometry and depth of sediment reworking.

Another concept important in understanding transgression and regression is Bruun's Rule. Bruun (1962) stated that a rise in sea level will cause erosion of material from the upper beach and deposition on the near-shore bottom. This concept has been tested in the field and laboratory by Schwartz (1965, 1967) and found to be valid. Dubois (1975) supported Bruun's (1962) theory, and clarified it further on the basis of his investigations as follows:

> If a beach and nearshore profile is at equilibrium, as sea level rises (a) the foreshore zone retreats parallel to itself as beach erosion takes place, (b) the foreshore zone is elevated landward in direct proportion to the increase in elevation of the water level, (c) the volume of sediments eroded from the foreshore is equal to the

> volume of sediments deposited on the nearshore bottom, and (d) due to deposition in the nearshore, the increase in elevation of the nearshore bottom is equal to the increase in elevation of sea level.

Based on maps and photographs covering a period of 30 years, Fisher and Regan (1977) found that loss of sediment along Rhode Island beaches as a result of shoreline erosion due to sea level rise was less than the increase in the offshore sediment sink; they therefore suggested that Bruun's Rule may require modification.

Marginal coastal deposits in the surf zone of a transgressing sea may be completely eroded, resulting in a disconformity called a "ravinement" by Stamp (1922). In a discussion on the role of coastal erosion in shaping transgressive deposits Swift (1968) states that "in the ravinement process, the sea destroys part or all of its own marginal record of low energy marsh and lagoon deposits and high energy barrier island sands." The coast of New Jersey (Fischer, 1961) and Delaware (Kraft, 1971a) is presently undergoing ravinement due to the post-Pleistocene rise in sea level. Wells (1960) suggested that transgression occurred more rapidly than regression because in transgressive-regressive sequences, records of the former were usually thinner than those of the latter. Van Straaten and Kuenen (1957) showed that a major transgression may initially produce very fine-grained sediment.

Fischer (1961) suggested a model explaining the potential retention of a coastal sedimentary record in a transgressing sea. In such a situation there are two possible conditions (Fischer, 1961):

(1) Complete reworking and resulting loss of marginal deposits, and hence the record of transgression.

(2) Partial preservation of marginal deposits, and separation from the succeeding later sediments by a disconformity.

This model proposed by Fischer (1961) was modified by Kraft (1971a, 1971b) to suit the Atlantic coast of Delaware, which is also the area of this investigation, and is shown in Figure 7. As can be observed from this diagram, a rapid sea level rise can result in total retention. Transgression is caused solely by coastal erosion when there is little or no sea level rise. Sedimentary environment units at the edge of the transgression must hence be exposed on the submerged beach face, and must therefore be encountered in drilling. Offshore seismic evidence (Moody and Van Reenan, 1967; Sheridan, Dill, and Kraft, 1974) from coastal Delaware does not prove this, but suggests that the deeply incised pre-Holocene topography is covered by a variable thickness of Holocene sediments. If transgression caused by sea level rise and coastal erosion occur at the same time, partial retention of the sedimentary

RETENTION OF COASTAL SEDIMENT RECORD IN A TRANSGRESSING SEA

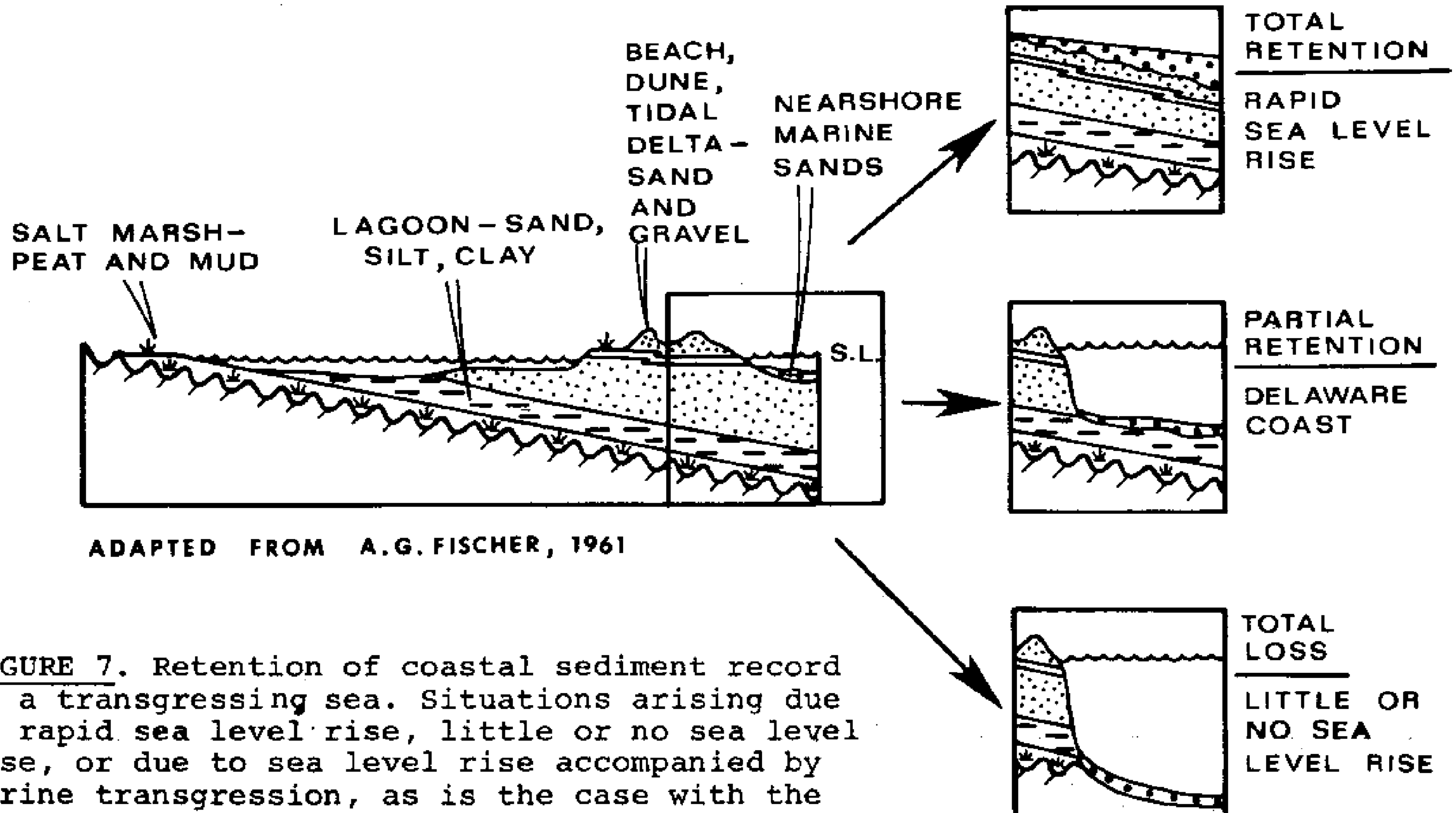


FIGURE 7. Retention of coastal sediment record in a transgressing sea. Situations arising due to rapid sea level rise, little or no sea level rise, or due to sea level rise accompanied by marine transgression, as is the case with the Delaware coast, are shown. (After Kraft, 1971a)

record may be possible. It has been determined by Kraft (1971a, 1971b) that a thin veneer of sand eroded from the beach face is underlain by back-barrier environments, which are exposed on the submerged beach face. Hence, all presently available evidence in the area of this study suggests that "the ongoing transgression in the Delaware coastal area is leaving behind a partial record of shoreline environments covered by a thin veneer of shallow marine sediments" (Kraft, 1971a).

WALTHER'S LAW

The term "facies" was first introduced into geological literature by Nicolaus Steno (1669). It was later elaborated and clearly defined by Swiss geologist Gressly in 1838 (Teichert, 1958). However, indiscriminate usage of this term for a wide range of concepts has prompted much discussion. Longwell (1949), Teichert (1958), and Markevich (1960) provide good reviews on the subject. Moore (1949) defined sedimentary facies as "an areally restricted part of a designated stratigraphic unit which exhibits characters significantly different from those of other parts of the unit." The rock record of any sedimentary environment was termed "lithofacies" (Moore, 1949).

It is generally much easier to observe the lateral sequence of facies in modern sediments than the vertical sequence. For ancient sediments the case is just the reverse (Blatt, Middleton, and Murray, 1972). Walther's Law is a concept relating horizontal facies patterns to vertical sequences, and was enunciated in 1894 by Johannes Walther, a pioneer German stratigrapher and sedimentologist. The original translated statement of Walther's Law as given by Middleton (1973) is as follows:

> The various deposits of the same facies-area and similarly the sum of the rocks of different facies-areas are formed beside each other in space, though in a cross-section we see them lying on top of each other. As with biotopes, it is a basic statement of far-reaching significance that only those facies and facies-areas can be superimposed primarily which can be observed beside each other at the present time.

The underlined second part of the above statement was emphasized by Walther (1894) and Middleton (1973). Walther's Law, also referred to as the Law of Correlation of Facies by Krumbein and Sloss (1963), can be briefly stated as "a conformable vertical sequence of facies was generated by a lateral sequence of environments" (Selley, 1976).

It was not clear to Markevich (1960) whether Walther had used the term facies to mean "different aspects of contemporaneously formed rocks", or as "a lithologic expression of a sedimentary environment." Middleton (1973) was convinced that the term was used in the latter sense. In a significant paper on the use of the vertical profile in environmental reconstruction, Visher (1965) gave much importance to Walther's Law. Walther understood that though all facies developed horizontally, sometimes even important ones may be absent in a vertical succession at a particular point. Also, the stratigraphic sequence should not have major time breaks (Blatt, Middleton, and Murray, 1972). The best English language discussion of Walther's Law is provided by Middleton (1973) and Woodford (1973).

The concept stated in Walther's Law is the basic premise underlying the studies of the Holocene transgression on the Delaware coast by Kraft (1971a, 1971b, 1971c), and Kraft, Biggs, and Halsey (1973). This law has been used to construct models of the vertical sedimentary sequences for the Delaware coastal area. Figure 8 shows that the vertical sequence of sedimentary environments is being formed in the same order as the modern day lateral sequence of coastal sedimentary environments observable on the coast of Delaware, and is therefore a schematic illustration of Walther's Law. The elements of coastal change in such a dynamic situation where the coastal geomorphic forms are being constantly altered due to continuation of the ongoing Holocene marine transgression are depicted in this diagram. The present investigation is also essentially a proof of Walther's Law.

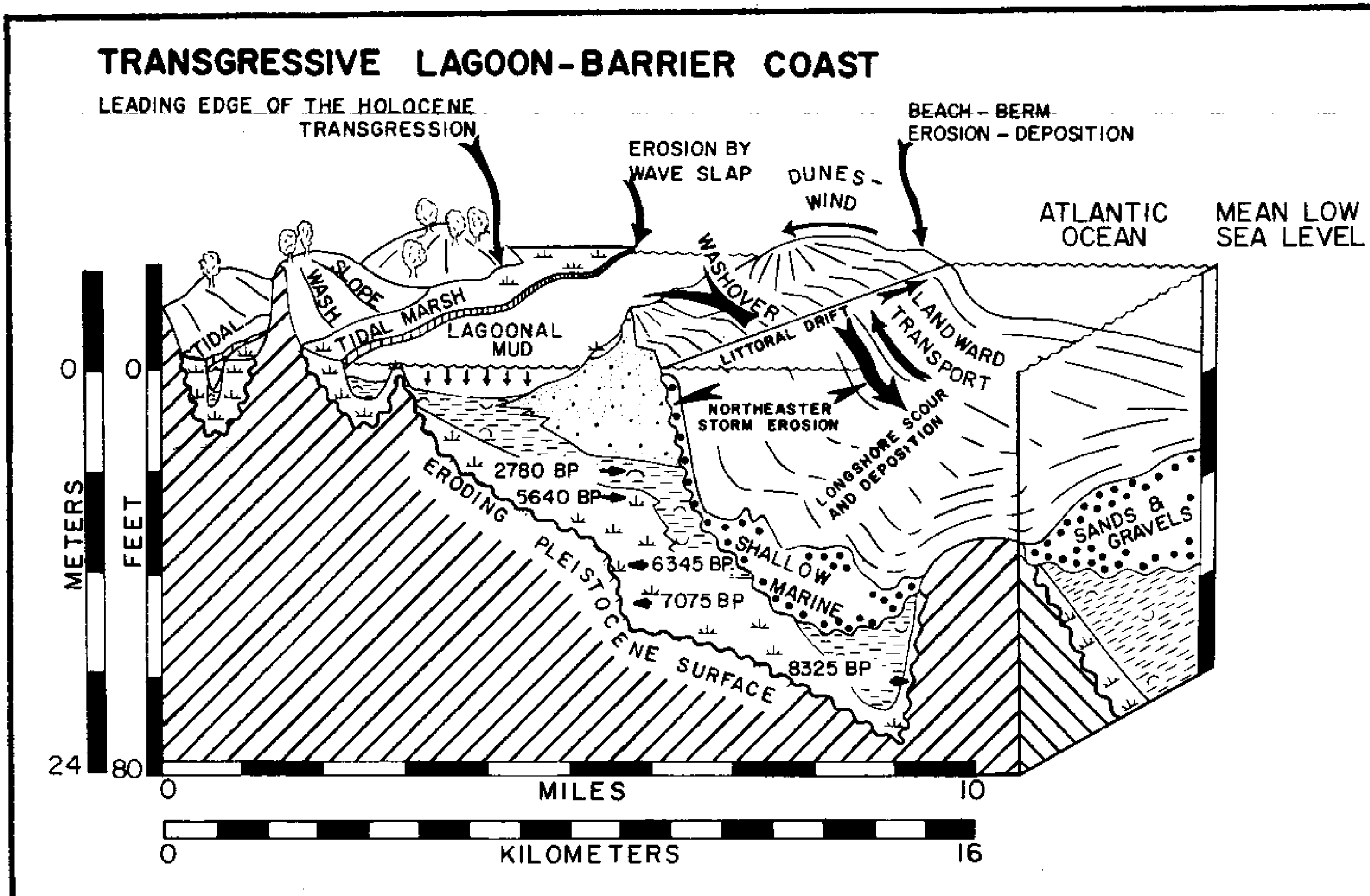


FIGURE 8. A schematic illustration of Walther's Law as applied to the Delaware coast. (From Kraft and John, 1976)

STORM EFFECTS ON BARRIERS: THE OVERWASH PROCESS

Coastal storms can in a few hours bring about geomorphological changes on barriers and beaches which would normally occur only after years of normal wave action. Gretener (1967) considered a high energy storm as a "rare event", in other words, "an event with the low probability of a particular interplay of various factors", and held it responsible for the ultimate distribution of nearshore sediment rather than the normal daily wave and current action. Hayes (1967a, 1967b) also made a similar observation. Hurricanes occur on an average of once in every 2.5 years (Reineck and Singh, 1973), but the frequency of occurrence may vary greatly from place to place. The importance of coastal storms and hurricanes as geological agents with respect to destruction, erosion, and sedimentation in coastal areas has been thoroughly studied and documented by many investigators (Price, 1936, 1947, 1953, 1958, 1959; Johnson, 1956; Morgan, 1958; Caldwell, 1959, 1966; El-Ashry and Wanless, 1965; Hayes and Scott, 1964; Ball, Shinn, and Stockman, 1967; Hayes, 1967a, 1967b; Perkins and Enos, 1968; Scott, Hoover, and McGowen, 1969; Hayes and Boothroyd, 1969; Dolan and Godfrey, 1973; and Yasso and Hartman, 1975).

Saville (1950) found that on equilibrium storm beaches sediment is mainly transported in suspension by the littoral current, while on equilibrium summer beaches almost all sand is transported by beach drifting as a result of direct wave action. Hurricanes are accompanied by torrential rains which cause flooding, and the hurricane surge, a moving wave of sea water of great size, which is geologically the most significant for bringing about geomorphological changes. The hurricane surge is caused by low atmospheric pressure and wind stress on the water surface. The hurricane surge stage lasts for 2.5 to 5 hours. It is preceded by a rise or fall of water level being dependent on area location with respect to the storm track; it is followed by "resurgences", in other words, more or less free oscillations of the water body of considerable magnitude (Groen and Groves, 1962). Storm surges are more destructive when they occur at normal high tide (U. S. Army Coastal Engineering Research Center, 1964, 1973). Recession of the beach, destruction of the dune system and buildings close to water, flooding of low lying areas, deposition of sediment on the landward side of the barrier complex, mixing of faunas from different environments in a single deposit, and displacement of sedimentary processes causing formation of normally unrelated sedimentary structures and textures are common effects of coastal storms (Hayes, 1967b).

During storms the flood tide of sediment-laden water may breach the dune system and move across the barrier and onto the marsh and lagoon, depositing sediment in a fan-like shape due to splitting up of the main flow channel into distributaries and lowering of flow velocity. This process is known as "overwash" and the resulting sedimentary deposit is termed a "washover" (Gary, McAfee, and Wolf, 1972). The process itself was first described by Johnson (1919). Lobeck (1939) initially termed the resulting deposit as a "washover". To signify the general shape of the deposit, fan-like or semi-circular, Price (1947) coined the term "washover fan". When washover fans converge together they form a "washover apron" (Fisk, 1959). Washover deposits are wedge-shaped in cross section, and may or may not have a conformable relationship with the underlying sediments. Such deposits generally have a shell-rich layer at the base, grading upward into horizontal laminated sand without shells (Andrews, 1970). Often the washover fan may consist of a series of superimposed fans due to deposition caused by successive coastal storms. Washover features occur commonly along most storm-affected barrier coastlines, and the area of this investigation is no exception. The size of washovers indicates that a very large volume of sand can be transported onto the barrier by overwash (Pierce and Colquhoun, 1970). The overwash process therefore causes widening of the barrier by marsh expansion and addition of material on the lagoon side; this also at the same time results in landward migration of the barrier. Washover sediments in lagoons are often preserved as discrete sand bodies surrounded by lagoonal mud (Scott, Hoover, and McGowen, 1969), as will also be shown later in this study. They also interfinger with sediments of the beach, dune, barrier flat, tidal flat, marsh, and lagoon (Dickinson, Berryhill, and Holmes, 1972).

A diagrammatic illustration of the overwash process and the resulting washover deposit is shown in Figure 9. As seen in this figure, erosion is predominant in the initial stages in the throat section. Depending upon the intensity of the storm surge, the sand will be transported to the washover fan, or further onto the marsh and lagoon. Channel flow types of sedimentary structures will be produced in the washover fan. Later on, a decrease in storm surge velocity will cause deposition of material in the throat and fan sections. When conditions return to normal, the wind will rework the washover fan making contributions to the dunes, marsh, and beach, depending upon wind velocity and direction (Fisher, Leatherman, and Perry, 1974). Sediment mean grain size and thickness of the washover decreases from throat to the fan as a result of lesser capacity and competency of water flow as the storm surge travels forward. Dunes, when present, constitute a major

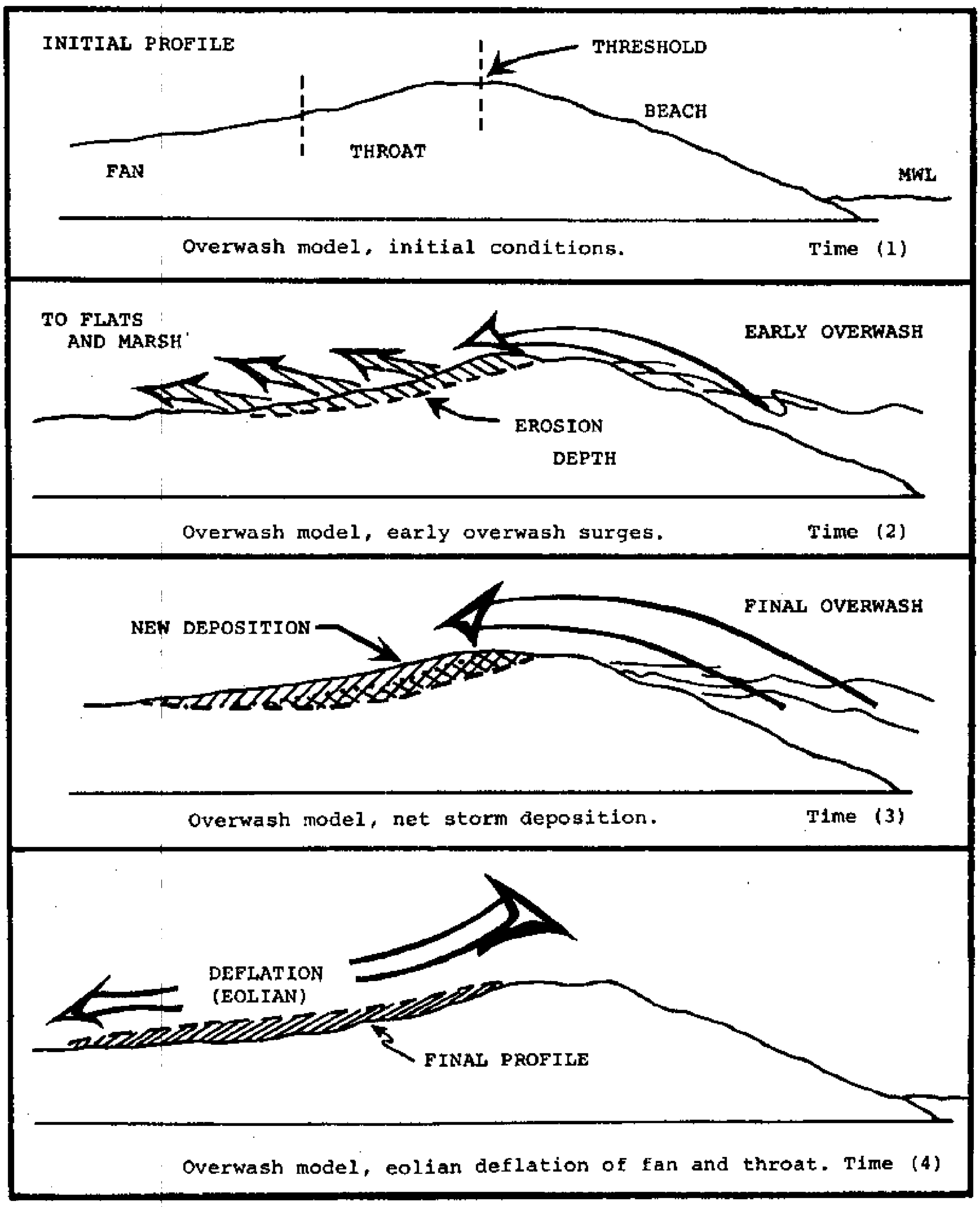


FIGURE 9. Diagrammatic representation of the overwash process. (After Fisher and others, 1974)

source of sand to storm overwash surges (Leatherman, 1976).

There have been several studies examining the significance of washover fans as a depositional element of barriers (Andrews, 1970; Nordquist, 1972; Schwartz, 1975; Leatherman, 1976; Allen, Maurmeyer, and Kraft, 1977). In fact, Swift (1975) pointed out that "it is helpful to regard a barrier as a large scale composite sand body, consisting of a wave and current graded shoreface, attached to washover fans." Godfrey and Godfrey (1973) have suggested that overwash is essential for maintenance of a barrier complex despite the danger of flooding. The characteristics of washover deposits as summarized by Schwartz (1975) are given in Table I. Pierce (1970) has elaborated on the genetic relationship of tidal inlets and washover fans. Biogenic structures made by the fiddler crab (Uca pugilator), and the ghost crab (Ocypode quadrata), in washover fans of the Georgia coast have been studied by Frey and Howard (1969), and Frey and Mayou (1971). The ecological effects of washovers on the natural barrier complex has been the subject of discussion by Godfrey (1970), Dolan (1972, 1973), Godfrey and Godfrey (1973, 1974), Hosier (1973), and Dolan, Godfrey, and Odum (1973).

It is well known that barrier environments are favorable sites for oil accumulation. Hence developing criteria for recognizing washover deposits in modern

TABLE I: CHARACTERISTICS OF WASHOVER DEPOSITS*

Characteristic	Description
Petrology	Detrital, locally derived, mainly from shoreface, beach and sometimes foredune. The foredune itself may largely consist of washover material. Composition similar to that of adjacent beach. Faunal remains predominantly marine. Nonmarine faunal remains possible with excavation of underlying nonmarine units. Plant fragments, root remains, and carbonaceous material may be present. Heavy mineral concentrates common.
Texture	Texture inherited from adjacent facies. Textural parameters dependent upon position of sample within sedimentary structure and lateral position in sand body. Unimodal distributions with good to excellent sorting common within similar parts of stratigraphic units, bimodal distributions with poor sorting in composite samples and within some sedimentation unit samples. Typically clean. Rounding good. Shells fragmented to whole.
Sedimentary structures	Horizontal (planar) stratification abundant; medium-scale delta-foreset strata (topset, foreset, and bottomset). Lamination (textural or mineralogical) may be conspicuous depending upon source material. Orientation of sedimentary structures variable, but tend towards unimodality in landward direction. Increased dispersion of dip directions result from deposition on lobe (fan) flanks. Scoured contact common below individual horizontal stratification units and delta-topset units. Other structures include local small-scale crossbeds in pockets within horizontal stratification facies or ripple marks in runoff channels. Small-scale channeling occurs locally. Current-oriented plant fragments or vertical plant remains depending upon storm placement versus poststorm growth.
Internal organization	Lateral structural sequence from washover neck towards terminus if from horizontal stratification facies to delta-foreset facies. Delta-foreset facies show upward vertical trend of horizontal or low angle bottomset to tabular foreset to horizontal or low angle topset strata. Horizontal stratification facies usually consistent throughout vertical sequence of a single storm deposit. Vertical rhythmic textural or mineralogic variation typical. Inverse or normal textural grading occur between apparently different layers in horizontal stratification. Lateral increase in grain size of horizontal sedimentation units toward washover terminus.
Geometry	Elongate (parallel or at high angle to shoreline) or semicircular, isolated to coalescing. Tabular to prism shapes. Direction of placement at high angle, commonly normal, to shoreline in landward direction. Widths (shore-parallel) from tens of feet to more than several miles. Thickness variable, several centimeters to less than 1.5 meters for a single storm. Greater cumulative thickness.
Associated lithologic types	Variable according to extent of washover, nature of shoreline movement (transgressive-regressive) or lateral shift of subaerial environments. In general, most closely associated with eolian facies. Occurs anomalously with many barrier (spit) facies. Washover extending to the back-barrier or lagoon may result in anomalous, abrupt association with mudflat or lagoonal facies. Multistory washover sand bodies common.

*From Table 3, p. 55, U. S. Army Coastal Engineering Research Center, Tech. Mem. No. 61, 1975: Nature and Genesis of Some Storm Washover Deposits, by, R. K. Schwartz.

barrier sequences, as will be attempted later in this study, should prove useful to the petroleum geologist in the recognition of ancient barrier environments in the quest for oil.

****

PREVIOUS LITERATURE

It is most convenient to review previous literature directly or indirectly relating to this study in three parts as follows:

(A) Barriers - modern and ancient

(B) Sedimentary structures and environments

(C) Grain-size parameters and environments

(A) BARRIERS - MODERN AND ANCIENT

A vast amount of geological literature exists on transgressive and regressive barrier complexes. From a perusal of this literature it appears that the consensus of opinion favors barriers preserved in the geologic record as being regressive in nature. Klein (1975) stated that "nearly all preserved barrier systems in the stratigraphic record owe their origin to progradation." However, it should be pointed out here that though a barrier may appear regressive, detailed examination of the same is likely to reveal transgressive elements, since it is reasonable to assume that before regression begins, a transgression must have taken place. Reasons given for the obscurity of ancient barriers in the geologic record are:

(1) a barrier coastline is usually a narrow zone;
(2) barriers are comparatively fragile geomorphic forms capable of being altered beyond recognition in the high energy littoral zone (this applies more in the case of transgressive barriers than regressive ones); and
(3) barriers usually occur with thick coastal plain sequences and thus could be easily obscured by these much thicker sedimentary bodies (Dickinson, Berryhill, and Holmes, 1972). Publications which will provide the interested reader with an overall review and insight into different aspects of modern and ancient sand bodies, including barriers, coastal environments, sedimentary structures, and depositional processes include Coastal Research Group (1969), Selley (1970), Pettijohn, Potter, and Siever (1972), Rigby and Hamblin (1972), King (1972), Shelton (1973), Schwartz (1972, 1973), Reineck and Singh (1973), Busch (1974), Shawa (1974), Klein (1975), Harms, Southard, Spearing, and Walker (1975), Dickinson (1975), Davis and Ethington (1976), Hayes and Kana (1976), and Conybeare (1976).

The coastal environmental setting, framework, and other aspects of Delaware's Atlantic coast transgressive barrier complex, which is also the area of this study, have been previously studied and described by Kraft (1971a, 1971b, 1971c, 1972b), Kraft, Sheridan, and Maisano (1971);

Kraft and Margules (1971), Kraft and Caulk (1972), Kraft, Biggs, and Halsey (1973), Kraft and Belknap (1975), Kraft and Allen (1975), Kraft, Allen, Belknap, John, and Maurmeyer (1976), and Kraft and John (1976). Relevant portions of these investigations will be mentioned at appropriate places later in this study. The present study, as stated earlier, will go into the detailed internal organization of this barrier complex.

This transgressive barrier complex is the best documented and most completely investigated barrier complex in the world.

A spit is a depositional feature comprised of sand and gravel attached to an older landmass at one end and projecting into a water body at the other. It normally ends in either a single or a series of landward hooks or recurves, caused by wave refraction (Evans, 1942). Spits are usually built in the direction of littoral transport. Spits are constantly changing geomorphic forms, and such changes have been documented using maps and aerial photographs by Farrell (1969), King (1970), Shepard and Wanless (1971), and others. The origin of spits in lagoons has been discussed by Zenkovich (1959). Though models are, as stated by King and McCullagh (1971), "simplified replicas of reality", these authors have presented a computer simulated model of a complex recurved spit in order to study the effects of different coastal processes on spit building. The characteristics of natural beaches have been described by Bascom (1954).

The geomorphic elements of the Cape Henlopen spit-dune-marsh complex, which forms the northernmost part of the barrier complex under study, is shown in Figure 10. This is a region of constant change brought about by the interaction of waves, tides, and wind. Details of this area will be discussed later in this report. Figure 11A gives a general summary of Recent sediments in this area. The marsh edge, shown in black, represents part of the leading edge of the Holocene marine transgression of the Delaware coast caused by sea level rise at a rate of 12.5 cm (0.41 ft.) per century (Belknap, 1975), and coastal erosion. Figure 11B shows typical average grain-size curves for different sedimentary environments in the area. Atlantic Ocean beaches and western lagoon beaches have coarse and well sorted sands. Tidal delta sands are relatively less sorted than beach sands and contain small amounts of clay and silt. In places where tidal delta sediments come in contact with lagoonal sediments a bay-fringe sediment mixture is produced, and fine to coarse sands together with clay and silt are found in such areas. Similar sediments are also found where washover sands enter lagoons. The barrier-bar lagoon border region is where sands of the barrier are mixed with silt

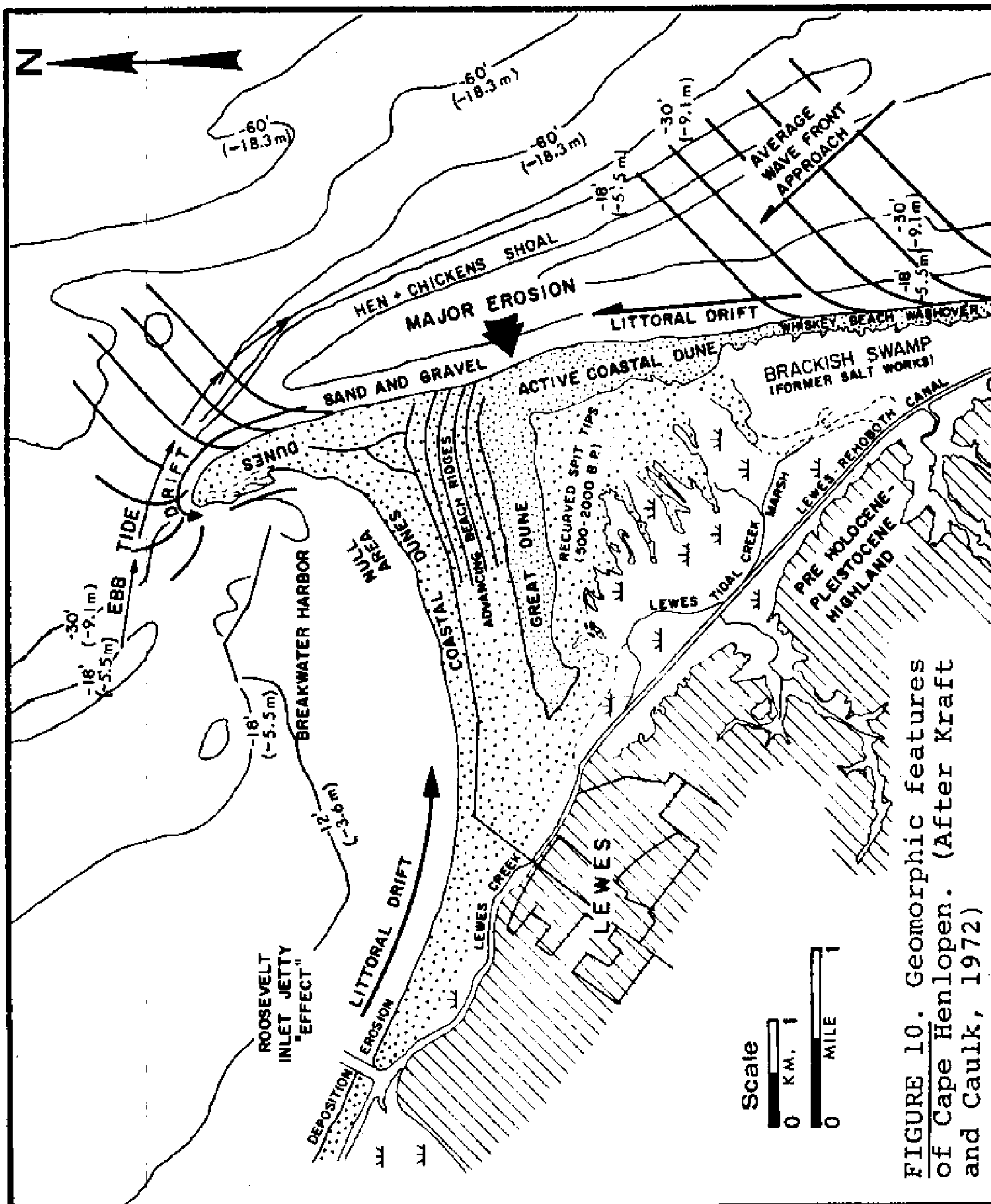


FIGURE 10. Geomorphic features of Cape Henlopen. (After Kraft and Caulk, 1972)

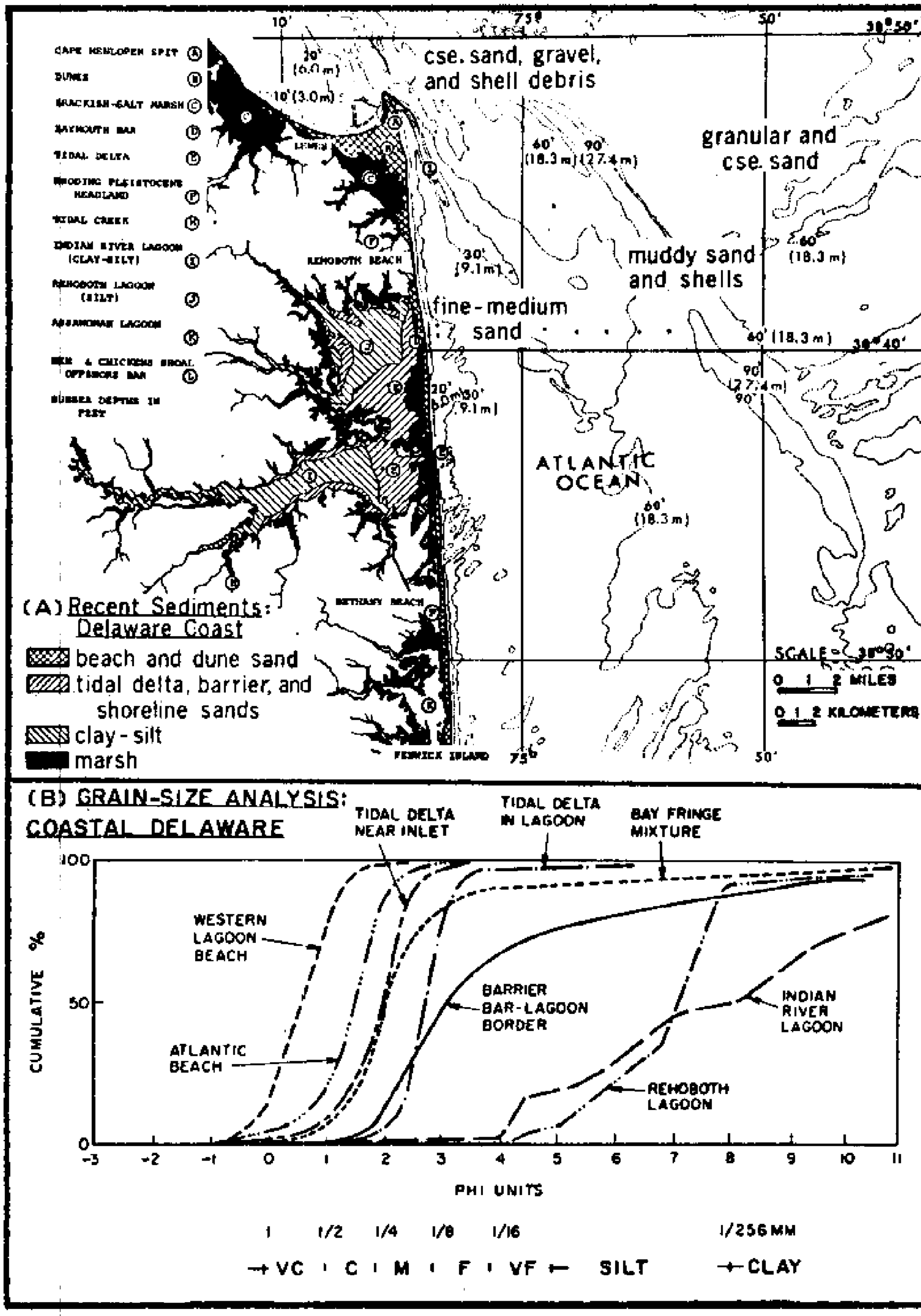


FIGURE 11. (A) Recent sediments of the Delaware coast. (B) Average grain-size analysis of samples from different coastal environments of Delaware. (Modified from Kraft, 1971b)

and clay from the lagoons. The two coastal lagoons, that is, Rehoboth Bay and Indian River Bay, contain mostly clay and silt in their central parts, with the percentage of sand increasing towards the margins. Erosion of Pleistocene material along the lagoon margins contributes sediment to the lagoons.

The four major types of variations found in this barrier complex and their respective vertical sequences were discussed by Kraft, Biggs, and Halsey (1973), and are shown in Figure 12. Each of these types has been formed in response to wave conditions and the nature of the land surface undergoing transgression. In the beach-spit-dune model (Figure 12A) either a transgressive vertical sequence (see right side of Figure 12A), or a regressive vertical sequence (see left side of Figure 12A) is possible. In the case of the transgressive vertical sequence, lagoon sediments are overlain by marsh sediments, which in turn are covered by coastal beach and dune sands. The regressive vertical sequence is produced by the spit migrating over shallow marine-estuarine sediments. Hence, in this case, fine to medium dune sands overlie medium to coarse spit and beach sands and gravel, which in turn overlie shallow marine-estuarine sediments. In the washover barrier model (Figure 12B), Pleistocene sediments are overlain by marsh sediments, which are overlain by sands of the washover barrier. Small

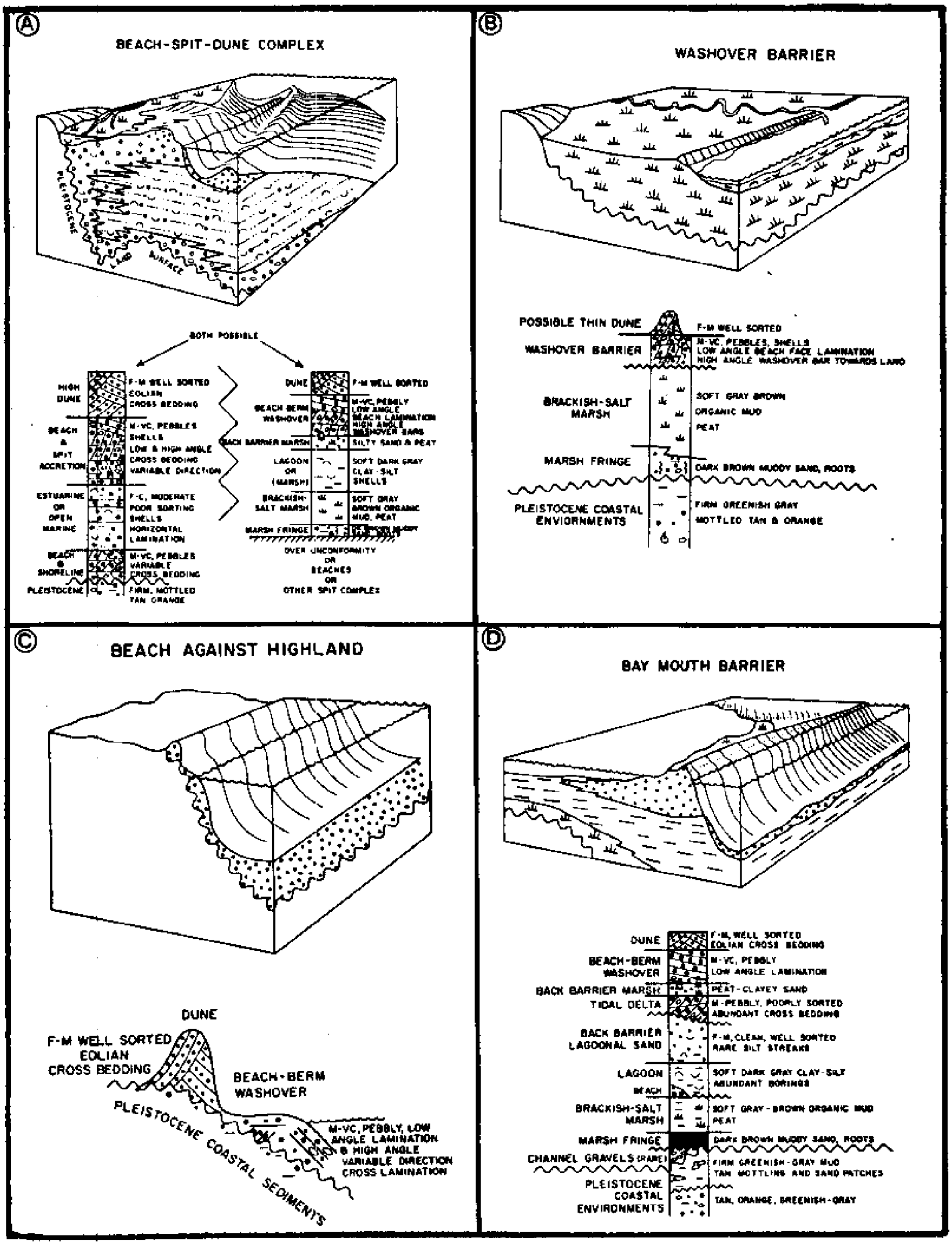


FIGURE 12. Block diagrams illustrating the four major variations in Delaware's Atlantic coastal barrier complex, and their respective vertical sequences. (Modified from Kraft and others, 1973)

dunes, which stand little chance for preservation in the geologic record, often develop on top of the washover barrier. When a beach truncates against a low lying pre-Holocene highland, a situation such as shown in Figure 12C is developed. Erosion of such highlands, especially during storms which may remove the entire beach, provides sediments to the littoral transport system. Here again, the small dunes developed inland of the beach stand little chance of preservation in the stratigraphic record. The best illustration of Walther's Law, discussed earlier in this report, is provided by the baymouth barrier model (Figure 12D). The vertical sequence encountered on drilling is analogous with the presently observed horizontal sequence of environments in the direction of transgression. As can be seen from Figure 12D, the barrier sands have a sharp contact with the underlying lagoonal muds, and this is a characteristic of transgressive barriers. A good general description of Holocene transgressive sediments is provided by Curray (1960). Sapelo Island, Georgia, where erosion is the dominant process (Pilkey and Richter, 1965), and Charleston Island, Rhode Island, are other examples of well documented and investigated transgressive barriers.

The best known and documented example of a regressive barrier is Galveston Island, Texas, initially studied in detail by Bernard, Major, and Parrott (1959), Bernard, LeBlanc, and Major (1962), and Bernard, Major, Parrott, and LeBlanc (1970). The regressive barrier model provided by these authors has been widely used for recognition of ancient regressive barriers. The Holocene geology of the Galveston Bay area has been described by Lankford and Rogers (1969). In the process of progradation or regression, the barrier sediments seaward are younger in age. The Galveston barrier is lenticular in shape, and has a maximum thickness of 15.24 m (50 ft.). The barrier sands thin out landward and seaward and are flanked on these sides by lagoonal and marine sediments, respectively. In the last 3,500 years the Galveston barrier has prograded seaward about 3.2 km (2 miles) (Davies, 1976).

The characteristic internal sequence of textures and sedimentary structures of the Galveston barrier have been used as a model by Davies, Ethridge, and Berg (1971) for identifying two ancient barrier complexes; one of these is in the Lower Cretaceous of Montana, and the other in the Lower Jurassic of England. Within both the Holocene Galveston barrier and the ancient examples from England and Montana Davies, Ethridge, and Berg (1971) found similarity in gradation upwards from the base, which they described as follows (from abstract):

> (1)Irregular interlaminations of siltstone and claystone at the base, through (2)burrowed and generally structureless

> sandstone, to (3) low-angle and micro-trough cross-laminated sandstone, terminating in two of the examples in (4) structureless and rooted sandstone. This sequence represents deposition in (1) lower shoreface, (2) middle shoreface, (3) upper shoreface-beach, and (4) eolian environments, respectively.

Lower shoreface sediments consist of highly bioturbated and interlayered fine-grained sand, silt, and silty clay, and may have a thickness of up to 1.8 m (6 ft.). Deposition takes place in about 9.1-12.2 m (30-40 ft.) of water about 1.6 km (1 mile) offshore. The high organic activity in this region destroys any sedimentary structures formed during deposition. Sediments of the middle shoreface are predominantly fine-grained sand with occasional layers of silt and clay, and shelly sand. They are usually structureless due to intense bioturbation, but may sometimes be cross-laminated. These sediments are deposited shoreward of the lower shoreface sediments in about 1.5-9.1 m (5-30 ft.) of water, and range in thickness from 3.1-10.4 m (10-34 ft.). Beach and upper shoreface fine to very fine grained sands range in thickness from 1-3.1 m (3-10 ft.) and are deposited shoreward of the middle shoreface sediments. Shells may be present, but biogenic activity is comparatively scarce. These sediments are characterized by planar low angle cross-lamination and some micro cross-lamination. Eolian sediments of the Galveston barrier generally show festoon and planar cross-lamination, as well as parallel lamination. However, these structures in the fine to very fine eolian sands are destroyed with age due to plant and animal activity, and ground water movement. Older eolian sediments are therefore structureless, but have plant roots and thin soil zones. Eolian sediments range in thickness from 0.6-2.4 m (2-8 ft.). It should be noted that Davies, Ethridge, and Berg (1971), and Davies (1976), pointed out that distinction between beach and upper shoreface at Galveston was made by Bernard, LeBlanc, and Major (1962) on the basis of sea level position, and that it was difficult to make this distinction solely based on sedimentary structures and textures in ancient sediments. In the Galveston case, the area of shallow water seaward of the beach was termed the shoreface. Based on their Galveston barrier investigations Davies, Ethridge, and Berg (1971), and again Davies (1976), proposed a model for aiding in identification of similar regressive barriers in the stratigraphic record.

The grain-size changes and sedimentary structures in a core from the Galveston barrier as given by Davies, Ethridge, and Berg (1971), and Davies (1976), are shown in Figure 13. These authors consider the increase in grain size from beach to the eolian environment (see Figure 13) as anomalous. Studies done by Dickinson and Hunter (1970) on Padre Island, Texas, Mason and Folk (1958) on Mustang

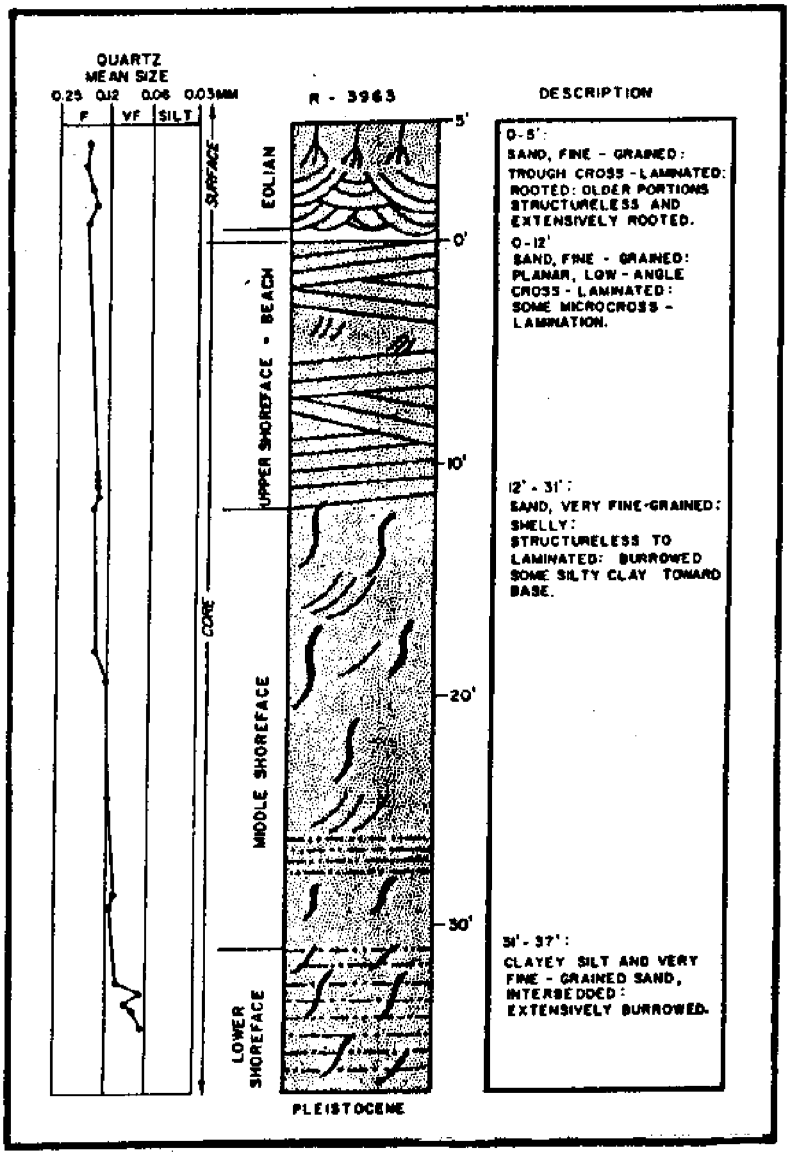


FIGURE 13. Vertical sequence and sediment sizes in the Galveston barrier. Core depth is in feet. (From Davies and others, 1971, with permission of The American Association of Petroleum Geologists)

Island, Texas, Giles and Pilkey (1965) on the Atlantic coast of America, and Gibbons (1967) from New South Wales, Australia, have shown the opposite result, that is, a vertical decrease in grain size from beach to the eolian environment. In a typical uninterrupted regressive sequence, grain size increases upwards from lower shoreface to beach, and the sequence gradationally overlies mostly marine, but also non-marine sediments, as in the case of barriers discussed by Hoyt (1967a). The typical vertical upward increase in grain size of regressive barriers has been used by Klein (1971, 1972, 1974) to estimate paleotidal ranges and water depths into which the barrier prograded. However, it is important to note that sediment supply from diverse sources can disrupt the typical vertical sequence in regressive barriers like the Galveston barrier (Dickinson, Berryhill, and Holmes, 1972). Colquhoun (1969a) also pointed out that increasing complexity of sediment sources and supply causes greater variations in transgressive barriers, and therefore the transgressive-regressive relationship in a barrier becomes more varied and complex. Corbeille (1962) has described the New Orleans barrier, which is made up of clean and well sorted sands that coarsen upwards. Conatser (1971) has studied the Grand Isle barrier in the Gulf of Mexico. The coastal geomorphology of barriers in Eastern Nigeria, Africa, has been discussed by Allen (1965a, 1965b). Barriers of the Zululand coast, South Africa, have been described by Orme (1973).

The Padre Island barrier, Texas, studied and described by Fisk (1959) was termed a "vertical build up" barrier by Blatt, Middleton, and Murray (1972). This barrier is mushroom-shaped in cross section, and lateral growth on the seaward and landward sides are due to beach ridge accretion and washover deposition, respectively (Hayes and Kana, 1976). The Northern Padre Island barrier, Texas, was referred to as a "stationary" type by Dickinson, Berryhill, and Holmes (1972) because it has been stationary for the greater part of its existence. Some areas of this barrier show a downward increase in sediment grain size. This barrier unconformably overlies a Pleistocene shell bed. It has an intertonguing relationship with lagoonal sediments, and a gradational lateral change to shallow marine sediments on the seaward side (Dickinson, Berryhill, and Holmes, 1972).

The fact that almost all of the previous literature deals with regressive barriers unfortunately leads one to conclude that regression is more dominant than transgression. Blatt, Middleton, and Murray (1972), pointed out that almost all barrier environments could be represented in a thick regressive vertical sequence, whereas transgressive sequences are usually thin and only sediments deposited in the shoreface, offshore, and nearshore regions may be found.

Transgression causes reworking and movement into deeper water of sediments found in other barrier environments. However, observation of the Eastern and Gulf Coasts of America show that transgressive barrier elements occur in at least about 50 per cent of the area (J. C. Kraft, oral communication).

Barrier preservation during burial depends on the amount of erosion caused by transgression. Eolian and beach sediments are usually eroded in this process, and therefore the preserved transgressive barrier will be mostly composed of shoreface sediments. Consequently "many preserved barrier sequences form asymmetric sequences with thin transgressive units alternating with regressive units" (Blatt, Middleton, and Murray, 1972). Hence it is easy to see how the transgressive part in what appears to be a regressive sequence could be easily overlooked. Field and Duane (1976) have found traces of transgressive barriers on the Atlantic inner continental shelf, and have concluded that transgressive sand bodies are buried in the subsurface. Adequate outcrop or core control and detailed internal sequence study are therefore vital for interpretation of transgressive barriers.

Recognition of ancient barriers is based on models and criteria developed from the study of modern barrier complexes in accordance with the philosophy of the present being the key to the past. Visher (1965) presented models for the interpretation of sedimentary sequences, but did not give any detailed model for a transgressive sequence. Other generalized sedimentation models and criteria for identification of sandstone bodies, including barriers, have been presented by Busch (1959, 1974), Sloss (1962), Potter (1967), Curray (1969), Selley (1970), Davies, Ethridge, and Berg (1971), LeBlanc (1972), Howard and others (1972), Pettijohn, Potter, and Siever (1972), Shelton (1967, 1973), and Davies (1976). Though present day barriers can serve as useful models, their deposition was probably not precisely identical to that of the ancient preserved barriers (Shelton, 1973).

There is a general tendency, as far as models are concerned, to place undue importance on ephemeral surface features in modern barriers which are unlikely to be preserved. Shelton (1973) considered an ideal sand body model to be one which was "in the initial stage of burial and readily accessible for direct observation." A short summary of environments and processes causing development of barrier sand bodies is given by Hayes and Scot (1964). Resio and others (1973) attempted to quantify a classification for transgressive and regressive barriers without considering internal organization of the barrier. The development of a series of coalescent regressive sand bodies has been described by Curray and Moore (1964). The nearshore zone off a barrier island is best documented and described in the work of Howard and Reineck (1972a, 1972b) on Sapelo Island, Georgia. Clifton, Hunter, and Phillips (1971, 1972) studied the nearshore zone along the open ocean Oregon coast, and suggested a sedimentary model for a land-attached high energy beach. Another sedimentary facies model for a nearshore barred coastline was proposed by Davidson-Arnott and Greenwood (1974, 1976).

Earlier identifications of ancient barriers were mainly based on their geometry. However, Visher (1969a) pointed out that "geometry of a sandstone body is probably the least significant criteria for the recognition of its origin." The undesirability of basing ancient barrier identification solely on geometry is further emphasized by the following statement made by Embry, Reinson, and Schluger (1974):

> The geometry of nearshore sandstones is variable. The length is controlled by shoreline morphology and sand supply, the width by duration of accretion and progradation processes and the thickness by depth of wave base and rate of subsidence.

Recent investigations, in addition to geometry, have also taken into account the important vertical sequence changes, together with sedimentary analyses and paleontologic information. Davies (1976) stated that great doubt surrounded the identification of an ancient sand body as a barrier unless the subaerial or fringing lagoonal sediments were preserved and recognized. Transgression tends to destroy subaerial sediments unless there is rapid sibsidence. The identification of a brackish or fresh water environment on the landward side, and an open marine environment on the other side are necessary pre-requisites for attributing a barrier origin to an ancient sand body (Weidie, 1968; Embry, Reinson, and Schluger, 1974; Davies, 1976).

In the United States geological literature, the first attempt at identification of a probable ancient barrier was by Rich (1923, 1926). However, the first definite identification was done by Bass (1934, 1936) who described the Bartlesville shoestring sands of Oklahoma as being of barrier origin (Dickinson, Berryhill, and Holmes, 1972). Hollenshead and Pritchard (1961) have provided excellent documentation of transgressive and regressive barrier sequences in the Cretaceous sandstone bodies of the Mesaverde Group of the San Juan basin in Colorado and New Mexico. Bridges (1960) has identified a well preserved transgressive barrier sequence of lagoon-barrier-marine deposits from 5-28 m thick, overlying basalts in the Lower Silurian of Southwest Wales. Thin sequences were attributed to be due to slowly transgressing narrow (<2 km) barriers, whereas, the thicker sequences were thought to result from broader (2-4 km) slowly transgressing barriers (Bridges, 1976). There are numerous other examples in the literature of ancient sandstone bodies being attributed a barrier origin. These include the discussions by Sears, Hunt, and Hendricks (1941), Ball, Weaver, Crider, and Ball (1941), Weimer (1961), Sabins (1962, 1963), Zimmerle (1964), Horn (1965), Harms, MacKenzie, and McCubben (1965), Shelton (1965), Thomas and Mann (1966), Boyd and Dyer (1966), Berg and Davies (1968), Exum and Harms (1968), Fisher and McGowen (1969), Davies (1969), Selley (1970), Weber (1971), Campbell (1971), Land (1972), Anderson (1972), Clifton (1973), Hobday (1974), and Conybeare (1976).

(B) SEDIMENTARY STRUCTURES AND ENVIRONMENTS

Though there are numerous papers describing sedimentary structures and surface features of barriers, none give any information on the detailed internal organization of sedimentary structures in a transgressive barrier complex. Information available on sedimentary structures, with the exception of the Galveston barrier structure described earlier, is mostly based on trench studies, short core samples, and box cores. Briggs (1966) emphasized that the study of primary sedimentary structures and paleocurrent patterns of sand bodies, besides being of academic interest, is also of great economic value as it aids in identification of potential reservoirs of petroleum. Potter (1967) stated that barrier sub-environments were usually grouped together as differentiation between them is generally not possible. Hayes, Anan, and Bozeman (1969) considered it risky to make paleogeographic reconstructions based solely on sedimentary structures. They state that "depending on the scale of the outcrop examined, completely opposing interpretations could be made about the transgressive or regressive nature of a shoreline."

Thompson (1937) described the structure of beaches, bars, and dunes. He pointed out that no single characteristic is distinctive for concluding the origin of an ancient sand body. Based on a study of heavy mineral percentages and mean grain size of sand on Pea Island, North Carolina, Boyd (1971) defined depositional environments within a beach. Howard (1969) used X-ray radiography as a tool to illustrate sedimentary structures and sedimentary facies changes on Sapelo Island, Georgia. He found that abrupt lateral changes in facies may occur within a few meters of each other. Howard (1972) considered trace fossils as a potentially valuable aid for barrier identification together with vertical and lateral sequence changes, and physical sedimentary structures. More general information on structures of coastal barriers and barrier complexes, beach ridges, nearshore bars, and Recent marine sediments is provided by van Straaten (1954, 1959, 1965), McKee (1957), de Ridder (1960), Siebold (1963), Moore and Scruton (1957), Logvinenko and Remizov (1967), Clifton, Hunter, and Phillips (1971, 1972), Reineck and Singh (1973), Moiola and Spencer (1973), Jennings (1973), Davidson-Arnott and Greenwood (1974, 1976), Harms, Southard, Spearing, and Walker (1975), Ingle (1975), and Barwis (1976). An excellent collection of papers edited by Middleton (1965) provides valuable information on the production and interpretation of fluvial sedimentary structures based on laboratory and field investigations. This information could be used for interpretation of flow conditions responsible for production of different types of sedimentary structures.

(C) GRAIN-SIZE PARAMETERS AND ENVIRONMENTS

Geologists for many years have experimented with the use of statistical grain-size parameters (mean, standard deviation, skewness, and kurtosis) for differentiating environments. The different techniques proposed for the statistical summary of grain-size data have been reviewed by Folk (1966). Inconsistent results of these studies have resulted in conflicting opinions among geologists. The general philosophy behind the use of grain-size parameters as environmental indicators is that grain-size distributions reflect the mode and energy of transport, and the environment of deposition (Friedman, 1961, 1967;

Martins, 1965; Visher, 1967). A major problem involved here is that similar sedimentary processes occur in different environments and these produce similar grain-size distributions and sedimentary structures (Visher, 1969b). Monocyclic sediments are more amenable to differentiation than polycyclic sediments (Hails, 1967).

Initial studies regarding grain-size distributions and derived parameters were done by Udden (1914), Wentworth (1929), Otto (1939), Keller (1945), Doeglas (1946), Inman (1952), van Andel and Postma (1954), and Inman and Chamberlain (1955). Besides grain-size parameters, heavy minerals in sand (Bradley, 1957), settling velocities of light and heavy mineral fractions in sand (Hand, 1967), and binocular studies of sieved coarse fractions of sand (Shepard and Moore, 1954) have also been used for environmental differentiation. Investigations by Shideler (1973a, 1973b) along the Outer Banks barrier chain of the Middle Atlantic Bight in North Carolina, revealed that textural patterns in sediments were mostly influenced by the nature of the offshore hydraulic regime, the aeolian regime, and the grain size of barrier source sediments. A distinctive size frequency distribution along the barrier was developed due to parallel and transverse sediment migration along the barrier in response to the aqueous and aeolian regimes, variations in which caused regional trends. Anan (1969) found that careful and detailed sampling of one sedimentation unit was vital for obtaining consistent results with statistical parameters.

Almost all work dealing with differentiation between sedimentary environments based on grain-size parameters has been with respect to beach, dune, and river sands. A good description of bar and barrier island sands is given by Weidie (1968). Moiola and Weiser (1968) suggested that though parameters calculated from half or whole phi sieve data could be used to effectively differentiate between some sedimentary environments, quarter phi sieve data were much more sensitive for this purpose.

Friedman (1961, 1967) found dune sands to be generally positively skewed, and beach sands negatively skewed. He differentiated beach and river sands by plotting skewness against kurtosis. Lagoon sediments have positive skewness (Biederman, 1962). Mason and Folk (1958) and Martins (1965) effectively differentiated beach and coastal dune environments by plotting skewness against kurtosis. However, Moiola and Weiser (1968) found this plot to be useful only in a few cases; they agreed with Friedman (1961) that a plot of mean grain size against skewness differentiated the same two environments more effectively. Again, Shideler (1974) found that plotting standard deviation against kurtosis most effectively differentiated beach and dune environments. When size parameters are used individually for differentiating between environments of deposition, mean diameter and standard deviation are most effective, whereas skewness and kurtosis are of little use (Shideler, 1974). Other investigators who consider plotting a combination of two grain-size parameters as a valid tool for differentiating sedimentary environments include Inman and Chamberlain (1955), Folk and Ward (1957), Harris (1959), Duane (1964), Hails (1967), Chappel (1967), Hails and Hoyt (1969), and Williams (1973).

Friedman (1973) stated that "textural parameters as clues to depositional environment have been a source of disenchantment." Shepard and Young (1961) and Shepard (1964) concluded that skewness or kurtosis were not useful for differentiating beach and dune sands. However, they found that differentiation is possible because dune sands had greater roundness, were better sorted, had higher silt content, and greater abundance of silt sized heavy minerals, whereas beach sands had greater amount of shell and mica and lesser quantities of silt. Other geologists belonging to this group who believe that grain-size parameters cannot be used for sedimentary environment differentiation include Schlee, Uchupi, and Trumbull (1964), Gees (1965), Hayes (1965), Sevon (1966), Adams and Thom

(1968), Andrews and van der Lingen (1969), Moiola and Spencer (1973), and Glaister and Nelson (1974). Hence we may conclude that although some investigators have used grain-size parameters to distinguish sedimentary environments, others have encountered little such success. Perhaps the utility of grain-size parameters depends on location as well as the investigator.

****

GEOMORPHOLOGY AND INTERNAL ORGANIZATION OF THE BARRIER COMPLEX

The results of this study will be presented and discussed in this section. The transgressive barrier complex of Delaware's Atlantic coast has four major variations proceeding along the length of the barrier complex from north to south (Figure 14):

(A) Cape Henlopen spit-beach-dune complex (Cape Henlopen to Whiskey Beach)

(B) Barrier-marsh (Whiskey Beach to Rehoboth)

(C) Beach-highland (Rehoboth)

(D) Barrier-tidal delta-lagoon (South Rehoboth to Cotton-patch Hill)

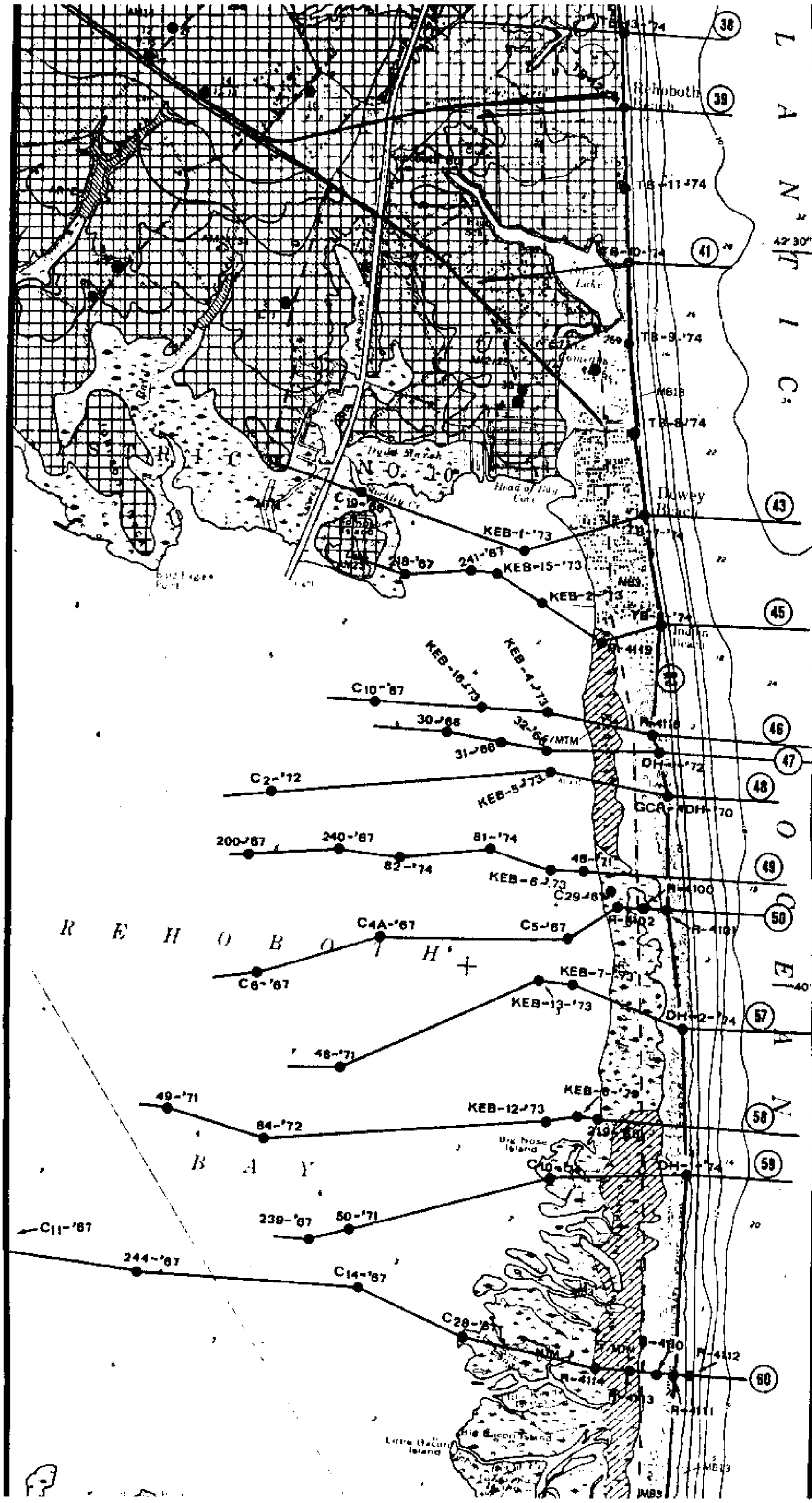
At the southern extremity of the study area (Cottonpatch Hill) the situation (C) given above is again repeated. In order to facilitate discussion, each of the four units outlined above will be treated separately. Figure 14 is an airphoto mosaic of the study area indicating all the prominent geomorphic features. Figure 15 is an index map of the study area made by joining together the appropriate sections of three Soils maps (see Figure 15 for references to maps). Locations of all cores and samples used in this

FIGURE 14

Aerial photo mosaic of part of Delaware's Atlantic barrier coast compiled from air photographs by the U. S. Department of Agriculture. Prominent geomorphic features are indicated.


DELAWARE BAY
Vibracore 1-'70
R-4109
Breakwater Harbor
DH-2-'68
DH-1-'68
R-4103
PENNSYLVANIA
U.S. MILITARY RESERVATION (FORT MILES)
R-4106A
Sand
DISTRICT NO 10
MB3
R-4105
MTM
ATLANTIC OCEAN
Cape Henlopen
47'30"
38°45'
75°05'
17
20
21
22
25
28
29
30
35
36

FIGURE 15


ATLANTIC OCEAN
REHOBOTH BAY
Rehoboth Beach
Dewey Beach
TB-11-'74
TB-10-'74
TB-9-'74
TB-8-'74
KEB-1-'73
KEB-15-'73
KEB-2-'73
218-'67
241-'67
C10-'67
30-'68
31-'68
C2-'72
KEB-5-'73
GCR-DH-'70
200-'67
240-'67
82-'74
81-'74
KEB-6-'73
C29-'67
C4A-'67
C5-'67
C6-'67
KEB-7-'73
KEB-13-'73
DH-2-'74
48-'71
49-'71
84-'72
KEB-12-'73
239-'67
50-'71
C11-'67
244-'67
C14-'67
Big Nose Island
Little Bacon Island
38
39
41
43
45
46
47
48
49
50
57
58
59
60

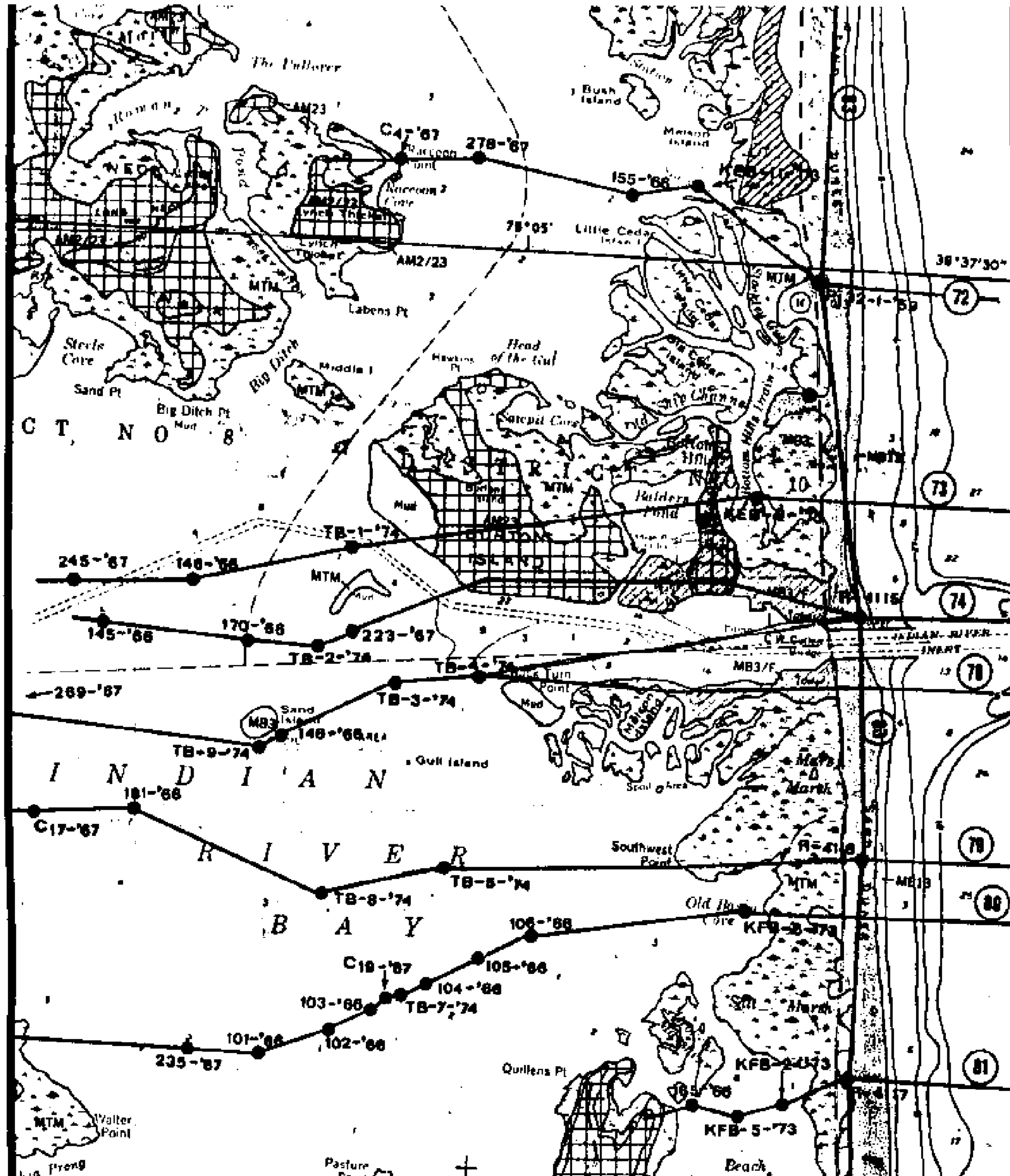


FIGURE 15. INDEX MAP OF THE STUDY AREA SHOWING CORE LOCATIONS AND LINES OF CROSS-SECTIONS. WATER TABLE, SURFACE DRAINAGE, AND ENGINEERING SOILS MAPS NUMBERS HA - 103 (LEWES AREA, DELAWARE: J. K. ADAMS, D. H. BOGGESS, AND C. F. DAVIS, 1964), HA - 109 (REHOBOTH BEACH AREA, DELAWARE: D. H. BOGGESS, J. K. ADAMS, AND C. F. DAVIS, 1964), AND HA - 122 (BETHANY BEACH AREA, DELAWARE: D. H. BOGGESS AND J. K. ADAMS, 1964), PREPARED CO-OPERATIVELY BY THE U. S. GEOLOGICAL SURVEY, DELAWARE GEOLOGICAL SURVEY, AND DELAWARE STATE HIGHWAY DEPARTMENT, HAVE BEEN USED AS THE BASE MAPS.

LEGEND

(15) FIGURE NUMBER OF CROSS-SECTION IN TEXT — FLOOD PLAIN AND SWAMP DEPOSITS

PLEISTOCENE HIGHLANDS — MARSH — FILL

SCALE: 1 — 1/2 — 0 — 1 MILE; 1 — .5 — 0 — 1 KILOMETER

CONTOUR INTERVAL IS 10 FEET AND DATUM IS MEAN SEA LEVEL. DEPTH CURVES AND SOUNDINGS IN FEET; DATUM IS MEAN LOW WATER. SHORELINE SHOWN REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER.

study, together with all cross section lines are shown in Figure 15.

(A) CAPE HENLOPEN SPIT-BEACH-DUNE COMPLEX

The Cape Henlopen spit is a simple spit situated on the southwest side of the entrance to Delaware Bay where it merges with the Atlantic Ocean, and is the northernmost point of this study area. It is about 1.6 km (1 mile) long, and from 0.4 to 0.8 km (¼ to ½ mile) wide. Since the seventeenth century the Cape Henlopen spit has changed from a complex recurved spit system, through a broadly rounded cuspate type, to its present simple configuration. These changes through the years have been described in detail by Kraft (1971b), Kraft and Caulk (1972), Maurmeyer (1974), and Kraft, Allen, Belknap, John, and Maurmeyer (1976). The Cape Henlopen spit is advancing at the present time at a rate of 30 m (98.4 ft.) per year in the northwest direction, whereas the whole complex is migrating west at a rate of 3 m (9.7 ft.) per year, averaged over the past 150 years (Kraft, 1971b; Brickman, Merrill, Belknap, Maurmeyer, and Kraft, 1977). Simultaneously, the Atlantic shore in this area is being continually eroded at a rate of 1-3 m (3.3-10 ft.) per year, averaged over the past 150 years (Kraft, 1971b).

The geomorphic elements of the Cape Henlopen spit-beach-dune-marsh complex as illustrated by Kraft and Caulk

(1972) was shown earlier in Figure 10. The coastal sedimentary environments of this area are the result of several competing processes generated by wind, waves, and tides. These environments are transitory at a given place and change in position and character as the system evolves through time. The transgressive relationship of these coastal depositional sedimentary environments to the pre-Holocene highlands in the area is clearly shown in Figure 10. The entire spit complex has been formed during the Holocene epoch, that is, since about 12,000 years ago; the pre-Holocene (Pleistocene) highland sediments were probably deposited more than 80,000 years before present, with some marine-estuarine deposition in the region about 28,000-29,000 years before present (Kraft, 1971b).

Littoral transport on the Atlantic coast of this barrier complex in the study area is towards the north (Figures 10 and 14). Sands and gravels derived mainly from coastal erosion are carried by littoral transport, which may at times develop current velocities of several knots (Putnam, Munk, and Traylor, 1949), and deposited at the tip of Cape Henlopen in water 18.3 m (60 ft.) or more deep. Ebb tides erode and winnow out fine to medium sand from the spit tip, and deposit it on the submarine Hen and Chickens shoal located southeast of the spit. Flood tides and wave refraction around the spit carry a stream of sediment which is deposited on the tidal flats on the western side (Delaware Bay side) of the spit. The spit is therefore advancing in the northwest direction as evidenced by the arcuate "growth rings" of sediment on this side (Figure 16). The beach on the Delaware Bay side is accreting. This accretion process is further aided by deposition of sediment brought in by littoral transport from the northwest side of Delaware Bay. The two opposing current directions create a null area in the southeast corner of Breakwater Harbor which therefore becomes the site of heavy sediment deposition (Figure 16). This harbor, which was at one time about 6-9 m (20-30 ft.) deep, is now being filled in with silt (Kraft, 1971b; Kraft and Caulk, 1972). Advancing beach ridges dating back to the eighteenth century (Kraft, 1971b) also provide further proof of continual beach accretion in this area. Giant swash bars with wavelengths of up to 30.5 m (100 ft.) and amplitudes of up to 0.3 m (1 ft.) are commonly observed migrating over the rippled tidal flats on the western side of Cape Henlopen spit. Trenches dug in these swash bars revealed planar beds several centimeters in thickness on the tops of the bars. Leading edges of the swash bars show differing angles of cross-beds varying from 3-38°. Swash bar movement depends on tide and wind patterns; greatest movement is produced by a combination of northwest winds and spring flood tides which concentrates wave energy on the tidal flats. Swash bar movements

FIGURE 16. Aerial photograph of Cape Henlopen looking southwards.
(Courtesy of Dr. J. C. Kraft)

ranging from 0-18.3 m (0-60 ft.) have been recorded within a five-month period (Halsey and Kraft, 1971).

The eroding Atlantic coast beach, made up of medium to coarse sands with little gravel, trends N 8° W and is approximately 90 m (295.3 ft.) in width measured from the seaward edge of the dunes to mean low water level (Maurmeyer, 1974). Whereas the backshore area is gently sloping, the beach-face slope, which is dependent on sand size and intensity of wave action (Bascom, 1951), is about 5°. The coarseness of the beach sands may be a contributing factor aiding erosion, since the depth of disturbance by waves is greater for coarse sand than fine sand (King, 1951). Part of the sand eroded is redistributed in the near-shore marine area as a thin veneer, but the greater part is carried to the spit tip by littoral transport.

The general direction of wave approach is from the southeast, and beach erosion takes place when these waves are low and have long periods. The Hen and Chickens shoal, a shallow submarine shoal about 16 km (10 miles) long extending southeast of the Cape Henlopen spit, affects waves approaching from the east and northeast. During storms and winter months, waves have greater height and short periods, and hence they are more destructive. At such times, erosion of the Atlantic coast beach and the tip of Cape Henlopen spit is caused by waves coming from the northeast and northwest directions respectively (Maurmeyer, 1974). It is obvious therefore, that a combination of these waves will cause major coastal erosion. Trenches dug at the Atlantic coast beach, as well as at the tip of Cape Henlopen spit show parallel laminations dipping seaward and parallel to the beach slope. These laminations indicate building up of the beach. Truncated laminae indicating erosion are also commonly observed.

Dune fields cover the Cape Henlopen spit area, and coast parallel dune fields are found along the Atlantic coast. Winds originating from the north, northeast, and southeast directions are primarily responsible for dune field formation (Kraft and Caulk, 1972). Such winds carry sand grains from the exposed beach and berm areas inland to the dunes. Dunes at the spit tip are much smaller than those found in the inner and therefore older areas; the latter range from 9.1-13.7 m (30-45 ft.) in height. Incipient dune growth may be observed in the Cape Henlopen spit area. Sand is trapped by clusters of grass forming small mounds which gradually grow in size becoming dunes. Dunes up to 6 m (19.7 ft.) in height have been observed to form in two years (Brickman, Merrill, Belknap, Maurmeyer, and Kraft, 1977). The Atlantic coast dunes are migrating landward over the Lewes Creek Marsh. Recurved spit tips of former Cape Henlopen found in the Lewes Creek Marsh are now covered by linear dunes and vegetation, but can still be observed on aerial photographs (Figure 14). On the basis of rate of spit advance during the last two centuries, and the dates of artifacts found on these recurved spit tips, Kraft (1971b) considered them to have existed from approximately 2000 to 5000 years before present. An anomalous dune in this area is the large 27.4 m (90 ft.) high and about 3.5 km (2.2 miles) long dune, called the Great Dune or the Galloping Dune of Lewes. It is perpendicular (east-west) to the Atlantic coast (north-south). From a study of historic maps of the area, Kraft (1971b) has found that this dune formed in the early nineteenth century, prior to which it did not exist. Removal of trees and other vegetation from the back-barrier area by man resulted in northwest winds transporting sand inland from the Breakwater Harbor area causing the development and growth of this dune (Kraft and Caulk, 1972). This dune has migrated 0.4 km (¼ mile) in the last century (Kraft, 1971b). Some parts of the Great Dune have now been stabilized by vegetation but most of it is still presently migrating southwards over a forested area, in the direction of Lewes Creek Marsh.

Figure 17 is a geologic cross section across the tip of Cape Henlopen spit. The spit is projecting into a water body at the confluence of the Delaware Bay (west) and

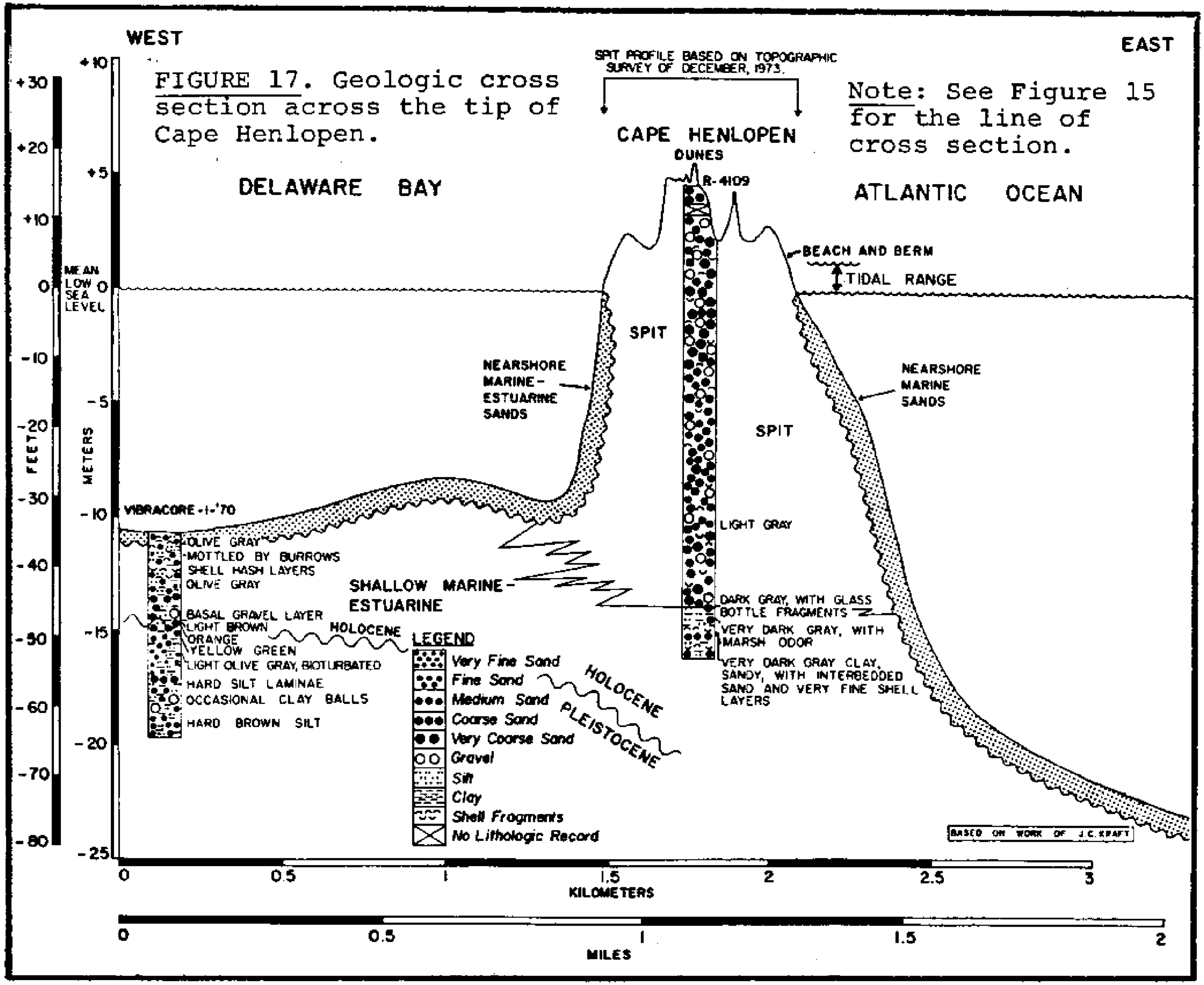


FIGURE 17. Geologic cross section across the tip of Cape Henlopen.

Note: See Figure 15 for the line of cross section.

the Atlantic Ocean (east). The thickness of the spit here is 18 m (59 ft.). Medium to coarse sands and gravels of the spit contain shell fragments and sharply overlie shallow marine-estuarine sediments. Hence this vertical sequence of spit sediments is regressive in nature in an otherwise generally transgressive barrier complex. Spit sediments are overlain by the fine to coarse sands of the beach and dune. The thickness of the spit is slightly greater on the north side than on the northwest side. The latter side is growing by sediment deposition as the spit continues to grow forward due to the large supply of sediment by littoral transport from the eroding Atlantic coastal areas to the south. As the spit grows into deeper water, it acts as a breakwater positioned between the Atlantic Ocean and the Delaware Bay (Figure 17) causing deposition of sediment on the lee side of it in the Lewes Harbor. The presence of a glass fragment almost at the base of the spit sequence (-18 m; -59 ft.) indicates man's infringement on nature, and also the fact that the whole vertical spit sequence is of recent development. Vibracore 1-'70 taken in Delaware Bay to the west of the Cape Henlopen spit encountered shallow marine-estuarine olive gray sediments, and also penetrated the Pleistocene sediments identified by their characteristic orange or oxidized color.

Environmental interpretations in the subsurface have been made on the basis of criteria listed in Table II. These criteria have been developed on the basis of studies of present day environments of the barrier complex by Kraft (1971b) and the work done during the course of this study.

Figures 18A and 18B are photographs of core R-4109 seen in the cross section (Figure 17) and located at the spit tip. These photographs show the sedimentary structures, color, and comparative grain sizes of the spit sediments. The sharp contact between the spit sediments and the shallow marine-estuarine sediments is clearly discernible in Figure 18B, on the basis of composition and color. Figure 19 shows detailed lithology, grain-size parameters, electric log curves, sedimentary structures based on photographs (Figures 18A and 18B), and environmental interpretations for core R-4109.

Electric log data consisting of the two basic curves (1) self or spontaneous potential curve (SP curve), and (2) the resistivity curve, in combination with the other characteristics of the core shown in Figure 19, often provide valuable aid for interpretation of depositional environments. Compositional changes in sediment reflecting changes in environment are shown in the electric logs. As seen in Figure 19, the SP curve is shown on the left side of the electric log, and the resistivity curve is shown on

TABLE II: CRITERIA FOR ENVIRONMENTAL IDENTIFICATION IN THE BARRIER COMPLEX OF THE STUDY AREA

ENVIRONMENT		SEDIMENTARY CHARACTERISTICS
BARRIER	Dune	Sands are medium to fine grained, well sorted, and positively skewed.
BARRIER	Beach-berm and sub-lagoonal washover barrier	Medium to coarse grained sands with little gravel and some shell fragments. Moderately well sorted to well sorted. Negatively skewed. Sub-lagoonal washover barrier sands are fine to medium grained and moderately well sorted, with some silt and shell fragments.
BARRIER	Spit	Medium to very coarse sands with gravel and some shell fragments. Moderately sorted and negatively skewed.
BARRIER	Washover	Fine to coarse and poorly sorted to well sorted sands. Often occurs as a sand lens between lagoonal and/or marsh sediments. Average thickness 1 m or less.
BARRIER	Tidal delta	Poorly to moderately sorted fine to coarse sands. Positively or negatively skewed. Cross-lamination common.
Lagoon		Gray to dark gray or brown silt and clay with lagoonal fauna (*Crassostrea virginica*, *Mercenaria mercenaria*, *Elphidium*). Occasional plant fragments.
Marsh		Gray, brown, or black silt with abundant plant fragments (*Spartina*) and/or peat.
Shallow marine-estuarine		Fine to medium sands with silt and clay. Shallow marine-estuarine fauna (*Macoma*, *Ensis*, *Pholas*, *Anomia*).
Pre-Holocene		Pleistocene sediments have an oxidized light tan, light green, blue, greenish-blue, orange or yellow coloring and mottling. Relatively stiff and compact sediment. Medium to very coarse sands with gravel, silt, and clay. These sediments underlie Holocene sediments with an unconformable relationship. Frequently a basal peat dated from 7,000 to 11,000 years before present overlies the Pleistocene sediments thus proving the pre-Holocene age of these sediments. Further, 10 definite Wisconsinan age radiocarbon dates and 12 greater than 40,000 years before present dates have been determined from this stratigraphic unit (Belknap, 1975). Miocene sediments are identified on the basis of their fauna.

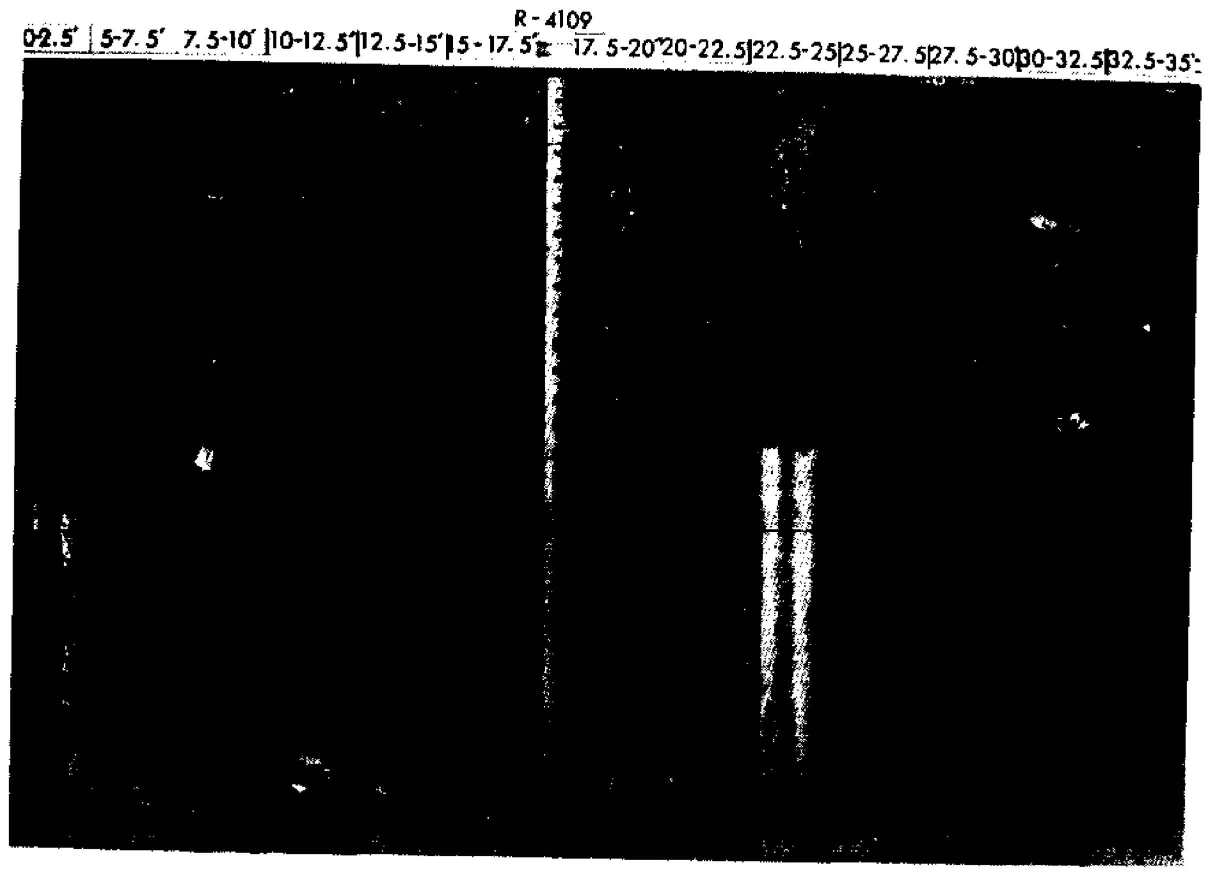


FIGURE 18A. Photograph of core R-4109 (0-35 ft.; 0-10.7 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

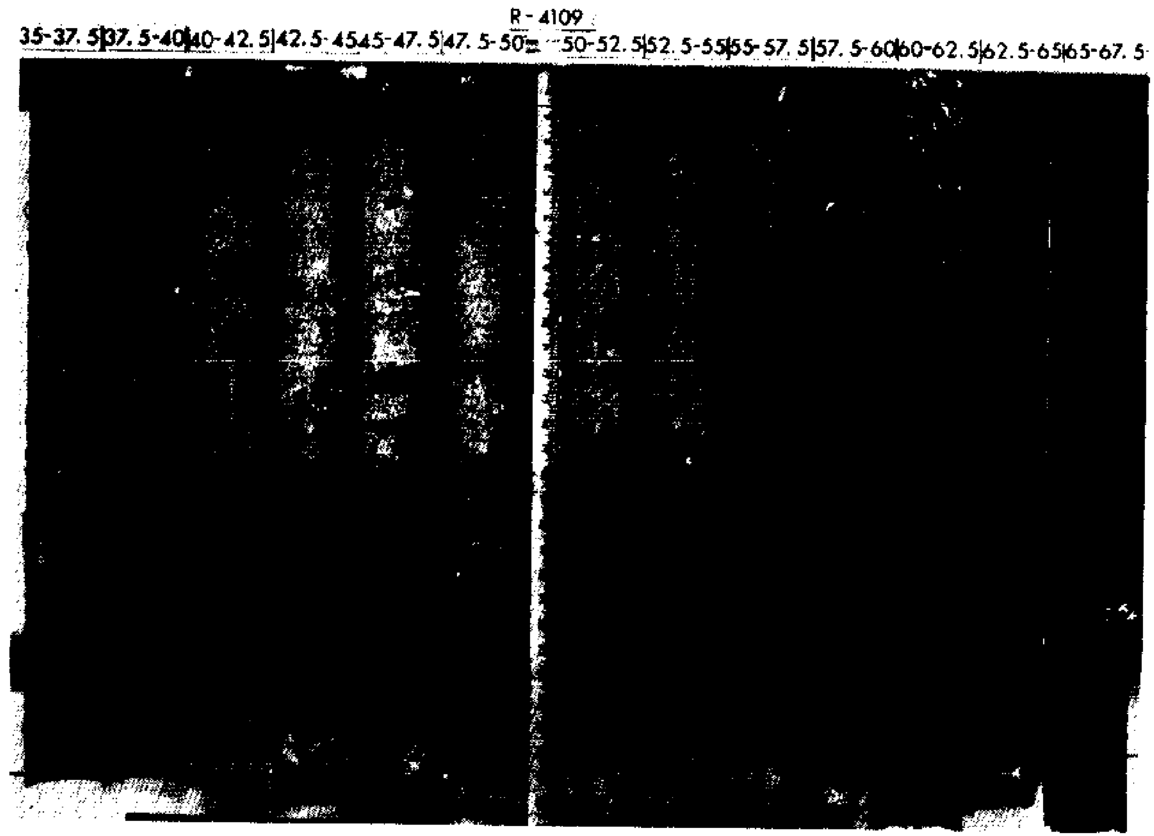


FIGURE 18B. Photograph of core R-4109 (35-67.5 ft.; 10.7-20.6 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

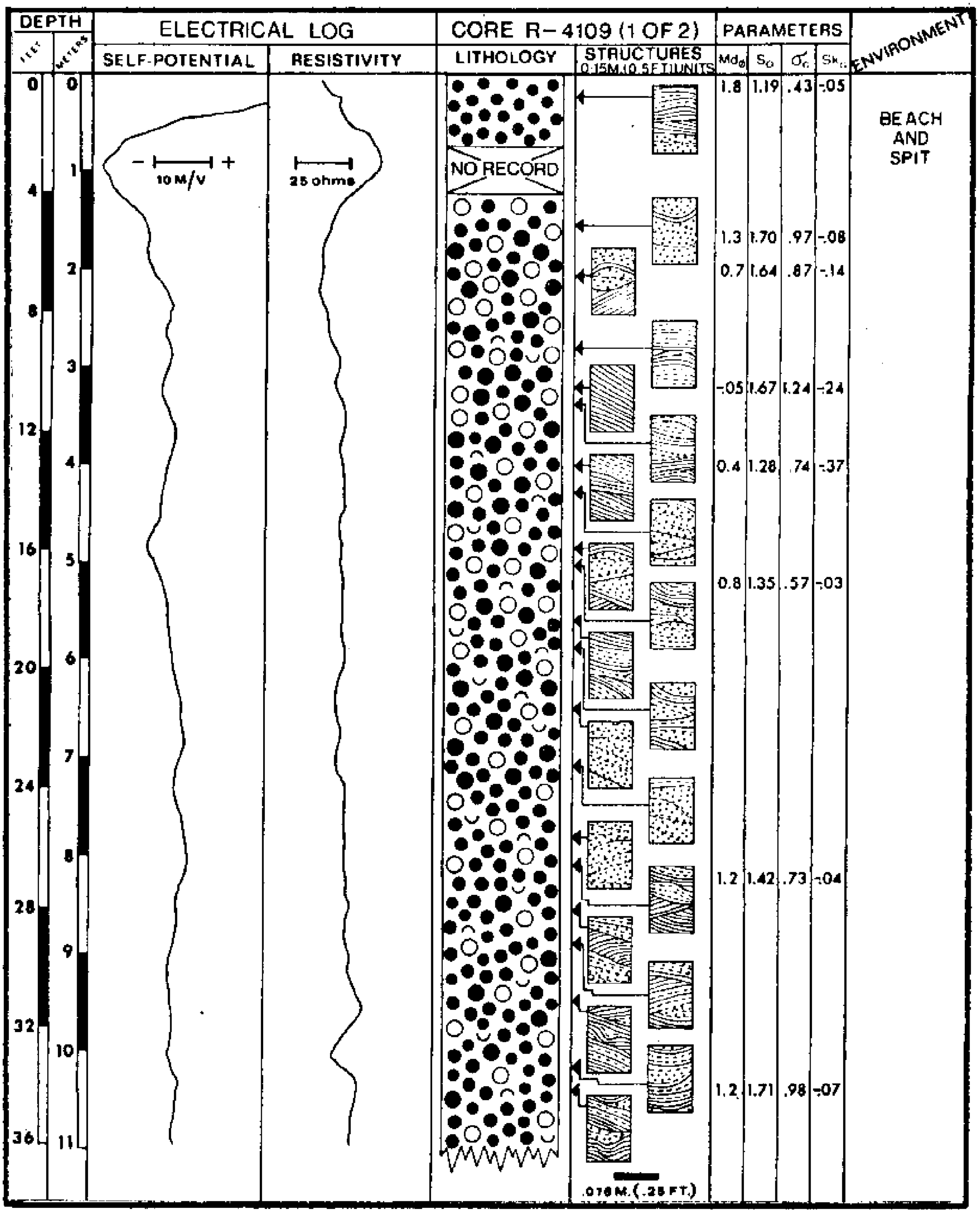


FIGURE 19. Geophysical, sedimentological, and sedimentary structure data for core R-4109. (cont.) →

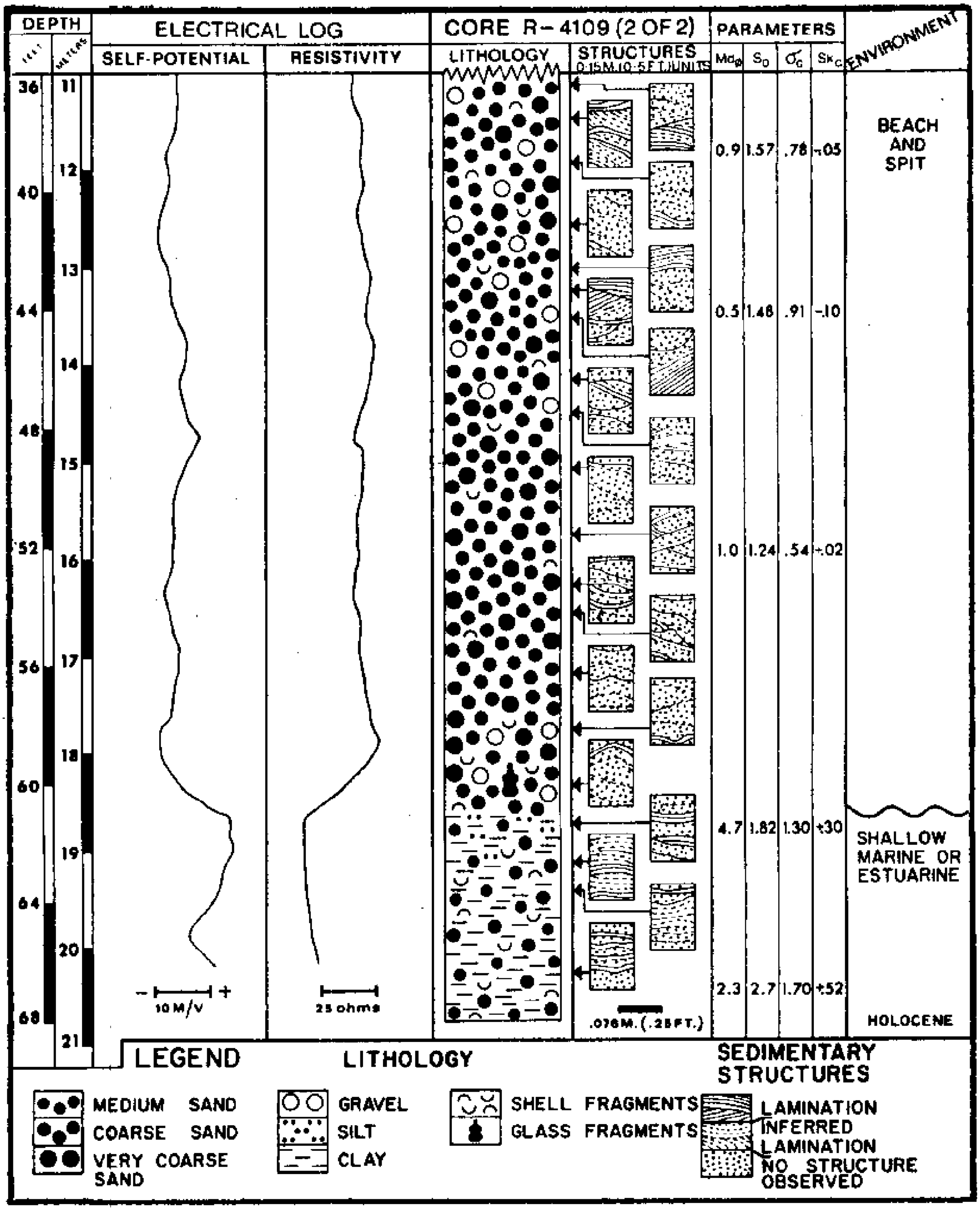


FIGURE 19 (cont.). Geophysical, sedimentological, and sedimentary structure data for core R-4109.

the right side. The SP log measures electrical difference between the fluid in the drill hole and the fluid contained in the rock or sediment body, whereas the resistivity curve measures resistance offered by a rock or sediment unit to the flow of an outside electric current. Much work has been done on attributing characteristic curve shapes to different depositional environments. General information on this subject can be found in Moore (1963), Fons (1969), Pirson (1970), Allen (1975), and Conybeare (1976). Transgressive and regressive sequences are indicated by a Christmas tree and an upside down Christmas tree SP curve pattern respectively (Fons, 1969). Again, Pirson (1970) related bell-shaped patterns to transgressive sediment bodies, barrel-shaped patterns to stable shorelines, and funnel-shaped SP curve patterns to regressive sand bodies. A transgressive sequence develops horizontal parallel fingers on the SP curve, the amplitude of which decreases upwards. In regressive situations, the SP curve fingers exhibiting horizontal parallel symmetry have amplitudes increasing upwards (Pirson, 1970). The relatively uniform curve pattern in Figure 19 for core R-4109 indicates periods of uniform conditions, rapid sediment deposition, and homogeneity of internal structure (Allen, 1975).

Before discussing sedimentary structures, a short review of the terminology used for this purpose would be appropriate for presenting a clearer picture. Stratification or layering is a characteristic of sedimentary bodies; it differs widely in form, size, and shape. Characteristic arrangements of layers (sedimentary structures) are generally attributed to different types of sedimentary environments (Kukal, 1971), and also thought to identify depositional processes. Unfortunately, different authors have applied descriptive terms to sedimentary structures in different senses causing vagueness, overlapping, and terminological confusion. Reineck and Singh (1973) provide some information on this subject. In the present study, a combination of the descriptive and quantitative terminology used by McKee and Weir (1953), Ingram (1954), and Campbell (1967), has been used. The terms "lamina", "lamination", and "cross-lamination" are the most frequently used. A "lamina" is defined as the smallest megascopic layer in a sedimentary sequence, and is generally measured in millimeters (Campbell, 1967). Other important characteristics of a lamina according to Campbell (1967) are as follows:

> (1)It is relatively uniform in composition and texture; (2) is never internally layered (at least megascopically); (3) has a smaller areal extent than the enclosing bed, except in some instances where laminae parallel bedding surfaces; and (4) forms in a shorter period of time than the encompassing bed.

McKee and Weir (1953) confined the term "laminated" to strata from 2 mm to 10 mm (0.08 to ½ inch) thick, and "thinly laminated" to strata 2 mm or less in thickness. When layers are inclined at one or more angles to the dip direction of the formation, and are less than 1 cm (½ inch) in thickness, they are said to be "cross-laminated". Depending on whether the lower bounding surfaces of sets of laminae are non-erosional, planar, or curved surfaces of erosion, the terms "simple cross-lamination", "planar cross-lamination", and "trough cross-lamination" respectively, are used. Again, when cross-lamination arches upward it is referred to as "convex", if it arches downward it is termed "concave", and when not arched it is called "straight". Also, when laminae are inclined at 20° or more they are considered as "high-angle" laminations; if less than 20°, they are "low-angle" laminations (McKee and Weir, 1953). Characteristics of beach laminae have been described by Thompson (1937).

It is generally believed by Grant (1943) and others, that laminations are produced due to variations in the transporting capacity of waves. In a similar manner, dune laminations result from variations in wind velocity. Single or many laminae may form in a day or several days, and no specific time interval is related to the formation of a lamina (Thompson, 1937). Lamination is often emphasized due to differing grain sizes and the presence of dark colored heavy minerals. A short discussion on types of lamination is given by Coleman and Gagliano (1965). Other relevant information is provided by McKee (1948, 1957), Emery and Stevenson (1950), Allen (1963, 1965), Crook (1965), Middleton (1965), Jopling (1965), and Hoyt (1962, 1967b).

Each of the sedimentary structure blocks illustrated in Figure 19 for core R-4109 represents a section which is 0.076 m (.25 ft.) in width, and 0.15 m (0.5 ft.) in length. The structures illustrated are seen at that part of the core indicated by the arrow, downwards. When studying these structures in a core it should be kept in mind that what is being looked at may be (a) the true internal structure of the barrier, (b) part of a larger structure, and (c) the internal structure of a larger sedimentary feature, like a giant sand wave, or something else. This is obviously a risk inherrent with core samples, and is difficult to avoid. Hence the interpretations of sedimentary structures are subject to misinterpretations because of limitations placed on observations in a core. As seen in Figure 19, high-angle laminations are common in core R-4109. These are probably produced by sediment deposition at the spit tip in deep water. Planar cross-laminations and in some cases convex and concave laminations are also observed.

Sedimentary parameters for core R-4109 are also shown in Figure 19. The average sediment grain size ranges from medium to coarse. Since all values of Trask's coefficient of sorting for the spit sediments are less than 2.5, they are considered to be well sorted. However, the Inman graphic standard deviation values indicate spit sediments to be moderately well sorted to moderately sorted. As is to be expected, the sands are negatively skewed. The sediments of the Cape Henlopen spit area, and also the other parts of this barrier complex, are coarser grained than those of the Texas Gulf Coast barriers as described by Shelton (1973). The interpretation of environments for core R-4109 is based on criteria listed in Table II, as well as the other characteristics shown in Figure 19. Sub-environments in the vertical sequence of the spit cannot be differentiated on the basis of grain-size parameters as they are not significantly different or characteristic.

Figure 20 represents a cross section of Cape Henlopen in a wider part of the spit, further south than that shown earlier in Figure 17. The thickness of the medium to coarse sand and gravel spit sequence in both these areas are approximately similar. Here again, the dune-beach-spit sediments sharply overlie the shallow marine-estuarine sediments thereby resulting in a regressive vertical sequence. Ebb tides erode and sort out

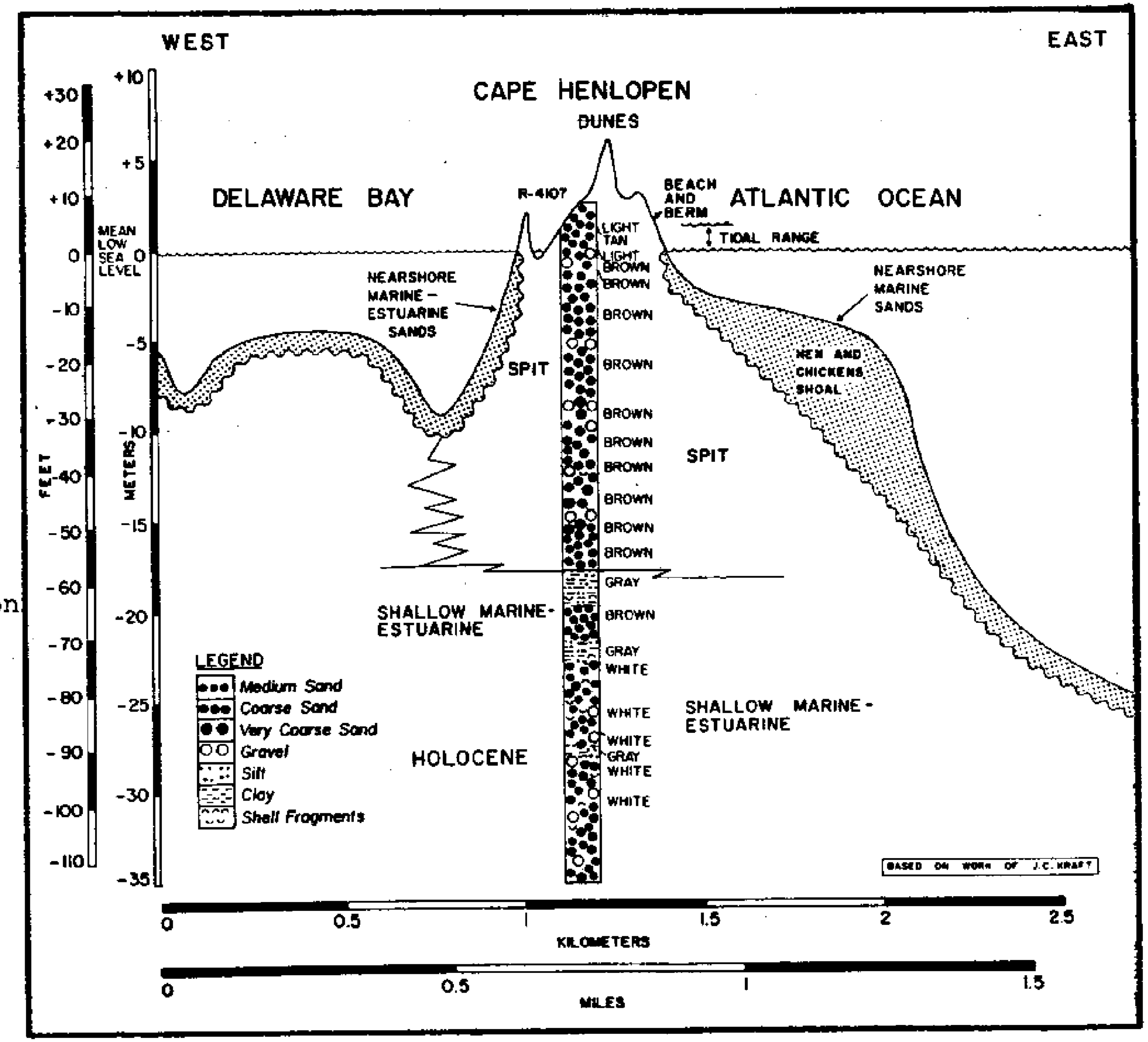


FIGURE 20

Geologic cross section across Cape Henlopen. See Figure 15 for the line of cross section fine to medium sands from the spit tip and deposit them on the Hen and Chickens shoal, shown in this cross section.

Figure 21 is a geologic cross section in which the general relationship of the Cape Henlopen spit to the Hen and Chickens shoal can be observed. The ancestral Delaware River channel lies to the east of the Hen and Chickens shoal. As before, the dune-beach-spit sediments are medium to coarse grained sands with gravel, and some shell fragments. These sands overlie the shallow marine-estuarine silty medium to coarse sand. The nature of the contact between sediments of the two environments in this case is rather gradational and not as sharp as was the case in the cross sections described earlier. The presence of silt in the sands and a greater amount of shell fragments indicates the change to the shallow marine-estuarine environment. Core DH-2-'68 has penetrated the Pleistocene sediments, identified on the basis of sediment compaction and color. In response to a rise in sea level, shoreline Pleistocene sediments were inundated by the transgressing sea, and shallow marine-estuarine sediments were deposited over it, as seen in the cross section. This represents a transgressive sequence. However, the story does not end here. Sediment brought in by littoral transport from the south to north was deposited at the end of the spit resulting in its growth into this transgressive environment,

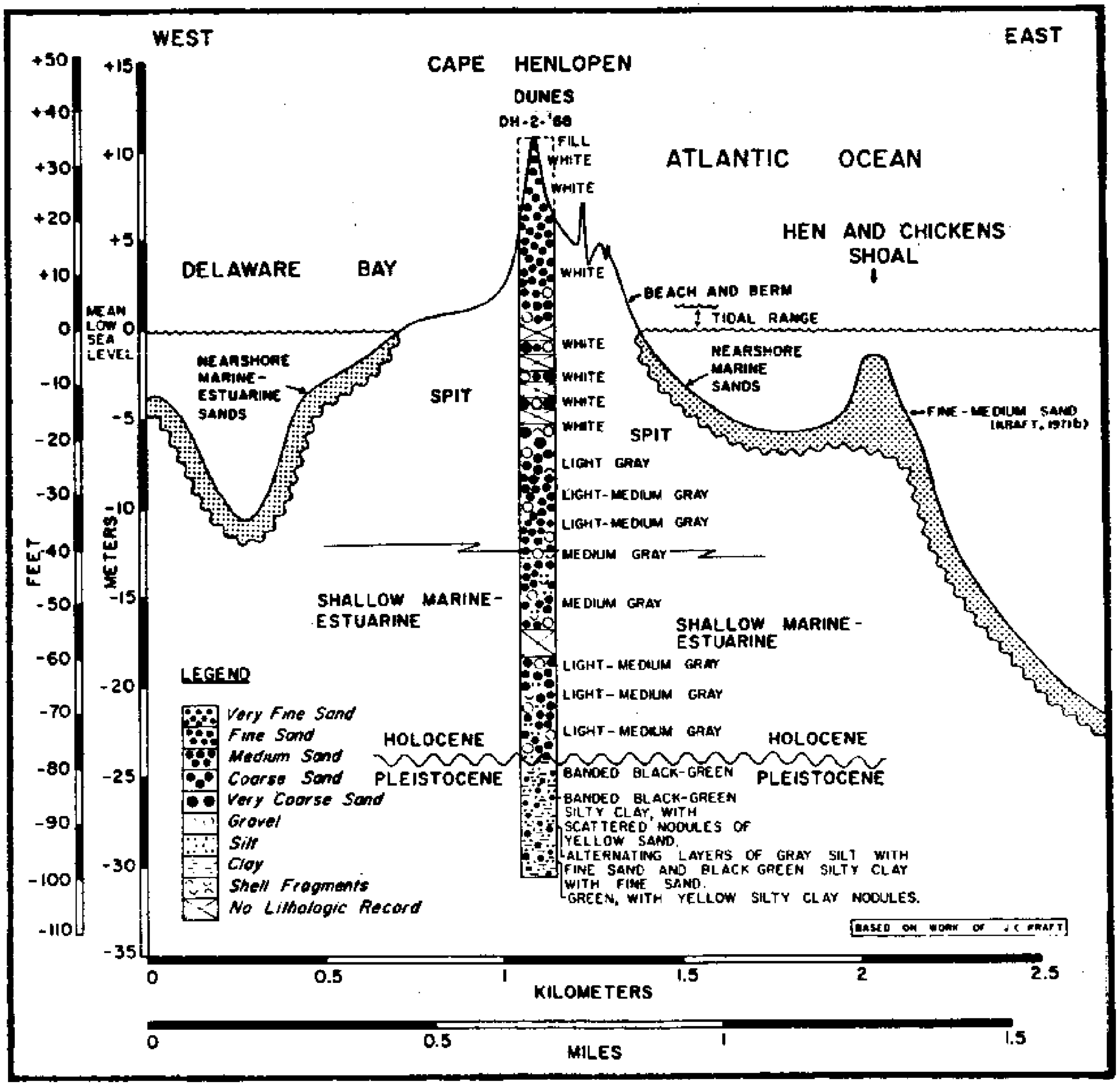


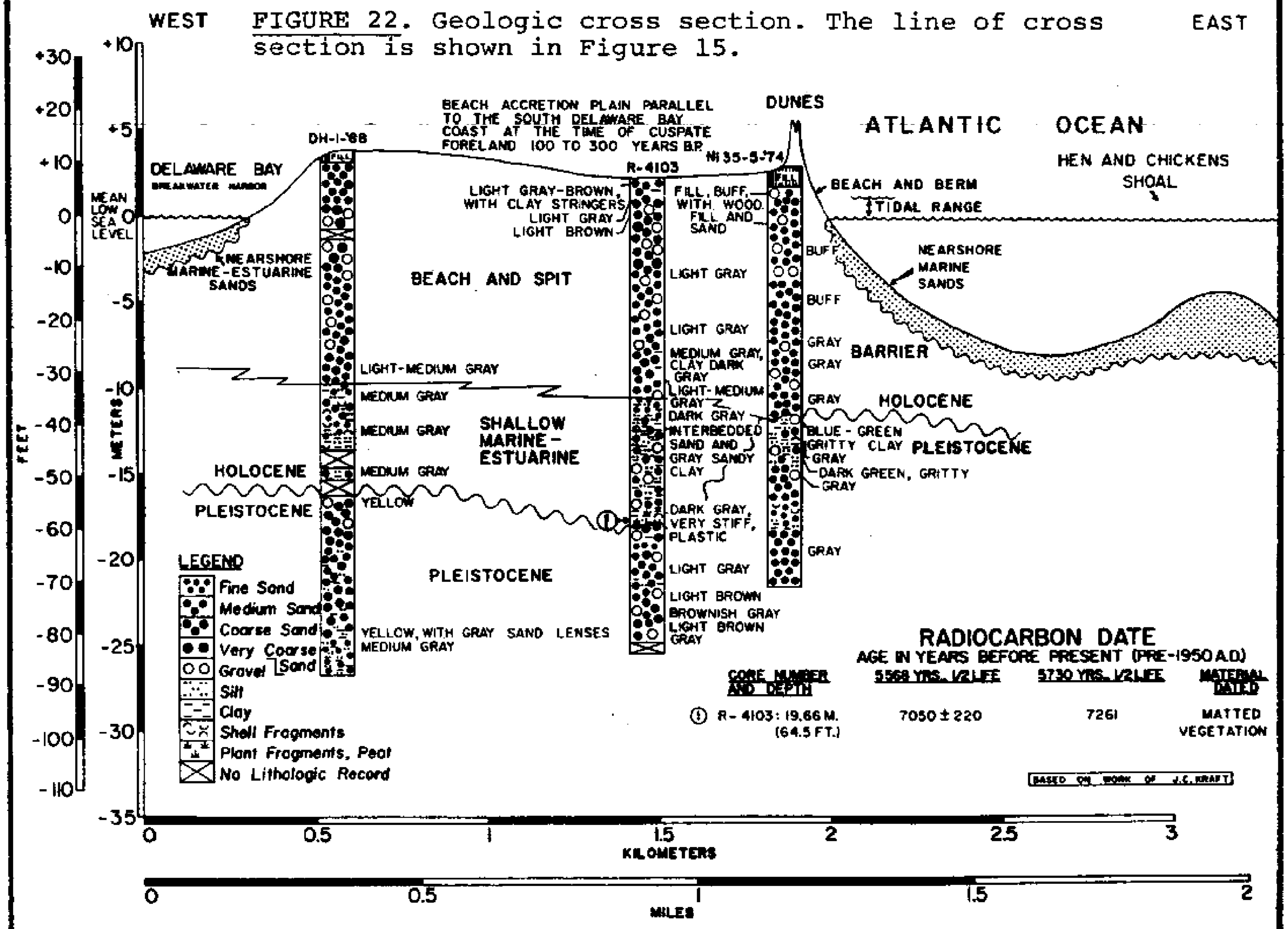
FIGURE 21

Geologic cross section across Cape Henlopen. See Figure 15 for the line of cross section.

thereby creating a regressive situation. Hence, the vertical sedimentary sequence in this cross section (Figure 21) indicates a transgressive sequence (shallow marine-estuarine sediments over Pleistocene sediments), as well as a regressive sequence (spit sediments over shallow marine-estuarine sediments).

The line of cross section for Figure 22 passes through the beach accretion plain which was developed when the spit was of a rounded cuspate type. Medium to coarse grained sands and gravels representing the beach accretion plain are seen overlying shallow marine-estuarine medium sands with gravel and shell fragments intermixed with silt and clay in cores DH-1-'68 and R-4103; in core Ni35-5-'74 the barrier sediments directly overlie Pleistocene sediments. The accretion of the Delaware Bay side beaches, causing silting in the present Breakwater Harbor, can be clearly seen in this cross section. A radiocarbon date of 7,250 years before present, obtained just above the contact between shallow marine-estuarine sediments and Pleistocene sediments in core R-4103, indicates that this area may have been occupied by an isolated small coastal marsh at that time before being overlain by shallow marine-estuarine sediments. Also, the general drop and rise of the Pleistocene surface from core DH-1-'68 to Ni35-5-'74 through core R-4103 indicates that the location of core

FIGURE 22. Geologic cross section. The line of cross section is shown in Figure 15.



R-4103 was probably the axis of an ancestral stream valley flowing into the Delaware River at that time. The barrier sediments seen in this cross section are of lesser thickness when compared to previously described cross sections to the north. This is to be expected, since the spit sediments are being deposited in deeper water, and consequently the resulting vertical thickness of sediments will increase northwards. Here again, as in the previous cross section (Figure 24), both transgressive and regressive sequences are represented. Figures 23A, 23B, and 23C, are photographs of core R-4103 seen in the cross section (Figure 22). Sedimentary structures and comparative differences in sediment grain size and color can be seen in these photographs.

Figure 24 is a detailed summary of the lithology, grain-size parameters, sedimentary structures, electric log curves, and environments for core R-4103. The electric log curves in this case do not show any strikingly characteristic shapes indicating either transgression or regression. However, the generally increasing amplitude of the SP curve from the boundary of the beach and spit sediments with the shallow marine-estuarine sediments, to the left of a base line, is indicative of a regressive situation in this part of the vertical sequence. The detailed lithology for core R-4103 (Figure 24) shows that

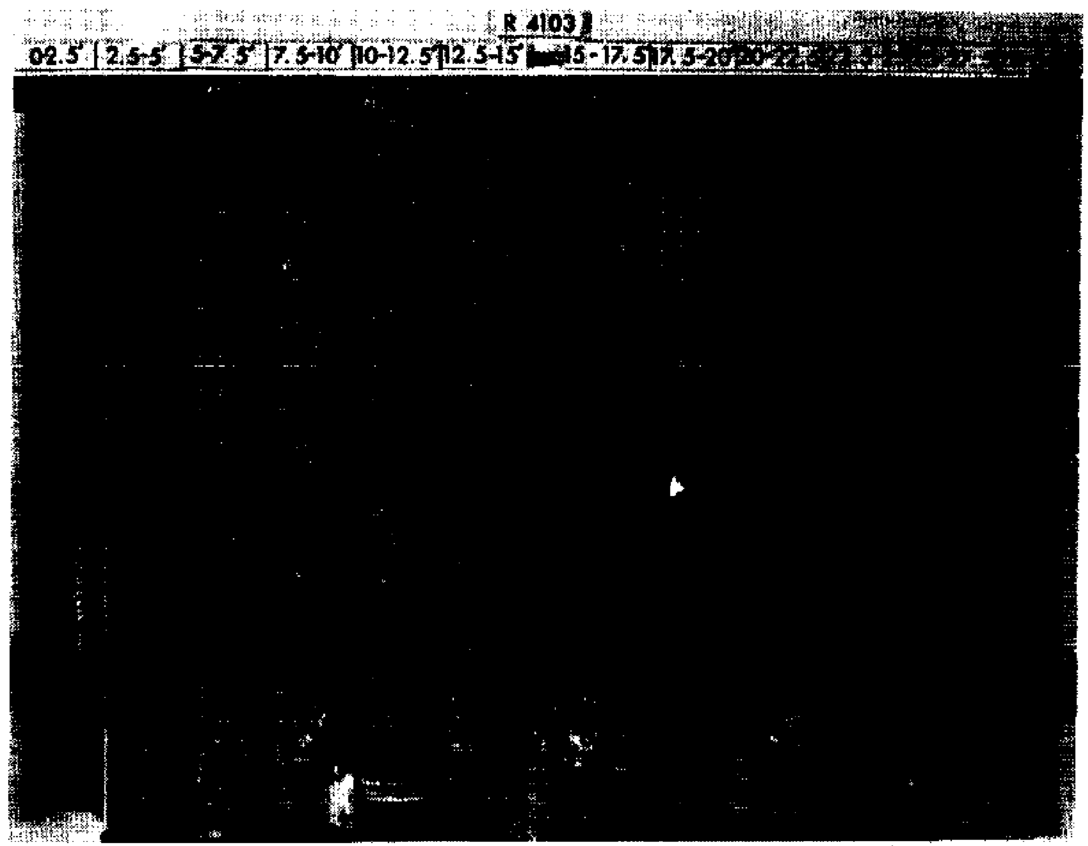


FIGURE 23A. Photograph of core R-4103 (0-30 ft.; 0-9.1 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

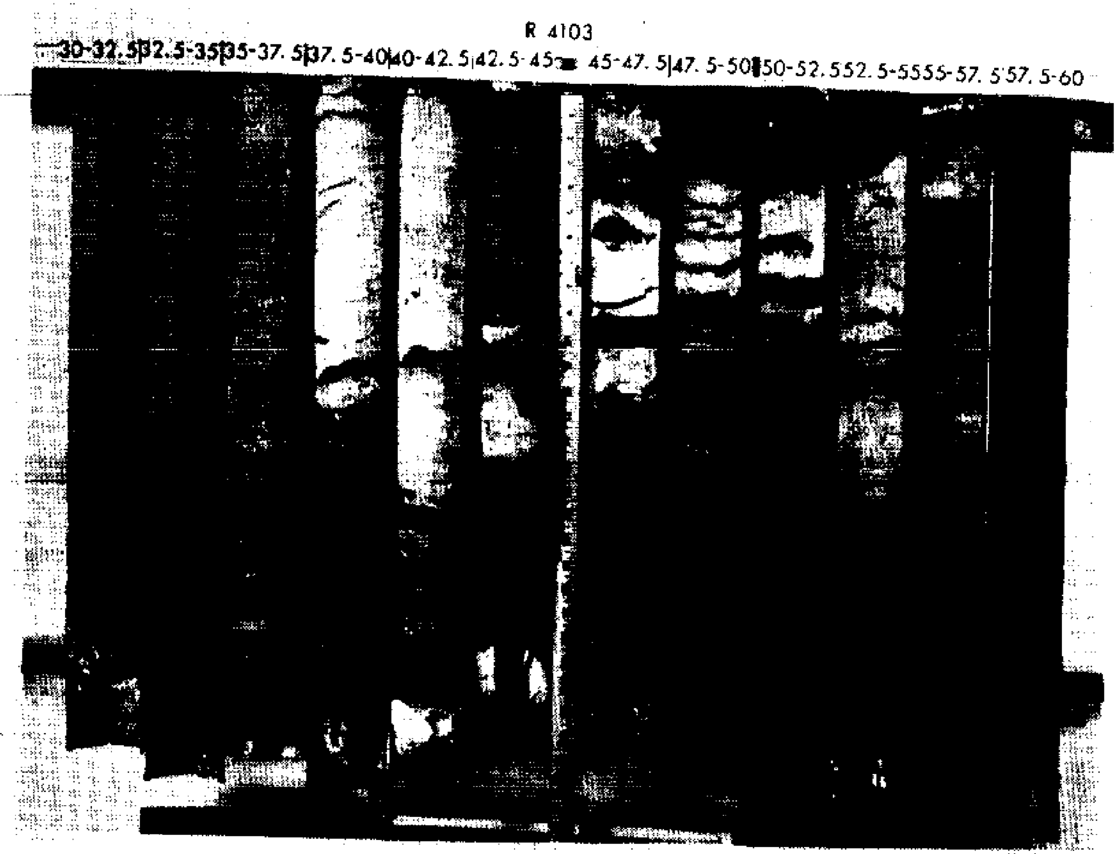


FIGURE 23B. Photograph of core R-4103 (30-60 ft.; 9.1-18.3 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

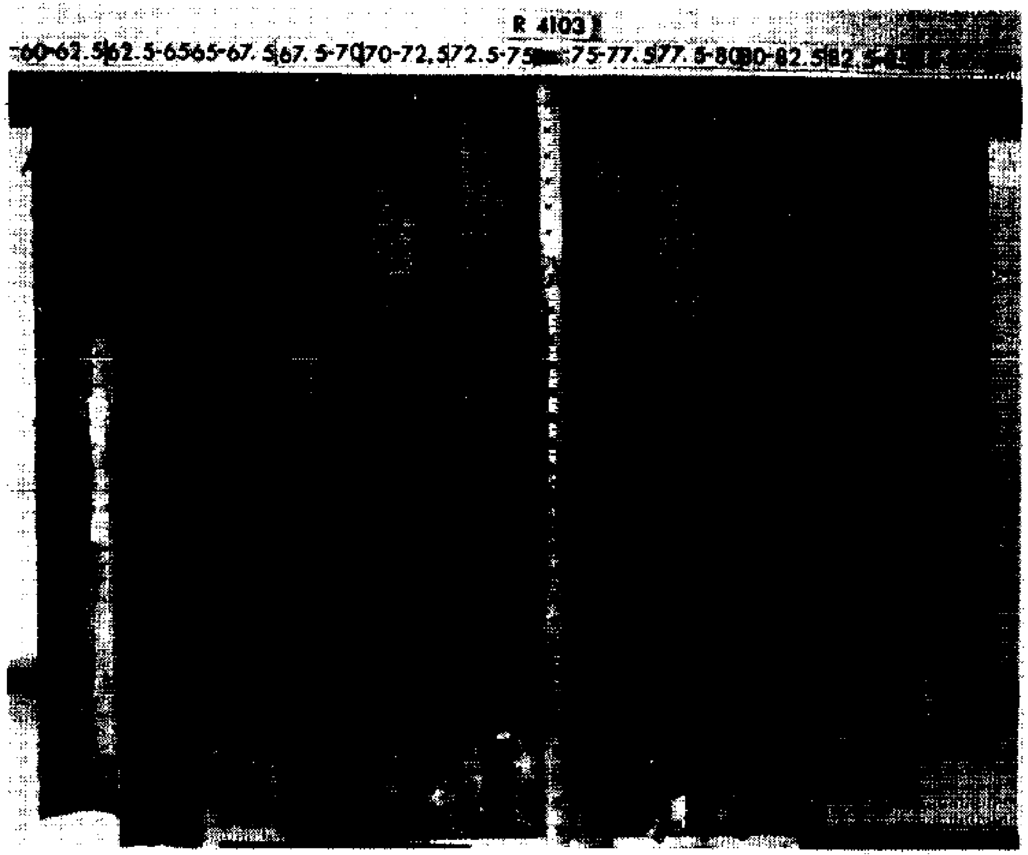
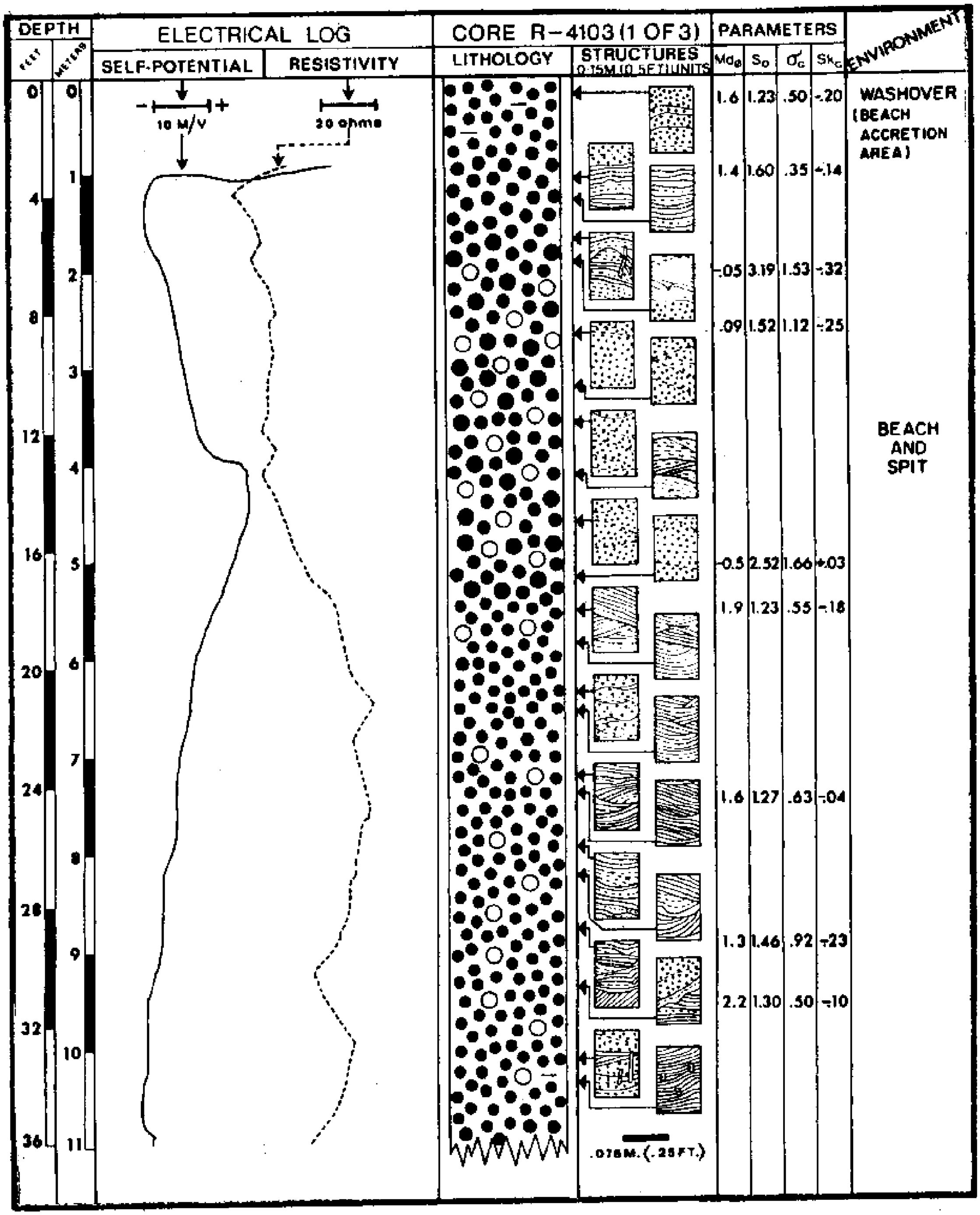


FIGURE 23C. Photograph of core R-4103 (60-87.5 ft.; 18.3-26.7 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)



Md	So	σ	Sk
1.6	1.23	.50	-.20
1.4	1.60	.35	+.14
-.05	3.19	1.53	-.32
.09	1.52	1.12	-.25
-0.5	2.52	1.66	+.03
1.9	1.23	.55	-.18
1.6	1.27	.63	-.04
1.3	1.46	.92	-.23
2.2	1.30	.50	-.10

FIGURE 24. Geophysical, sedimentological, and sedimentary structure data for core R-4103. (cont.) →

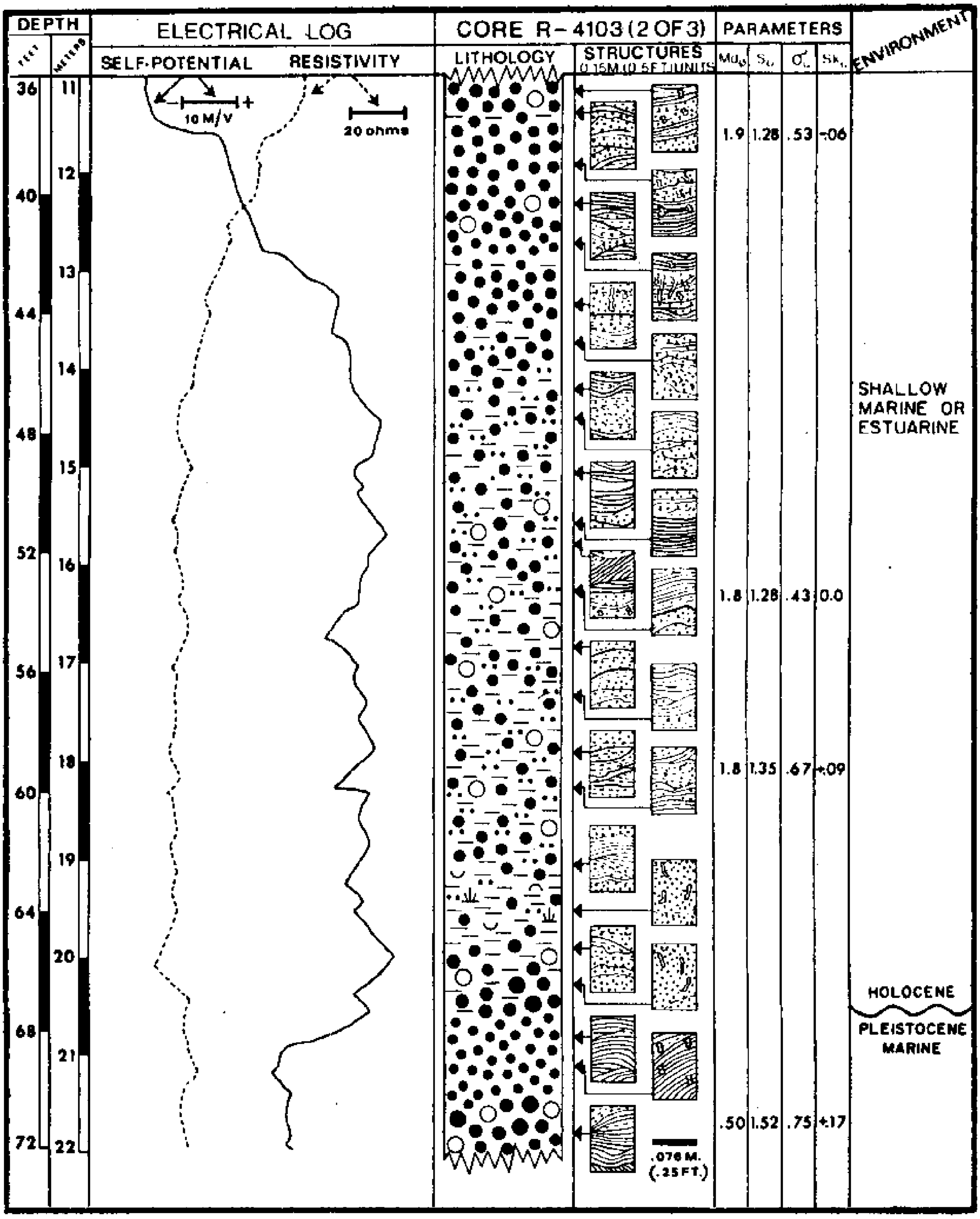


FIGURE 24 (cont.). Geophysical, sedimentological, and sedimentary structure data for core R-4103. (cont.)→

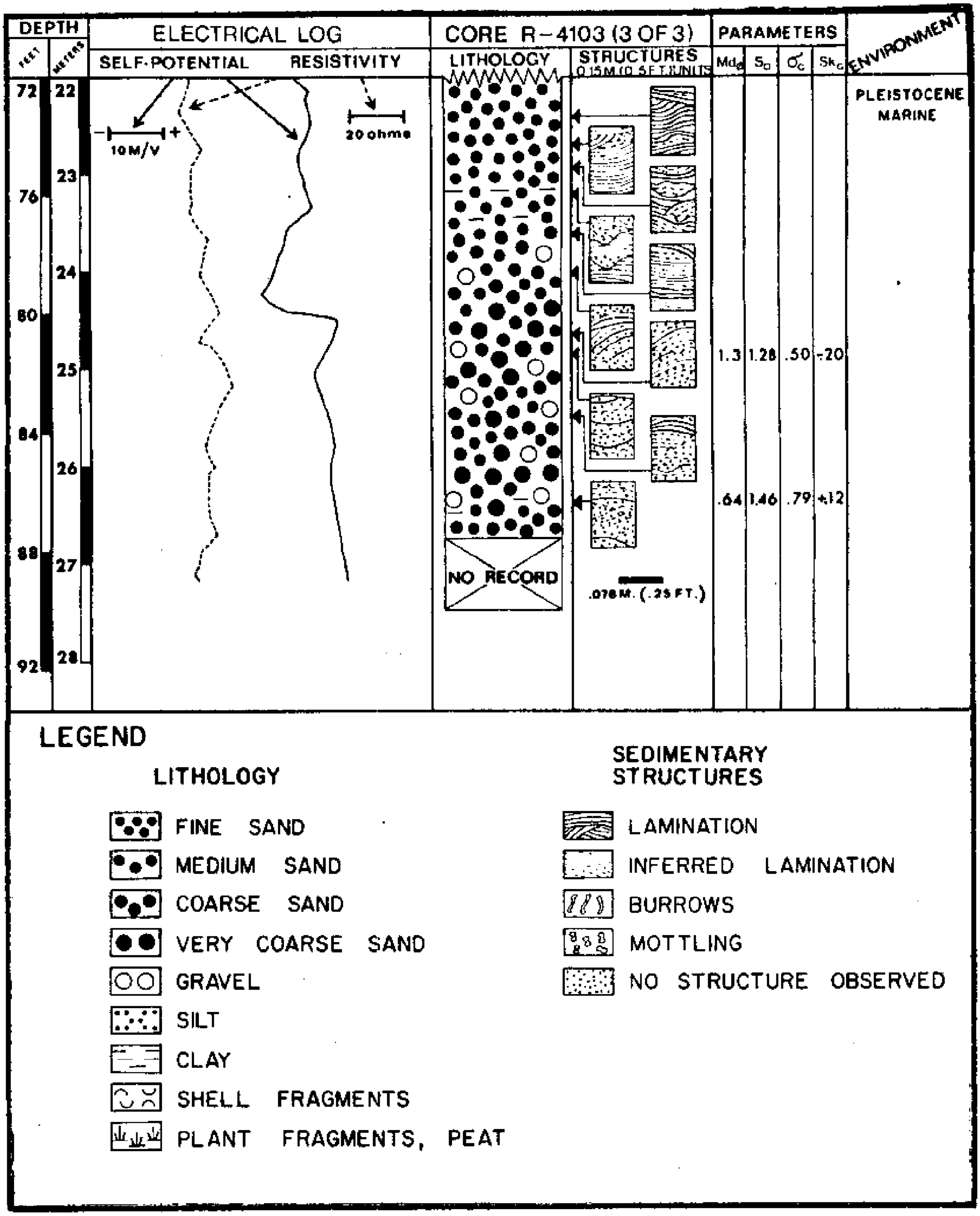


FIGURE 24 (cont.). Geophysical, sedimentological, and sedimentary structure data for core R-4103.

the beach accretion and washover area is characterized by coarse to very coarse sands and gravels; the beach and spit sediments are medium to coarse grained sands with some gravel. On the basis of Trask's coefficient of sorting values, all sediments in the core come under the well sorted category. Using graphic standard deviation values, the sediments of the beach accretion plain and washover area are poorly sorted, while the beach and spit sediments are generally moderately well sorted. Barrier sediments are negatively skewed. Since the grain-size parameter values are not significantly different within the barrier environment, sub-environments cannot be effectively delineated by plotting combinations of any two parameters. Sedimentary structures in the beach accretion plain and washover area, as seen in the core, consist of straight parallel laminations, and convex and concave laminations. Few burrows are also observed. Coming down the core into the beach and spit sediments, simple and planar cross-laminations and concave laminations are most prevalent. Burrows appear more common where some amount of silt and clay are intermixed with sand, especially near the contact with shallow marine-estuarine sediments. Mottling is also present in this part of the core, and in some cases is superimposed to varying degrees on the laminations. Mottling is readily recognized by mixing of colors, or by the presence of irregularly shaped lumps, lenses, pockets, or tubes of sediment which are randomly enclosed in another matrix of contrasting texture. Mottling is considered to be a secondary structure, and is generally caused by the burrowing activities of organisms. In some parts of the core laminations have been partially or completely obliterated. Where partially visible, they have been drawn by inference using a dashed line (Figure 24).

Figure 25 shows a geologic cross section which runs more or less along the axis of the Great Dune of Lewes, across the barrier, and into the nearshore marine environment. The barrier here is formed by the eroding edge of the high dune which is perpendicular to the Atlantic coast and is of small thickness. The medium grained dune sands overlie the coarse to very coarse sands and gravels of the spit, which in turn overlie the fine to medium grained shallow marine-estuarine sands and silty clay. Figure 26 is a photograph of core R-4106 showing the sedimentary structures observed in the dune sands. This core is similar in lithology to core R-4106A which is shown in the cross section, and is located adjacent to it. Figure 27 is a summary of lithology and electric log data for core R-4106 and also core R-4106A. The grain-size parameters shown and the sedimentary structures illustrated are for core R-4106. As seen in Figure 27, the SP curve does not show any

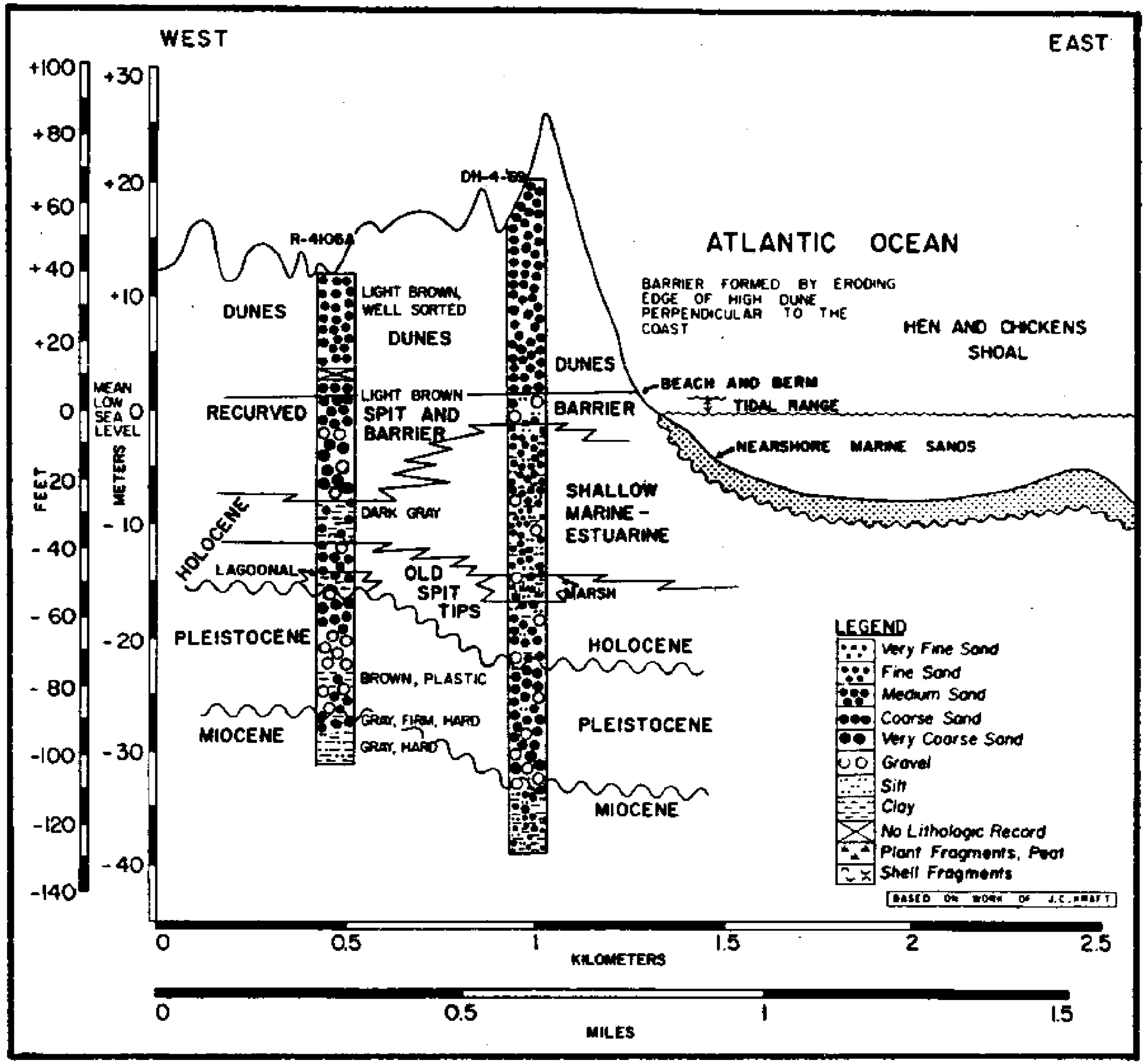


FIGURE 25

Geologic cross section. The line of cross section is shown in Figure 15.

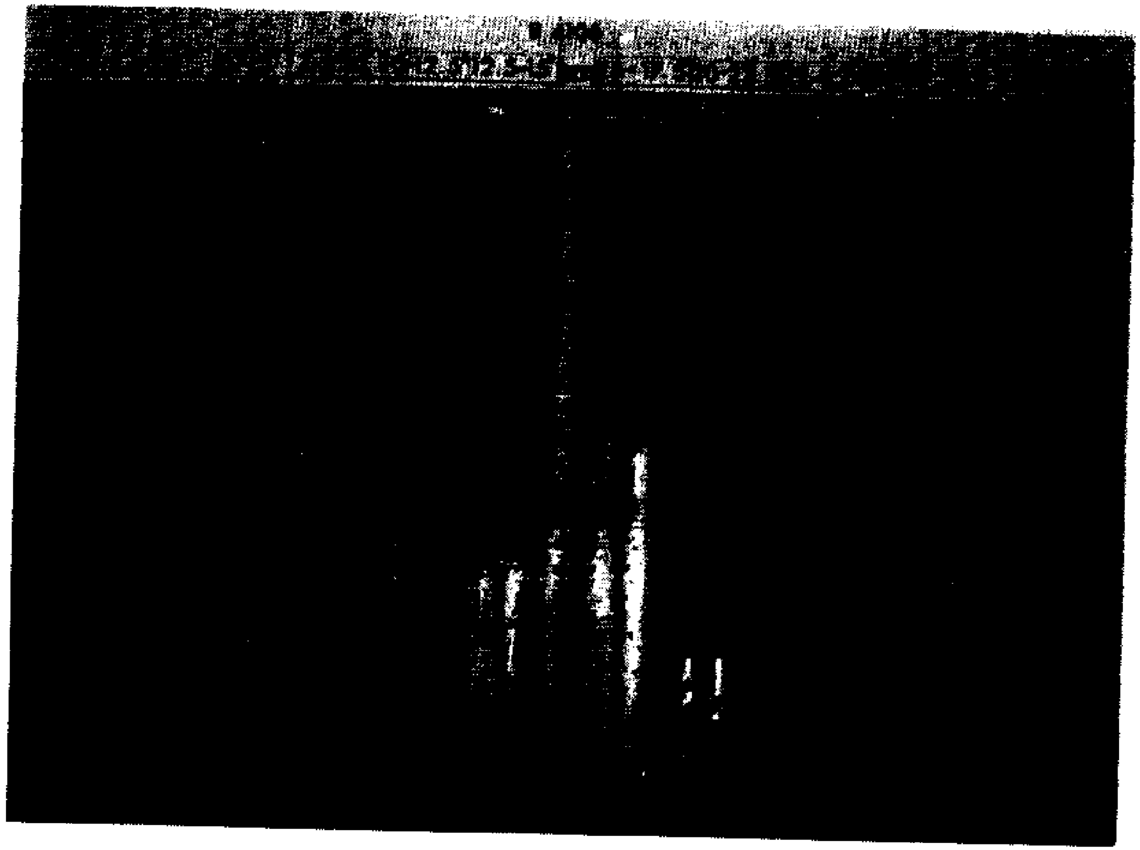


FIGURE 26. Photograph of core R-4106 (0-32.5 ft.; 0-9.9 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

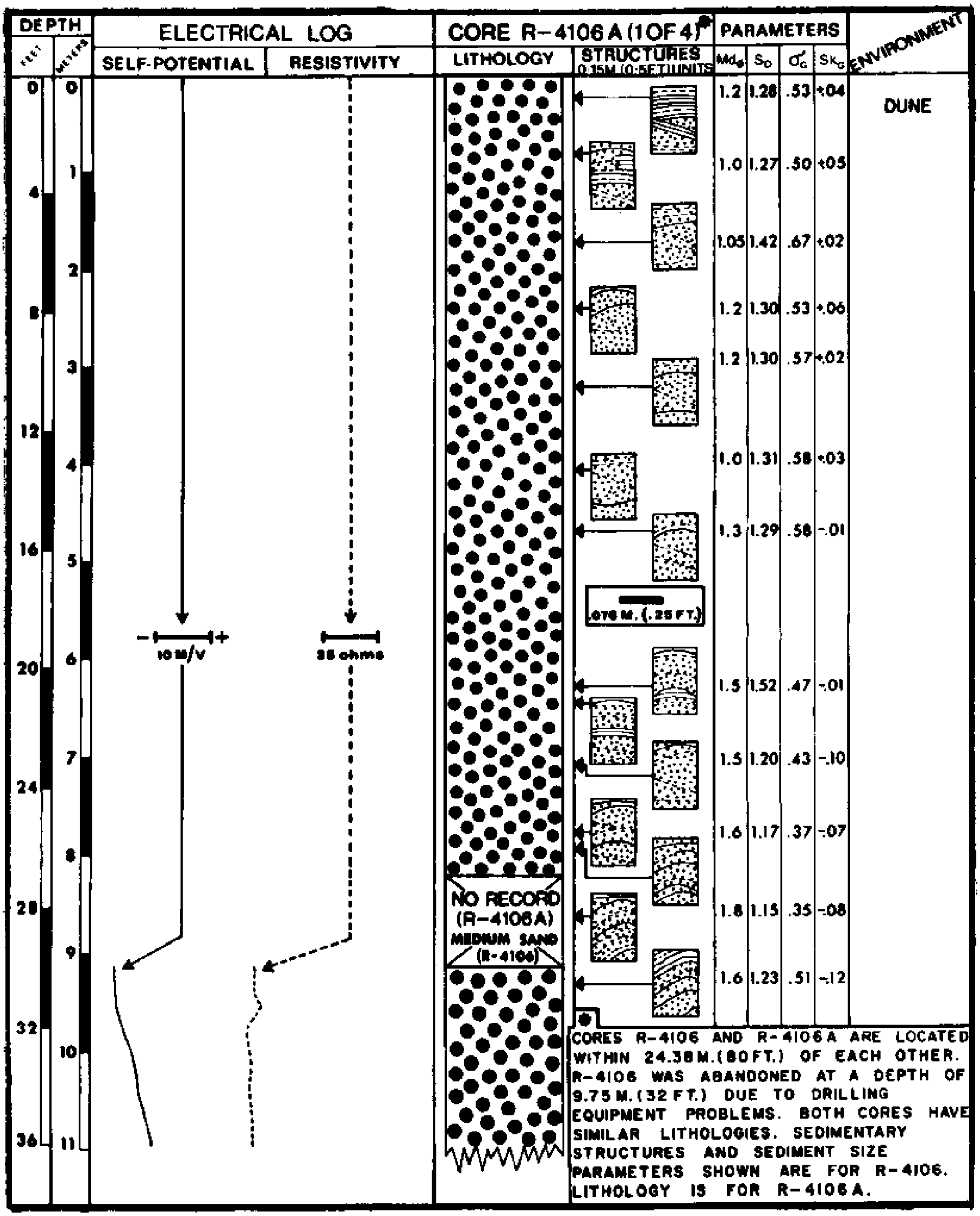


FIGURE 27. Geophysical, sedimentological, and sedimentary structure data for core R-4106A. (cont.) →

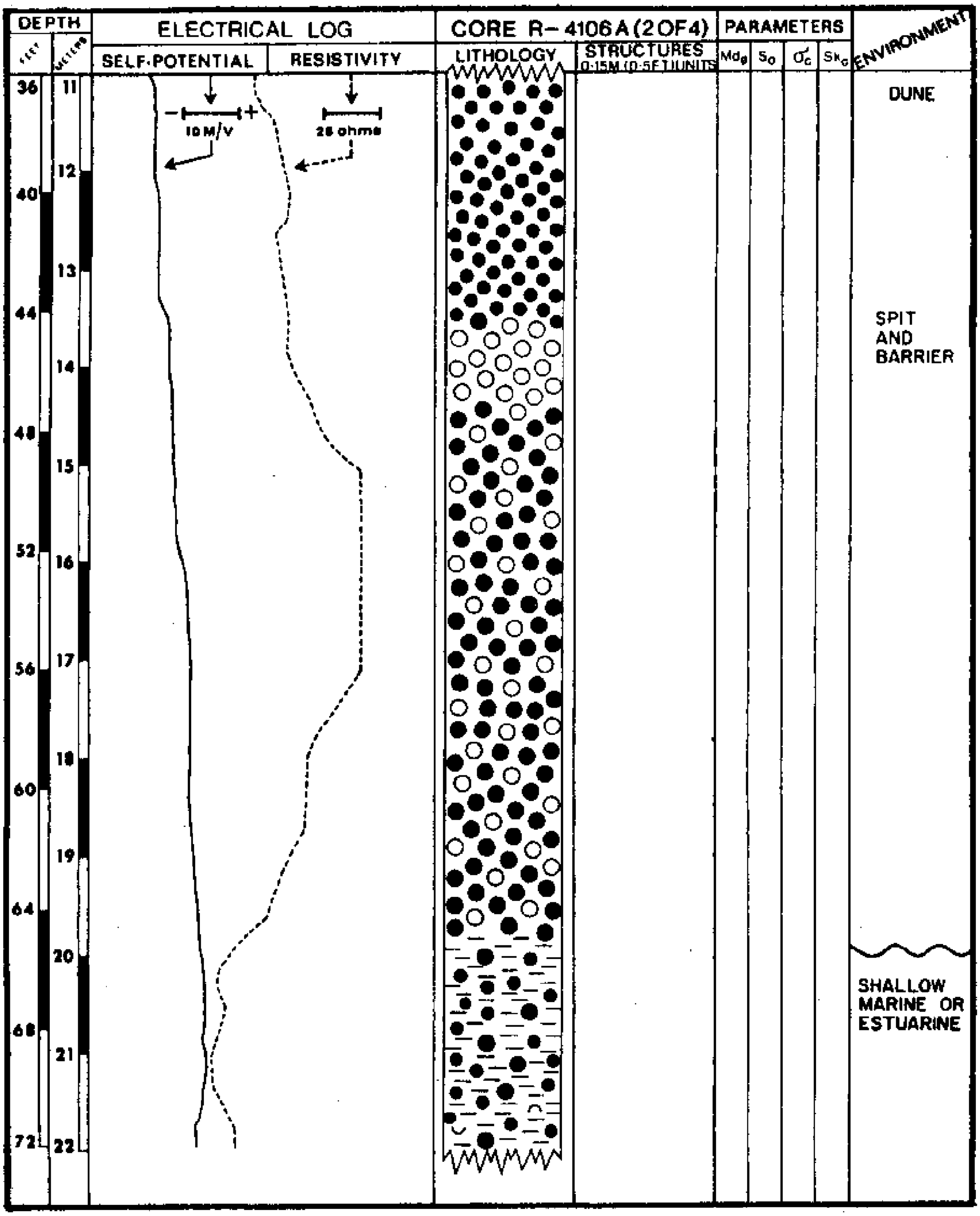


FIGURE 27 (cont.). Geophysical and sedimentological data for core R-4106A. (cont.)→

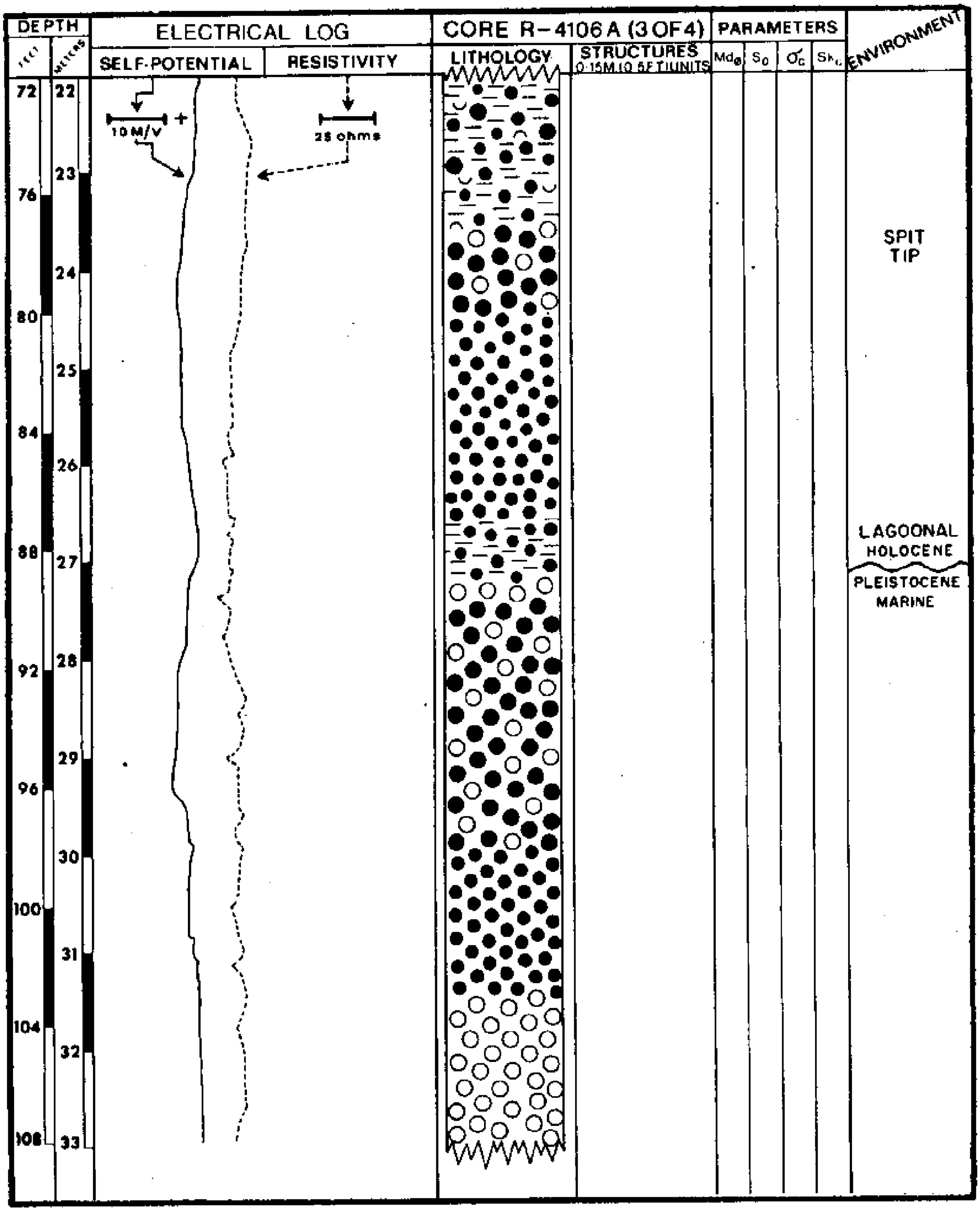


FIGURE 27 (cont.). Geophysical and sedimentological data for core R-4106A. (cont.) →

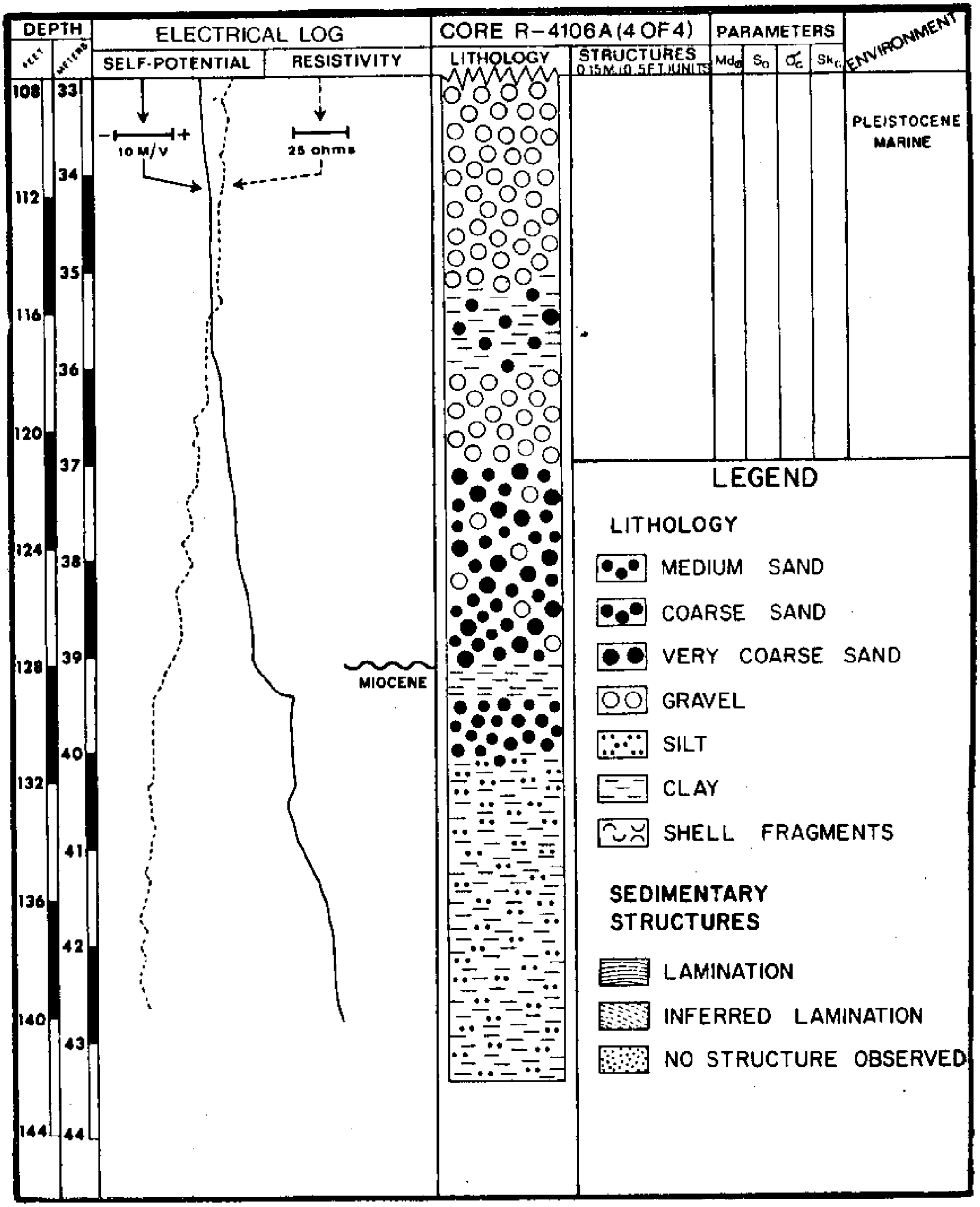


FIGURE 27 (cont.). Geophysical and sedimentological data for core R-4106A.

distinctive character, but the generally uniform pattern of the curve indicates uniform conditions of deposition, and a homogenous internal structure (Pirson, 1970). The grain-size parameters show the dune sands to be medium grained and well sorted. Sands in the upper part of the dune are positively skewed, while the sands of the lower part are slightly negatively skewed. This may be because the latter sands are intermixed with barrier sands to a greater degree than the overlying section. Grain-size data and photographs are not available for core R-4106A, and hence only the lithology of the complete core is shown in Figure 27. The spit and barrier sediments in core R-4106A are identified by an abrupt change in grain size from medium sands to coarse and very coarse sands with gravel. The contact of barrier sediments with the underlying shallow marine-estuarine sediments is also sharp and distinct, being marked by a significant increase in the amount of clay, as can be seen in Figure 27.

Figure 28 is a geologic cross section extending from the Lewes Creek Marsh to the Atlantic Ocean nearshore, and going across the recurved spit tips, coast-parallel dunes, and the barrier. The tendency of the dunes to migrate over the recurved spit tips and the marsh can be observed in this cross section. Sands of the dunes as well as those of the recurved spit tips and the barrier are

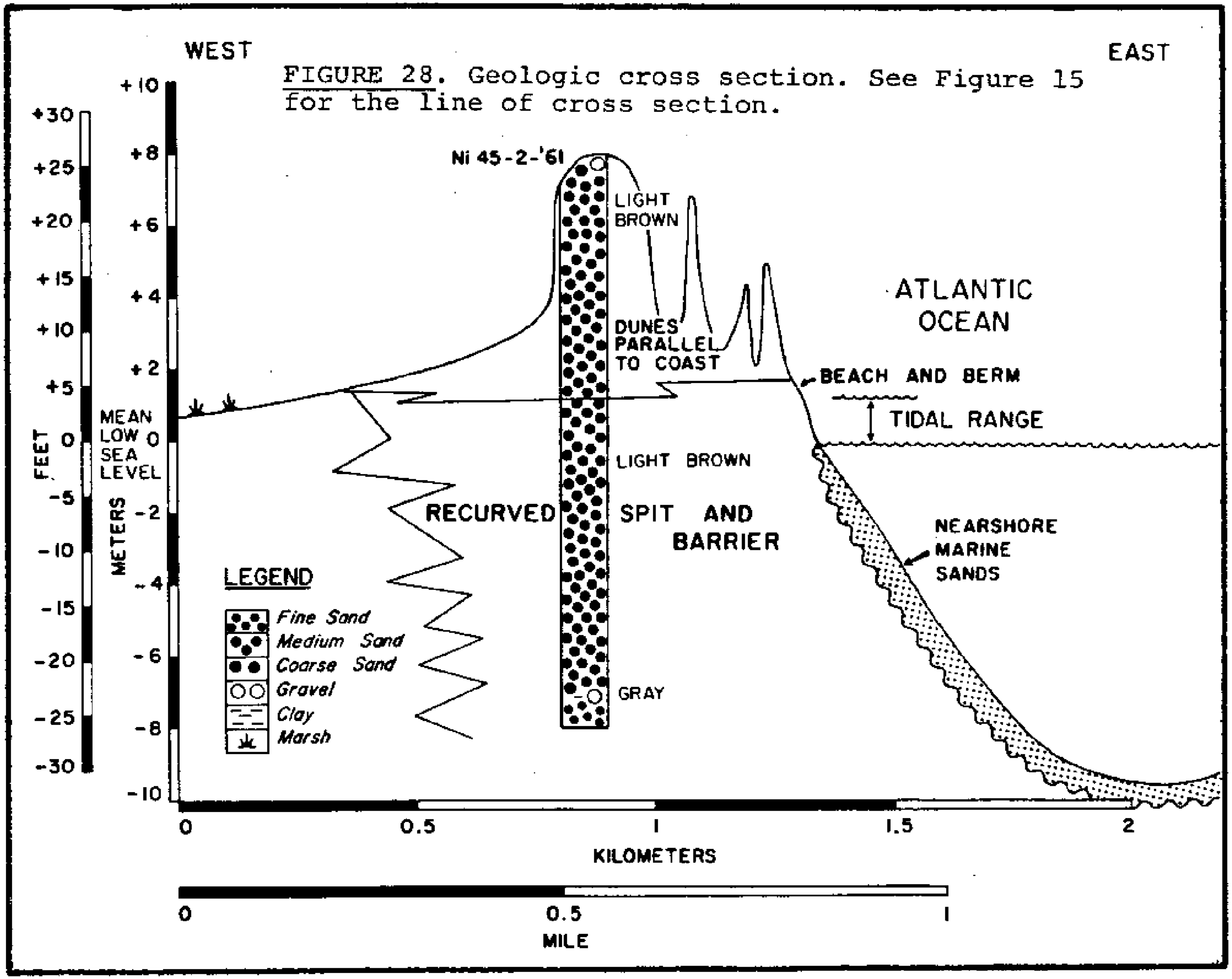


FIGURE 28. Geologic cross section. See Figure 15 for the line of cross section.

medium grained and well sorted.

Figure 29 is a geologic cross section across the Lewes Creek Marsh, the old recurved spit tips in the marsh, the transgressing coastal dunes, the beach, and into the nearshore marine area. Core R-4105 is located on a low-lying recurved spit tip in the Lewes Creek Marsh. This spit tip is about 10 m (30 ft.) thick, and consists mostly of coarse sand and gravel. Short core studies by Kraft (1971a, 1971b) have shown that the marsh sediments form only a thin cover and are underlain by a thick sequence of lagoonal sediments. The latter were deposited in a coastal lagoon, similar to the present day Rehoboth Bay, which once existed behind the barrier. Core R-4105 encountered a sequence of beach and spit sediments interfingered with another sequence of shallow marine-estuarine sediments. This also shows that beach sediments can be preserved in the stratigraphic record. This interfingering is probably due to fluctuations in sea level. The medium to coarse sands and gravels of the beach and spit in core DH-3-'68 overlie fine to medium grained shallow marine-estuarine sands with silt and shell fragments, thus again producing a regressive situation in an otherwise transgressive area.

Summarizing the above discussion on the Cape Henlopen spit-beach-dune complex, the following statements can be made with regard to this area:

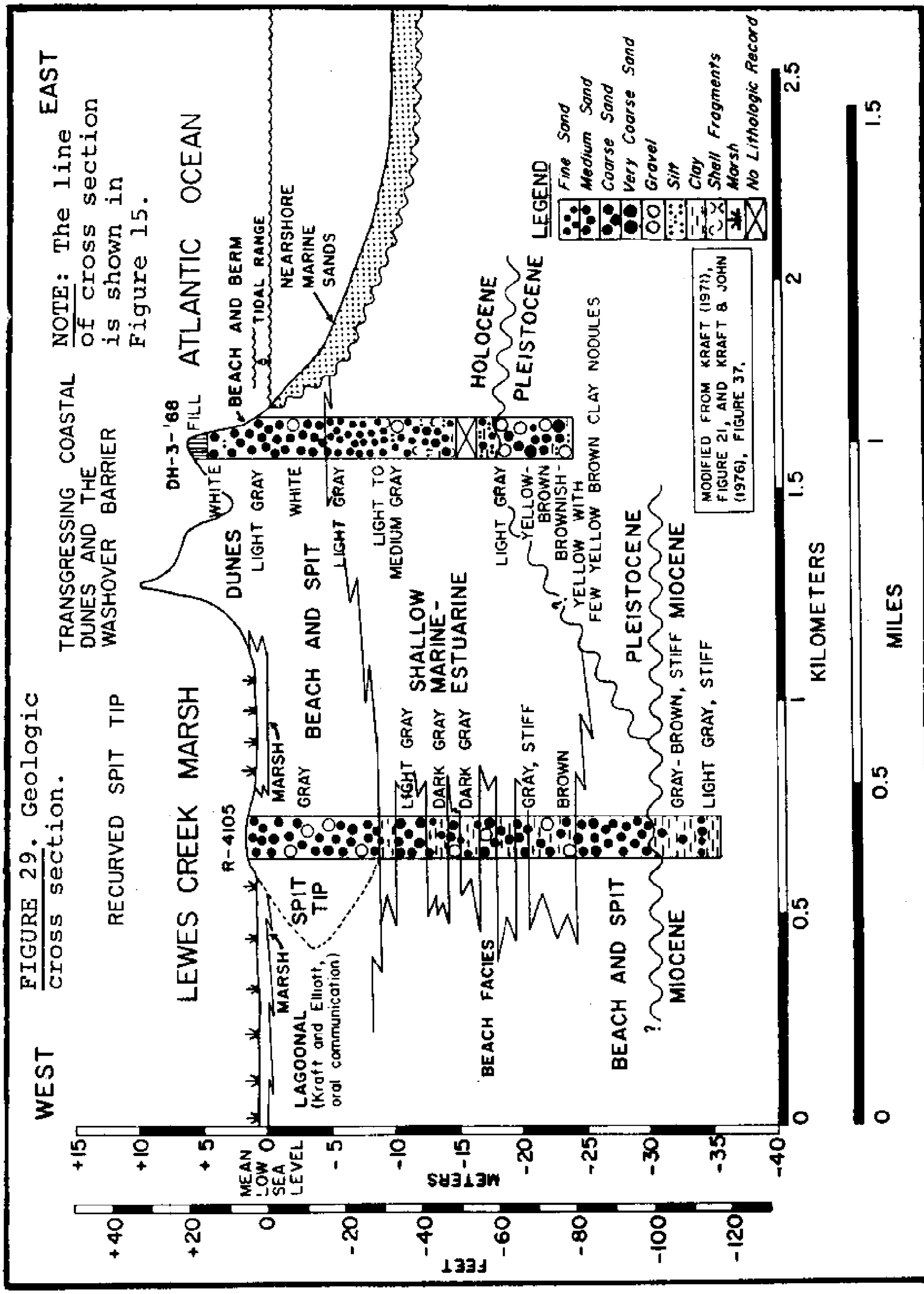


FIGURE 29. Geologic cross section.

(1) Spit sediments are thicker in the north than in the south of the area, as spit growth continues by sediment deposition in deeper water.

(2) Dune sands are generally well sorted, medium grained, and positively skewed.

(3) Spit and beach sediments are mostly medium to very coarse sands with gravel and shell fragments. They are moderately well sorted and negatively skewed.

(4) Pleistocene environments are transgressed by shallow marine-estuarine sediments, as seen in the cross sections. The latter are covered by spit and beach or barrier sands and gravels, which in turn are overlain by coastal dune sands.

(5) Both regressive and transgressive vertical stratigraphic sequences are found in this area. Coastal barrier environments migrating over the shallow marine-estuarine environment give rise to a regressive sequence. Barrier and marine environments overlying coastal or lagoonal environments give rise to a transgressive vertical stratigraphic sequence.

(6) The sedimentary environments of the area are migrating westward (landward) in response to relative sea level rise and coastal erosion, as the barrier complex evolves through time. The upper part of the vertical spit sequence is being destroyed by the ongoing transgression; simultaneously, the

lower part of the vertical sequence is being covered by a layer of shallow marine sediments.

(7) Barrier sub-environments cannot be differentiated on the basis of variations in grain-size parameters, as the parameter variations are not significantly different or characteristic within the barrier itself.

(8) Sediments at the spit tip show high-angle laminations. Other areas do not have characteristic sedimentary structures by which they may be distinguished. However, the most commonly seen structures in the cores are parallel laminations, concave and convex laminations, and simple as well as planar cross-laminations. Mottling and burrows are more prevalent at the boundary between the barrier sediments and the shallow marine-estuarine sediments.

(9) The SP curves, in general, do not show any characteristic patterns attributed to a transgressive or regressive sequence.

(10) Environmental interpretations are best made by considering all the characteristics, that is, electric log curves, lithology, sedimentary structures, and grain-size parameters together, rather than on the basis of any one of these features.

(B) BARRIER-MARSH

This section of Delaware's Atlantic transgressive coastal barrier complex extends from Whiskey Beach to Rehoboth Beach. The barrier here is narrow (Figure 14) and is capped by small dunes. During coastal storms this barrier is often inundated by storm waves. Overwash breaches the low-lying dunes, carrying large volumes of sands and gravels across the barrier and onto the surface of the Lewes Creek Marsh, where it is deposited in the form of large washover fans. These washover fans constitute part of the leading edge of the Holocene transgression in this area. A discussion on the overwash process was given earlier in this report. Overwash is the dominant process for increasing barrier width by transporting sand onto the landward side of the barrier. It is also primarily responsible for the migration of the barrier in the landward direction, with the continuing erosion of the Atlantic coast. A large volume of sediment is suddenly removed from the littoral transport system when overwash occurs, but a similar quantity is gradually reintroduced into the littoral stream as coastal erosion continues. Similar, but much smaller washover barriers exist all along the adjacent Delaware Bay coast. The continuation of the overwash process coupled with coastal erosion will eventually result in complete obliteration of the Lewes Creek Marsh which lies behind this barrier if landward migration of the marsh itself is stopped by human interference. If this happens, in a couple of centuries the Atlantic coastline will be abutting against the pre-Holocene highlands situated behind the marsh.

At low tide, the eroding marsh and lagoonal muds underlying this washover barrier are exposed at some places. Large clumps of marsh muds with Spartina grass fragments, termed "marsh rollers" by Kraft (1971b), eroded out from this section of the barrier complex, are carried by littoral transport northward and find their way onto the beaches near Cape Henlopen and the tidal flats west of the Cape. These marsh rollers provide evidence of coastal erosion caused by marine transgression resulting from relative sea level rise.

Figure 30 is a geologic cross section across the washover barrier. The entire sandy barrier is approximately 200 m (656 ft.) wide, and lies between the Lewes Creek Marsh to the west and the Atlantic Ocean to the east. The thickness of the barrier, including the dunes on top of it, is less than 5 m (16.4 ft.), and is above mean low sea level. This clearly indicates the ease with which the barrier could be breached, or even completely destroyed by high waves resulting from coastal storms. The dune and barrier sediments overlie a sequence of marsh muds which are

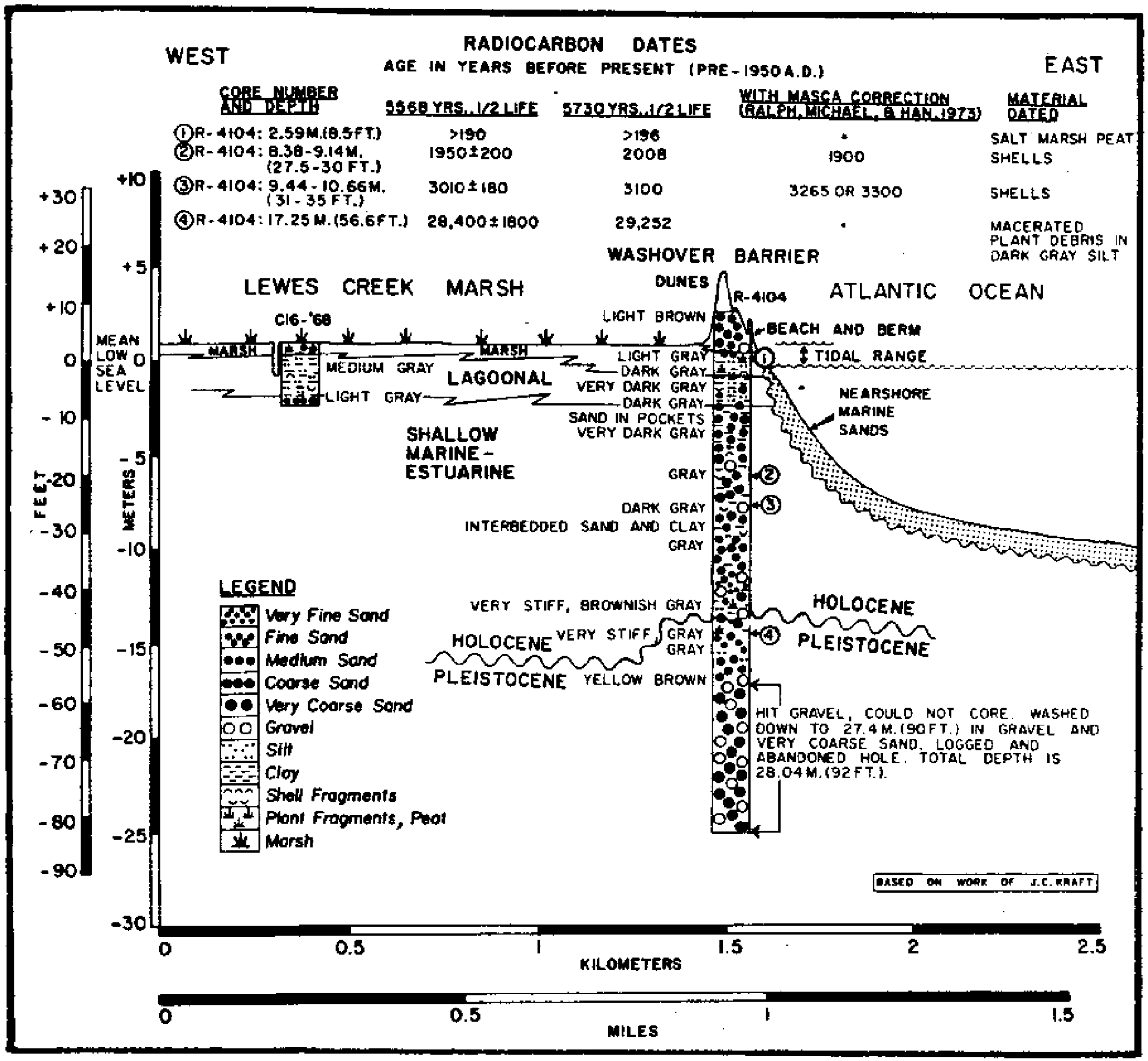


FIGURE 30

Geologic cross section. See Figure 15 for the line of cross section.

underlain by lagoonal sediments. The latter overlie shallow marine-estuarine sediments covering the Pleistocene deposits. The vertical stratigraphic sequence represented in this cross section is therefore transgressive in nature. Coastal erosion will destroy the thin stratigraphic record of the barrier, and a veneer of shallow marine sediments will be deposited over the marsh muds. The barrier record can only be preserved if the rate of subsidence becomes greater than the rate of coastal erosion. The marsh sequence underlying the barrier sediments has been dated to be at least 196 years old. These marsh sediments were deposited in a lateral continuation of the present day Lewes Creek Marsh, when the barrier was further eastward of its present position. Figures 31A and 31B are photographs of core R-4104 which is seen in the cross section shown in Figure 30. Sedimentary structures in the different depositional environments represented by core R-4104 can be observed in these photographs. The contact between the barrier sediments and the underlying marsh sediments is sharp, and can be identified very clearly on the basis of sediment composition and color difference. Figure 32 is a summary of the detailed lithology, sedimentary structures, grain-size parameters, electric log patterns, and depositional environments of core R-4104. The pattern shown by the SP curve could be better appreciated if it is kept in mind that the SP curve shown is enlarged lengthwise

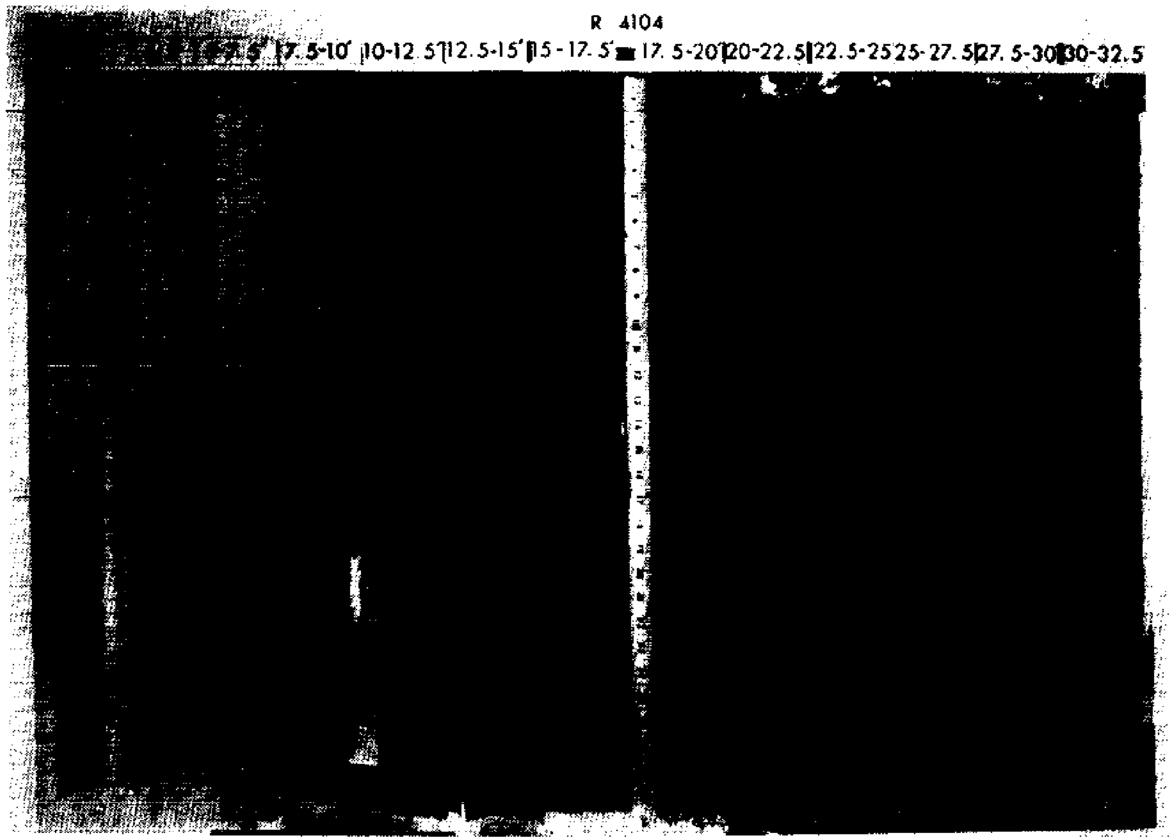


FIGURE 31A. Photograph of core R-4104 (0-32.5 ft.; 0-9.9 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

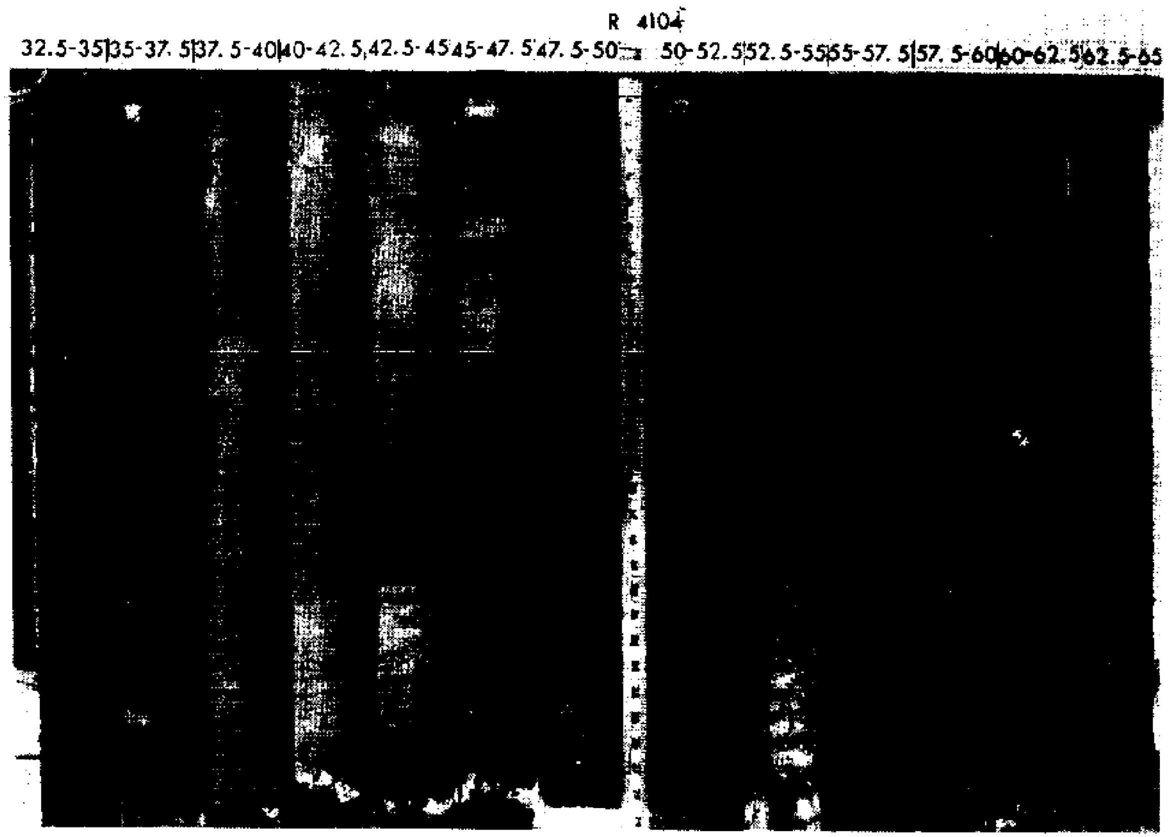


FIGURE 31B. Photograph of core R-4104 (32.5-65 ft.; 9.9-19.8 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

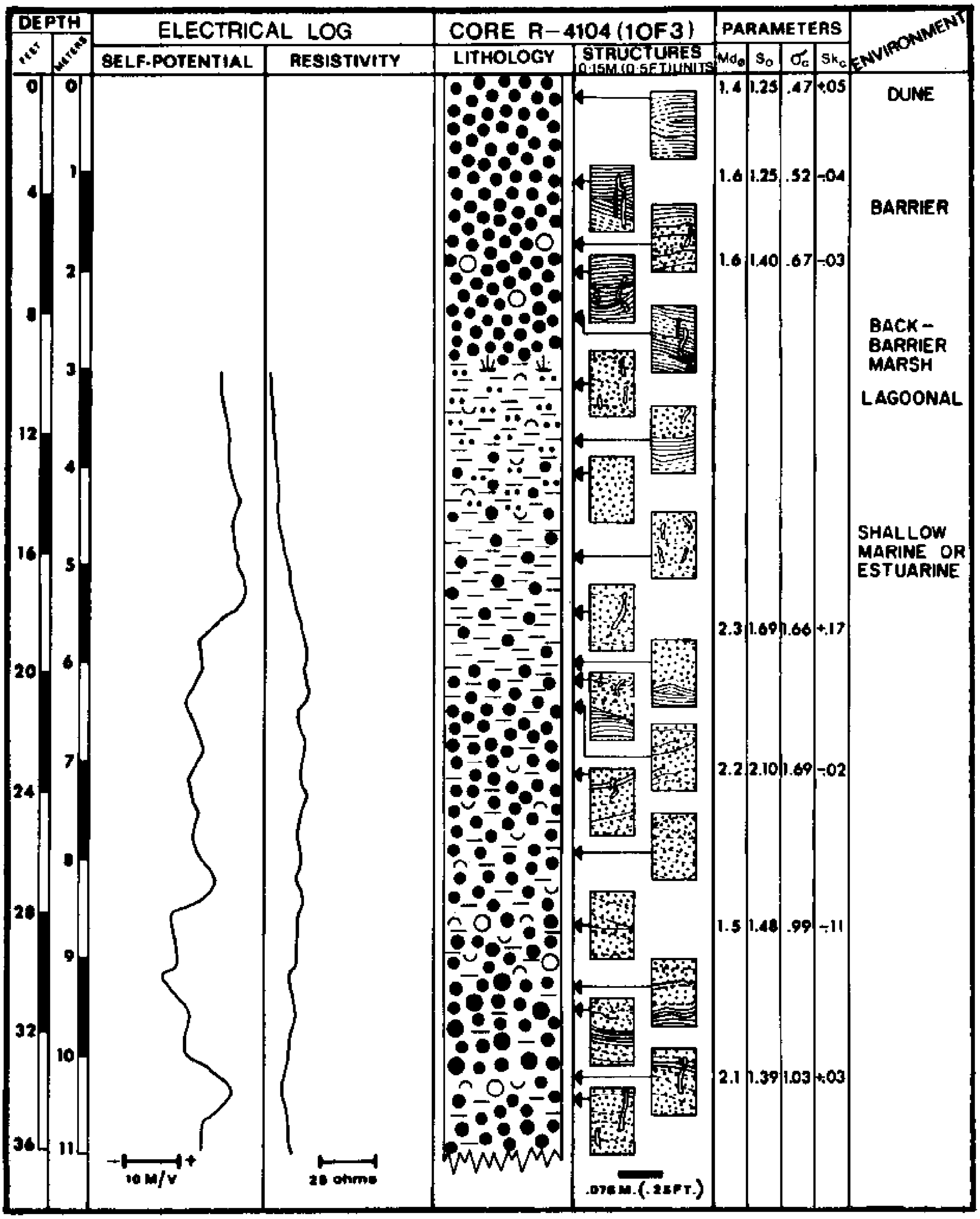


FIGURE 32. Geophysical, sedimentological, and sedimentary structure data for core R-4104. (cont.) →

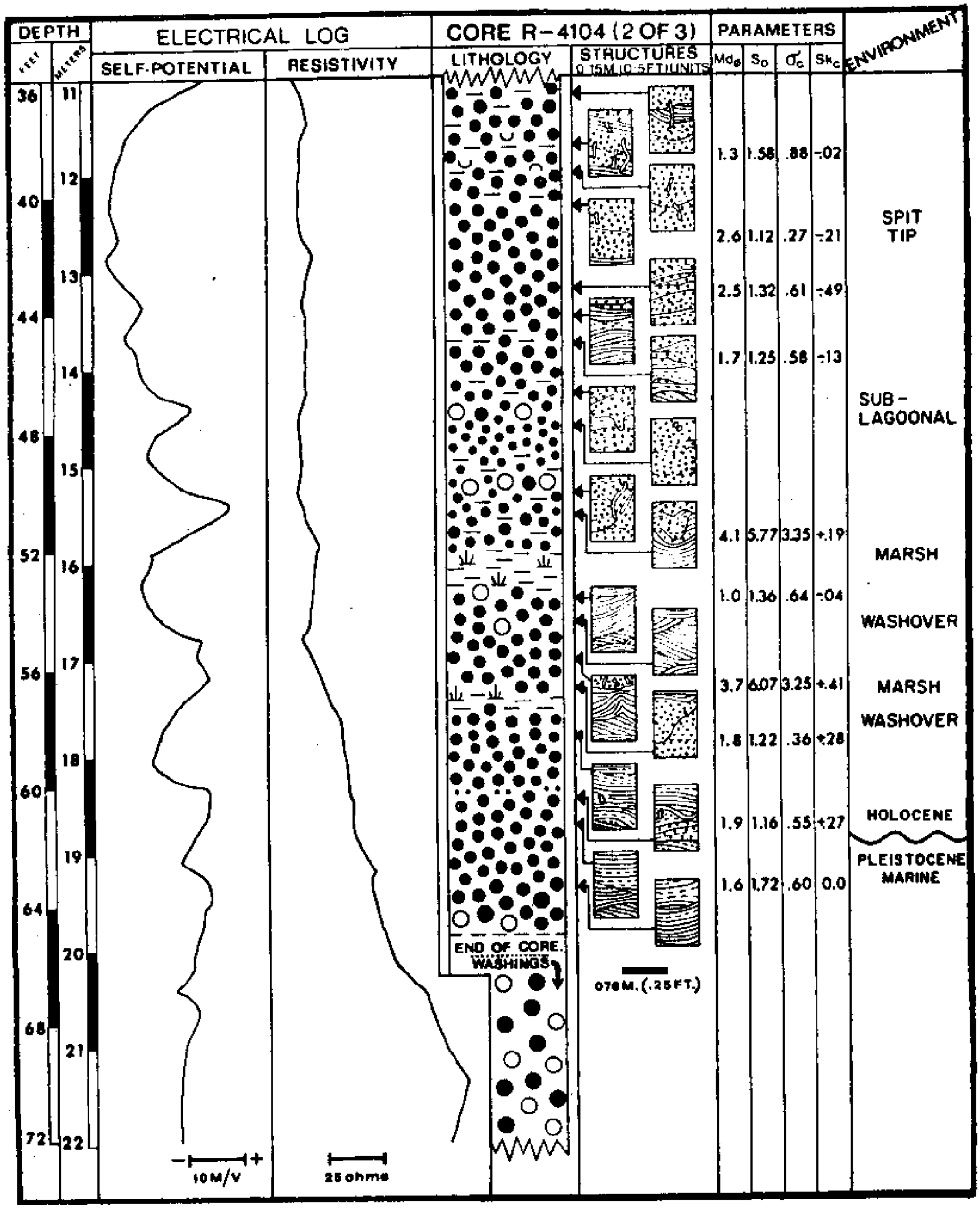


FIGURE 32 (cont.). Geophysical, sedimentological, and sedimentary structure data for core R-4104. (cont.)→

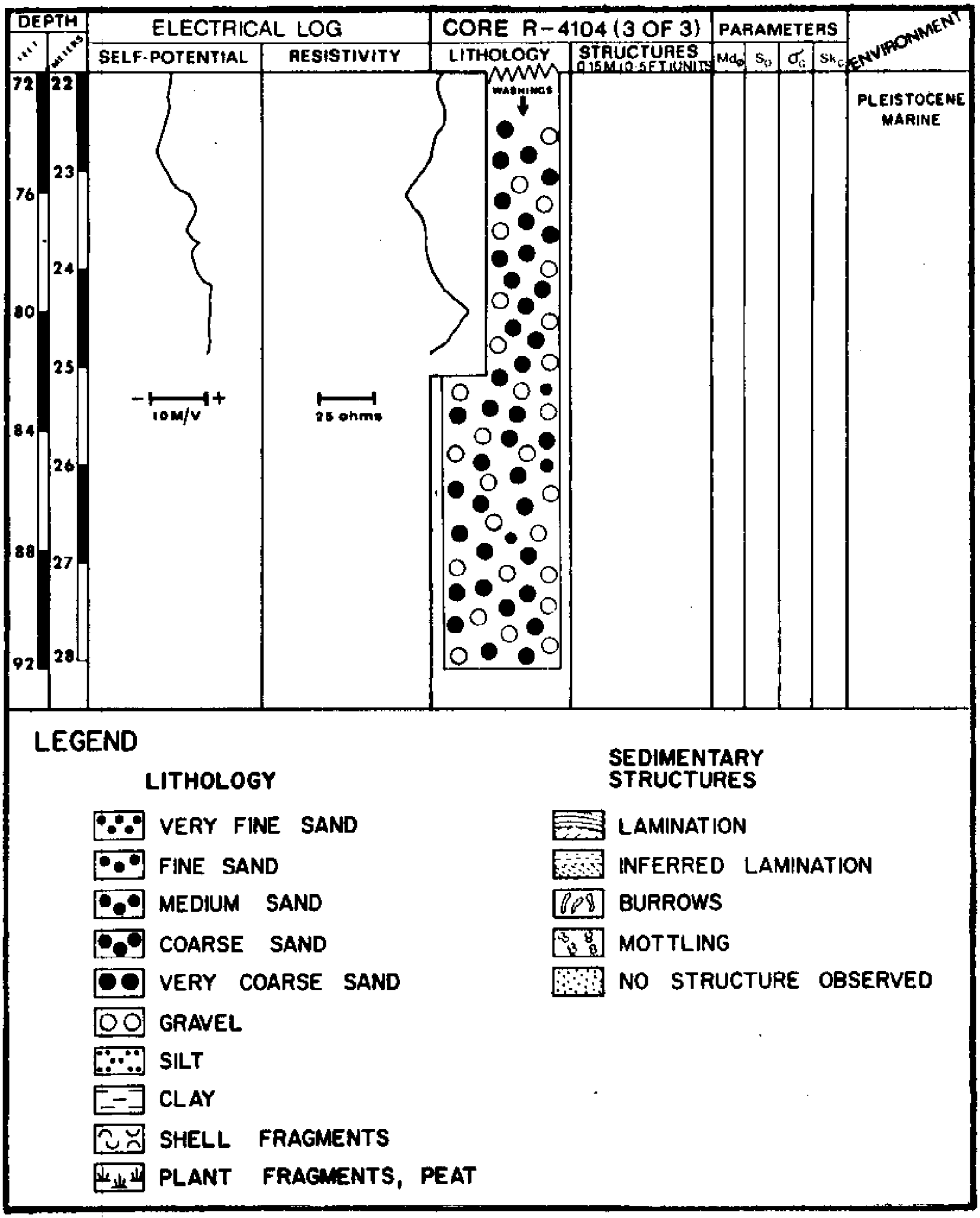


FIGURE 32 (cont.). Geophysical and sedimentological data for core R-4104.

from its original scale. If the curve shown is taken and compressed, one could see that a number of more or less parallel horizontal fingers develop along the curve, the amplitude of which generally tends to decrease upwards. This feature in the SP curve represents a transgressive sedimentation pattern (Pirson, 1970). However, it would be rather difficult to make this interpretation based on the curve itself, without a knowledge of the other core characteristics. The dune and barrier sands have parallel and planar cross-laminations. Burrows are found at the interface of the barrier and marsh sediments, and also at other places down the core where silt and clay are intermixed with sand. Two washovers have been preserved in the vertical stratigraphic sequence, a little above the boundary with Pleistocene marine sediments. Other sedimentary structures seen in the core include planar and trough cross-laminations, and concave and convex laminations. Grain-size parameters indicate that dune and barrier sands are generally well sorted and medium grained. Dune sands are positively skewed, whereas, the barrier sands are negatively skewed. Barrier sub-environments cannot be differentiated on the basis of grain-size parameters.

A typical section of this washover barrier coast is shown in Figure 33. The landward edge of the giant

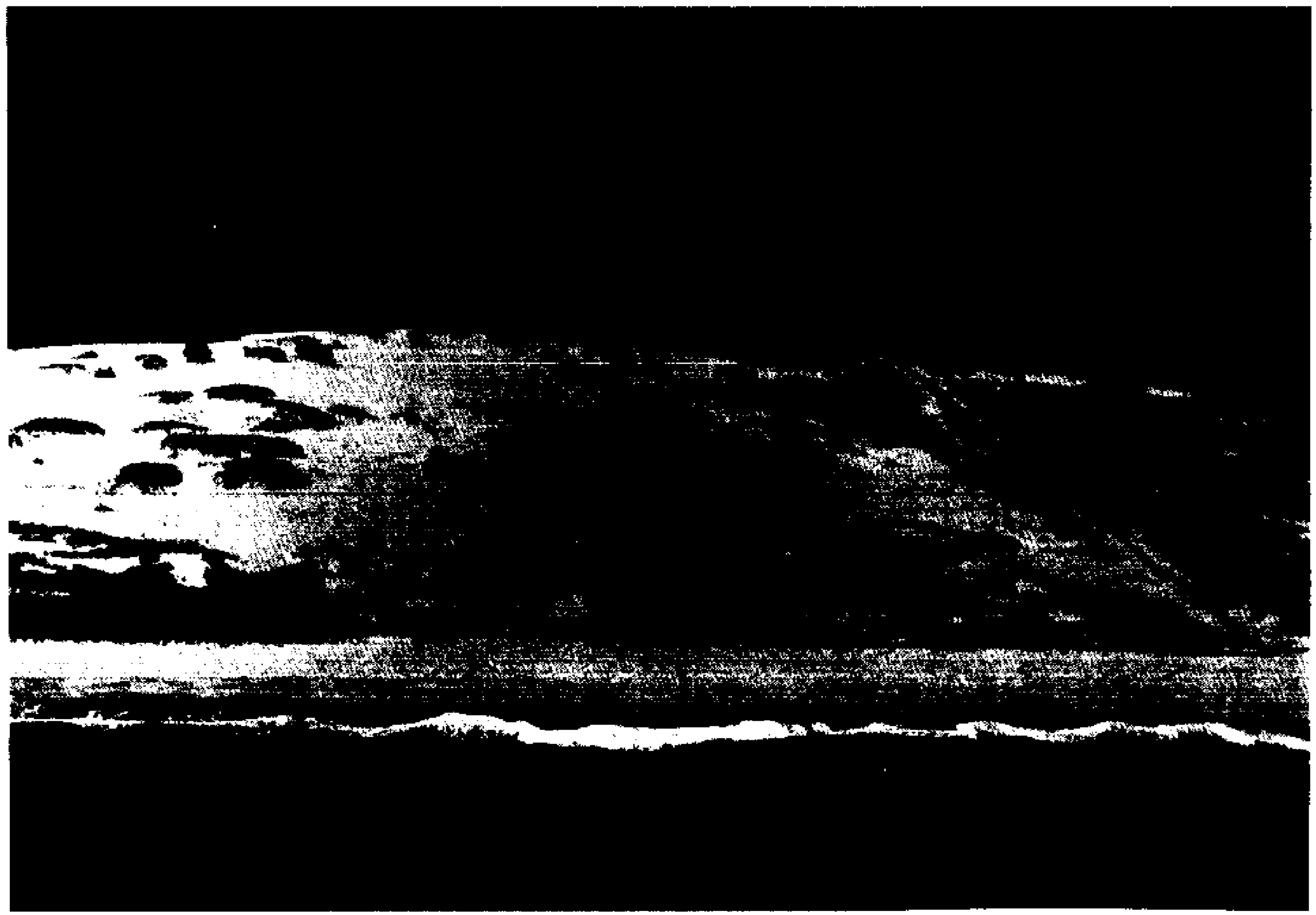


FIGURE 33. Aerial photograph of the washover barrier near Whiskey Beach. Old spit tips covered by vegetation are seen in the background.

washover is typically semi-circular or fan-shaped. The washover rests on the marsh surface, and partly covers some of the old recurved spit tips of Cape Henlopen. The giant washover fan seen in this photograph was caused by the disastrous storm of March, 1962. Other smaller wash-overs are probably superimposed on this giant washover fan as a result of overwash produced by later separate storms. Sediment for overwash is derived from the foreshore, beach, and adjacent dunes. Washover deposition takes place by unidirectional sediment-water gravity flow. Hence internal structures of the washover fan will be similar to those produced by channel or stream flow. Accordingly, sediments at the bottom of the washover fan are coarser than those at the top. As seen in Figure 33, the coast-parallel dunes at the landward edge of the beach are of small height; dune stabilization by grass growth and fences is being carried out at present. An extensive dune field has formed on top of the washover fan; parts of the older washover fans have been covered by vegetation.

A trench dug at the landward edge of a washover fan reveals its internal structure (Figure 34). The Atlantic Ocean is towards the left of the photograph, and therefore overwash direction is from left to right. Each unit on the measuring pole lying on the top side of the trench is 2 cm wide. Sedimentary structures seen in the freshly dug

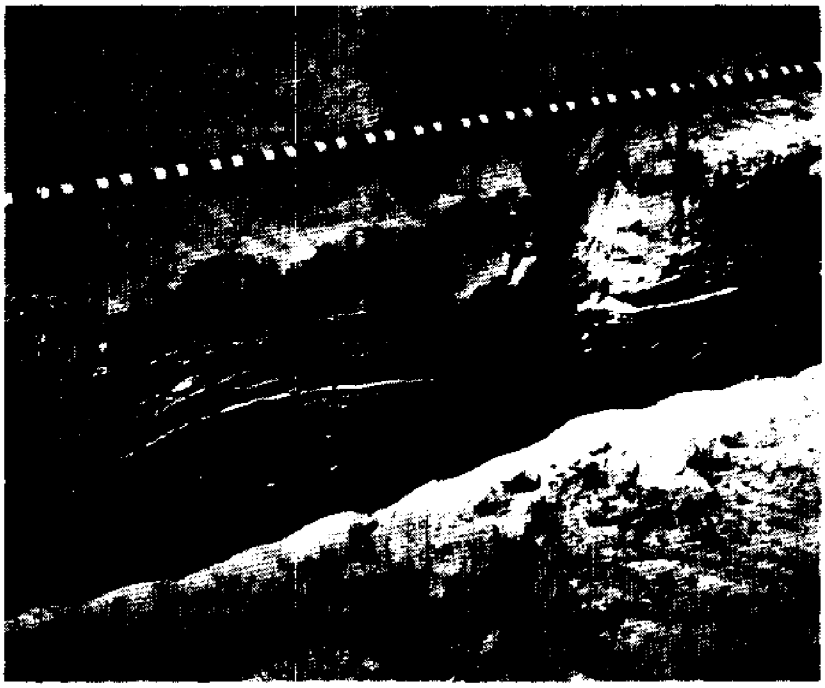


FIGURE 34. Photograph of a trench at the landward edge of a washover fan near Whiskey Beach. Scale: 1 unit = 2cm

trench (Figure 34) are etched and accentuated by wind action if the trench is left exposed for about one hour. The upper part of the washover is characterized by slightly landward dipping parallel and sub-parallel horizontal laminations. Convex laminations and trough cross-laminations, in addition to horizontal laminations, are seen in the middle and lower parts of the trench, mostly towards the left side of the photograph (Figure 34). Plant roots or burrows penetrating washover sediments cause laminae to bend downward at that site, and this can be observed on the right side of the trench in the photograph (Figure 34). In channel flow, as occurs during the overwash process, horizontal laminations are produced in the lower part of the upper flow regime by plane bed transport. Large-scale trough cross-laminations result from dune migration in water depths exceeding 0.3 m (1 ft.), whereas small-scale trough cross-laminations are produced by ripple migration. The former occurs in the upper part of the lower flow regime, whereas the latter is produced in the lower part of the lower flow regime (Harms and Fahnestock, 1965).

Figure 35 is a geologic cross section across the washover barrier, to the south of the area represented by the previous cross section (Figure 32). Here, the width and thickness of the barrier, including the dunes and

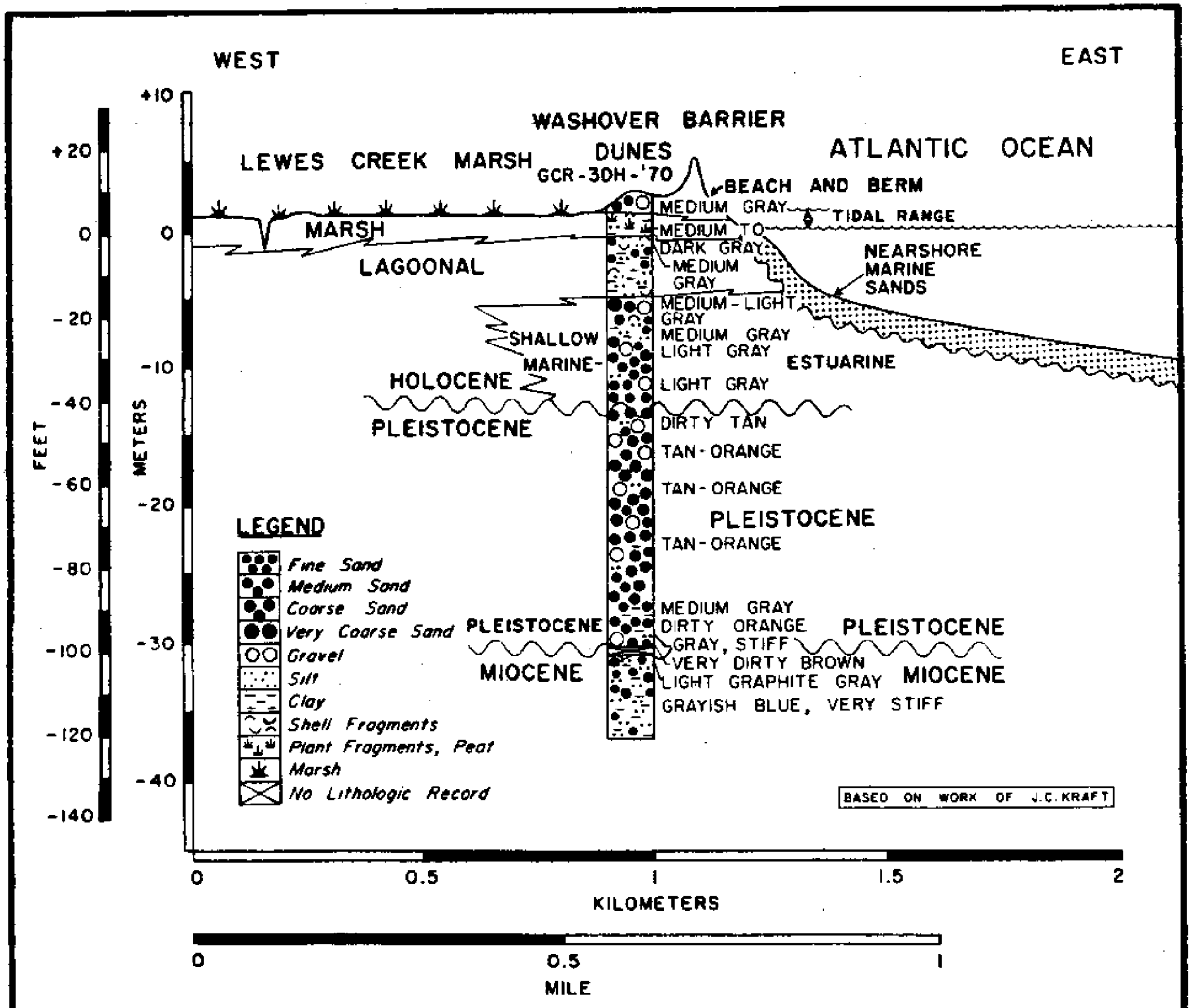


FIGURE 35

Geologic cross section. See Figure 15 for the line of cross section.

washover fans, is approximately similar to that in the previous case. Dune, washover, and barrier sediments overlie muds of the Lewes Creek Marsh which are being presently eroded at the beach face and outcrop at low tide. These marsh muds overlie lagoonal sediments which are underlain by shallow marine-estuarine sediments. The latter unconformably overlie Pleistocene sediments, which similarly overlie Miocene deposits. Most of this vertical sequence of sediments was deposited when the shoreline was further east of its present position. However, a thin sequence of shallow marine-estuarine sediments was deposited before the spit-barrier had built to the east of the present coast. The vertical sedimentary sequence seen in core GCR-3DH-'70 is transgressive in nature. The ease of storm overwash over the barrier is further emphasized in this cross section.

Figure 36 is the last cross section representing the barrier against marsh situation. In this case the marsh area behind the barrier has been covered by fill material. The general characteristics of this part of the barrier remain the same as in the previous two cases. Barrier sediments are underlain by a thin sequence of marsh muds; the latter overlie a rather thick section of shallow marine-estuarine muddy sands with shell fragments, which in turn unconformably overlie Pleistocene deposits. The shallow

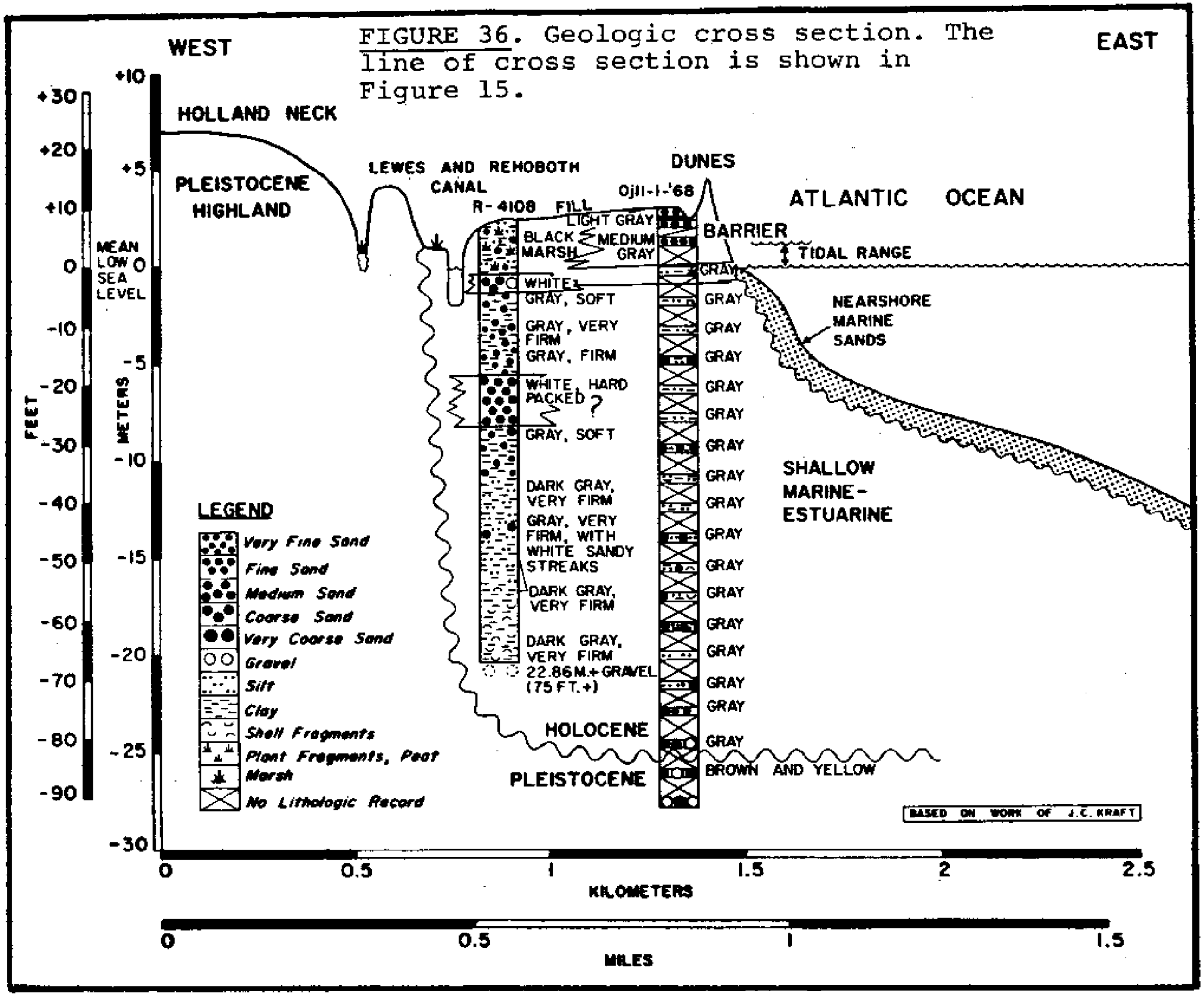


FIGURE 36. Geologic cross section. The line of cross section is shown in Figure 15.

marine-estuarine sediments were deposited in the ancestral Delaware Bay when the barrier was further east of its present position. A lagoonal sequence underlying the marsh muds has not been identified in this section. Also, the environment represented by the vertical stratigraphic sequence in core R-4108 below the marsh section is rather uncertain, especially since a similar sequence is not seen in core Oj11-1-'68. However, the nearness of the coastline to the Pleistocene highlands should be noted.

The general relationship of the transgressive coastal barrier complex to the Lewes Creek Marsh and the Pleistocene highlands is shown in Figure 37. A large number of washover fans, shown by white patches on the landward side, partly covered by vegetation, can be observed all along the barrier. Beach cusps formed at the seaward edge of the beach near the water line extend along the length of the coast. The irregularity in the coastline is primarily due to the building of a groin system at the naval facility which causes the bulge; erosion of the high dune and other areas produce the indentations.

On the basis of the above discussion of the barrier-marsh section of the coastal barrier complex, the following conclusions can be made regarding this area:
(1) Dune sands are medium grained, well sorted, and have positive skewness.

FIGURE 37. Aerial photograph of the barrier looking north towards Cape Henlopen. Washover fans partly covered by vegetation can be seen in this picture. The bulge in the coastline is due to the presence of a groin system near the naval facility.

(2) Barrier and washover sands are moderately well sorted, medium to coarse grained with some gravel, and negatively skewed.

(3) Barrier sub-environments cannot be distinguished on the basis of grain-size parameters, but dune and beach sands may be separated on the basis of skewness and sorting.

(4) The barrier, including the dunes, is of small thickness (5 m or 16.4 ft.) and width (200 m or 656 ft.). Barrier sands overlie marsh muds which in turn overlie lagoonal sediments. The latter cover shallow marine-estuarine sediments which unconformably overlie Pleistocene deposits. The former sediments were deposited in the ancestral Delaware Bay when the present barrier was further east of its existing position.

(5) This section of the coastal barrier complex is characterized by a large number of washover fans which constitute part of the edge of the Holocene marine transgression. Washovers overlie and migrate over the Lewes Creek Marsh. Overwash is the dominant mechanism for increasing barrier width by sand transport to the landward side. This sand is derived from the nearshore, beach, and adjacent dunes.

(6) The eroding marsh and lagoonal muds exposed at low tide indicate continuing coastal erosion resulting from relative

sea level rise and marine transgression.

(7) Marsh sediments underlying the thin sequence of barrier sands and gravels were deposited in an eastward extension of the present day Lewes Creek Marsh, when the barrier was further eastward of its present position and relative sea level was slightly lower than now.

(8) Vertical stratigraphic sequences in this area are transgressive in nature. The thin stratigraphic record of the barrier is likely to be destroyed by transgression. However, the lower part of this transgressive sequence may be preserved under a cover of marine sediments.

(9) Dune and barrier sands mostly show horizontal laminations and planar cross-laminations. Sedimentary structures observed in other environments represented by the cores include planar and trough cross-laminations, and both concave and convex laminations. Burrows are prevalent where sands are intermixed with silt and clay.

(10) The Pleistocene highlands are closer to the washover barrier in the southern part of this section than in the northern part.

(11) Environments represented by the vertical stratigraphic sequence are best judged by considering the sedimentological, structural, and geophysical characteristics taken together. These features were compared with the criteria for environmental interpretation listed in Table II for making the interpretions presented.

(C) BEACH-HIGHLAND

This section of the coastal barrier complex is characterized by a very narrow beach abutting against Pleistocene sediments of the Rehoboth highland. Active coastal erosion is occurring in this area, and a rather thin vertical sequence of beach-berm sands, with a small dune field at its edge, has been developed. During high intensity storms the entire beach sequence of sediments resting on Pleistocene deposits may be obliterated. At such times, major erosion of the highland takes place. Sediments so produced are carried north by littoral transport, and also distributed over the nearshore submarine area. Kraft (1971b) and Kraft, Biggs, and Halsey (1973) state that most of the sediments for the growth of the Cape Henlopen spit are derived from this area. When normal weather conditions are restored, the beach is built up again, this time a little further inland, as the previously occupied site was destroyed by storm erosion. The beach is made up of medium to very coarse sands. Sedimentary structures observed in the beach and back-beach areas are low-angle seaward-dipping laminations parallel to the beach face, and low-angle landward-dipping laminations parallel to the berm surface, respectively (Kraft, Biggs, and Halsey, 1973).

Figure 38 is a geologic cross section typical of this section of the coast. The relationship of the narrow

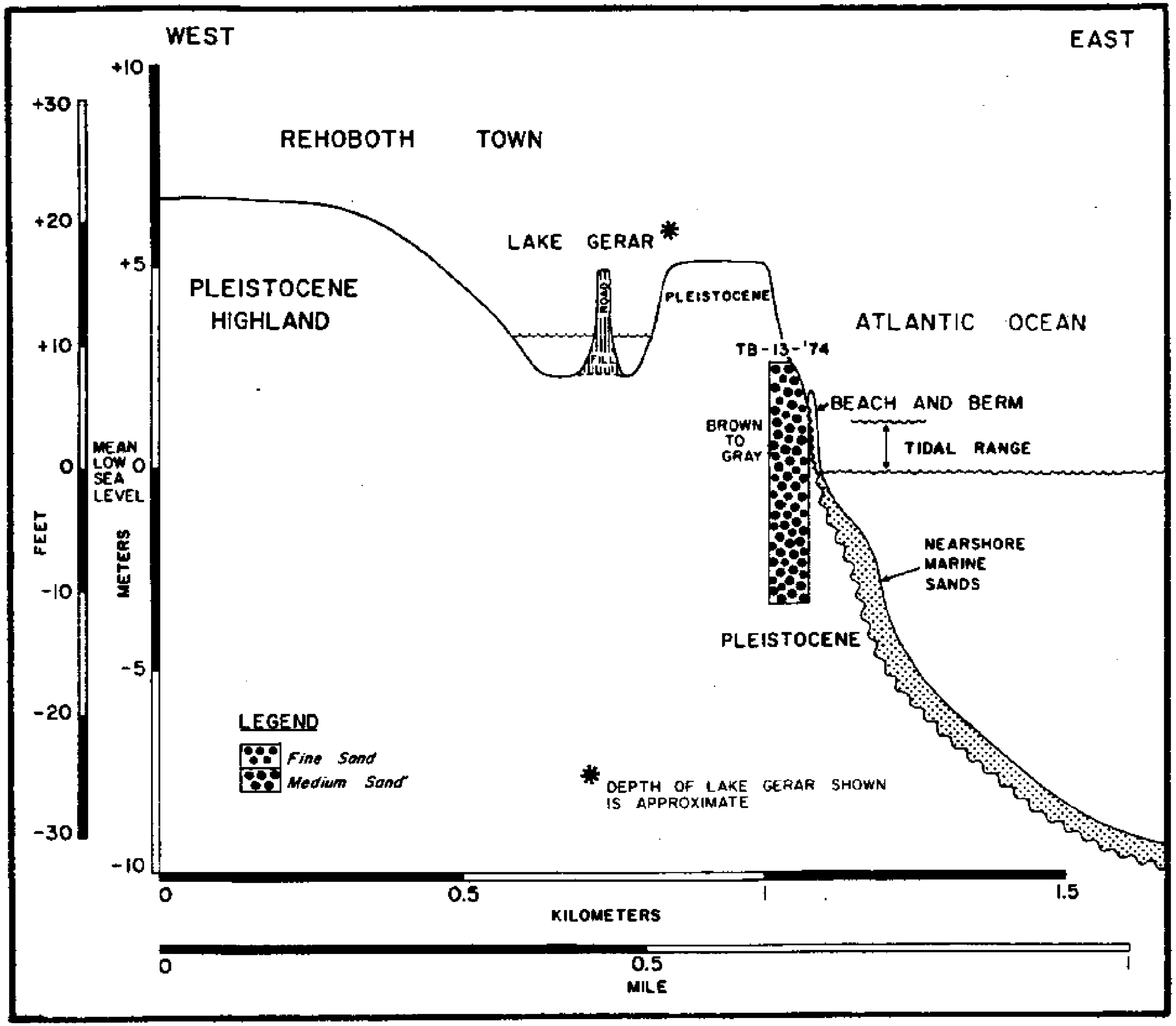


FIGURE 38

Geologic cross section. The line of cross section is shown in Figure 15.

beach to the Pleistocene highland against which it is developed is clearly seen in this cross section. Seismic work done by Sheridan, Dill, and Kraft (1974) has confirmed the continuation of the pre-Holocene or Pleistocene surface in the offshore area adjacent to the Rehoboth highland. Looking at this cross section (Figure 38) it seems rather doubtful whether the sedimentary units making up the beach here will be preserved in the stratigraphic record. However, it should be noted that a similar beach was found to the north of this area in the Cape Henlopen spit-beach-dune complex unconformably overlying the pre-Holocene sediments (Figures 25 and 29). Figure 39 is a geologic cross section at Rehoboth Beach. The general features and relationship of the beach to the Rehoboth highland are similar to those observed in the previous case. An aerial photograph of Rehoboth Beach through which the line of cross section passes is shown in Figure 40. The beach in this area is maintained by a groin system. The town of Rehoboth, as can be seen in the photograph, is built behind the beach-berm on the Pleistocene highland. However, the buildings behind the berm are vulnerable to storm wave attack and destruction as has been amply demonstrated in the past years on many occasions (Kraft, Allen, Belknap, John, and Maurmeyer, 1976).

Figure 41 is a geologic cross section located

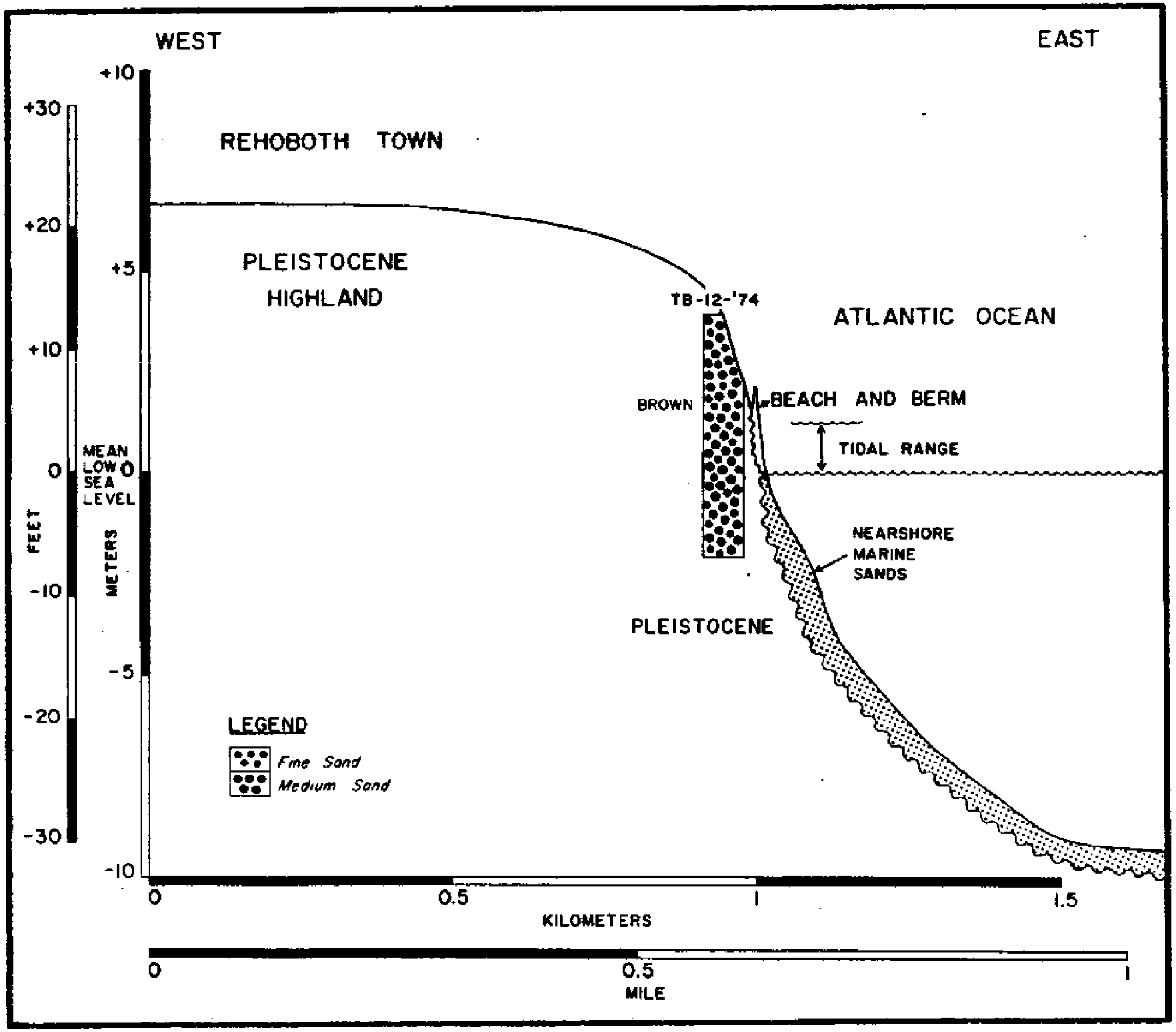


FIGURE 39

Geologic cross section. See Figure 15 for the line of cross section.

FIGURE 40. Aerial photograph of Rehoboth Beach and boardwalk.

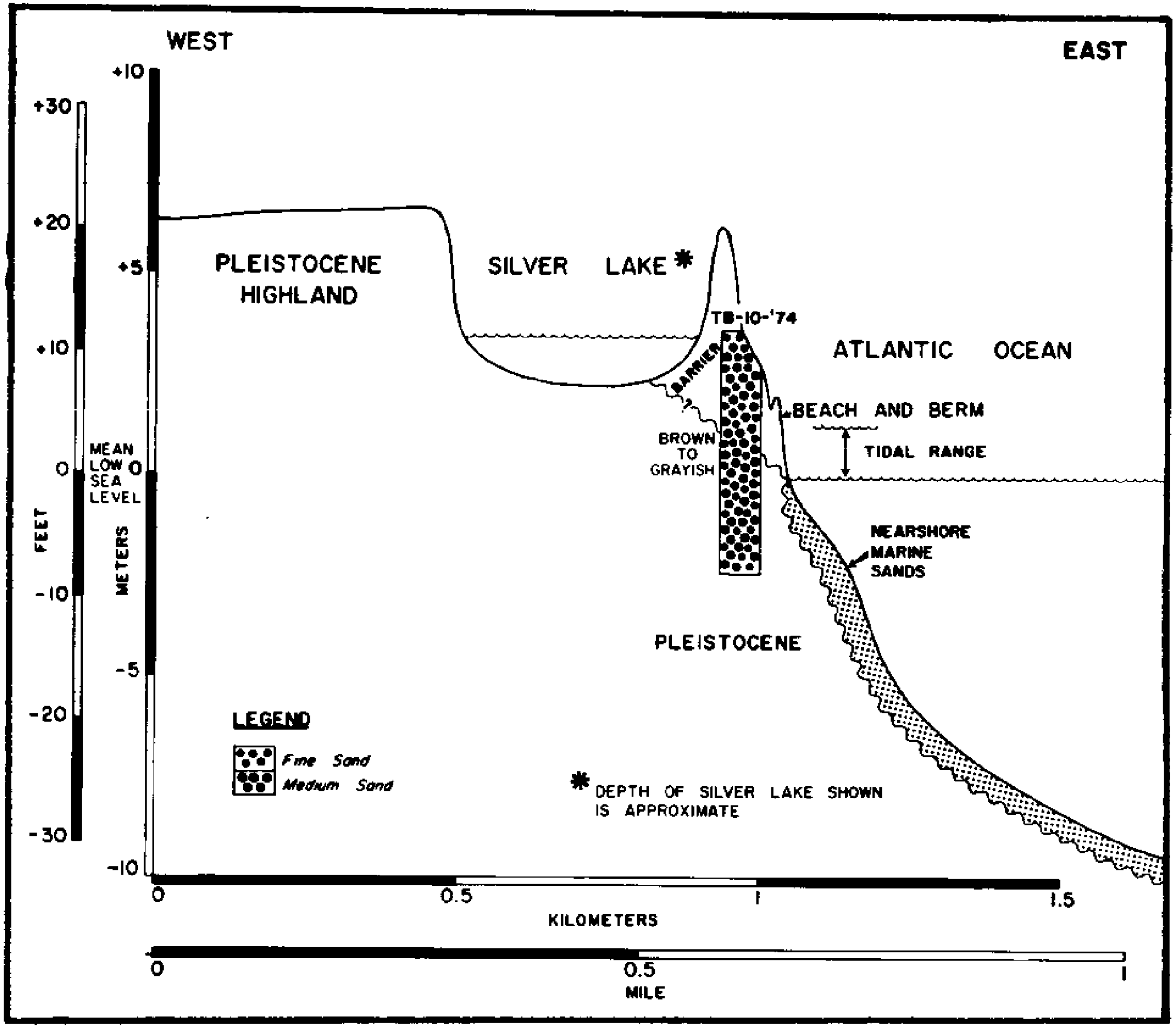


FIGURE 41

Geologic cross section. See Figure 15 for the line of cross section.

south of the previous cross section (Figure 39). The line of cross section in this case extends from the Pleistocene highland through Silver Lake, a beach, and into the near-shore marine area. An aerial photograph of this area is shown in Figure 42. The beach here is wider than in the other parts of this section of the coast described earlier; it is backed by Silver Lake which is formed in an ancestral stream valley incised into the Pleistocene highland (J. C. Kraft, oral communication). Washovers and a coast-parallel line of dunes on the landward edge of the berm can be observed in the photograph (Figure 42).

In summary, the following statements can be made about this beach-highland section of the transgressive barrier complex under study:

(1) The beach-berm is of narrow width, and is built against and over Pleistocene sediments.

(2) Storm wave attack can remove the entire beach. Eroded sediments are carried north by littoral transport, and also distributed in the nearshore zone. Return of normal weather conditions re-establishes the beach.

(3) Beach sediments consist of medium to very coarse sands and gravels which are moderately sorted.

(4) Coastal erosion of this pre-Holocene (Pleistocene) highland releases a large volume of sediment into the littoral transport system.

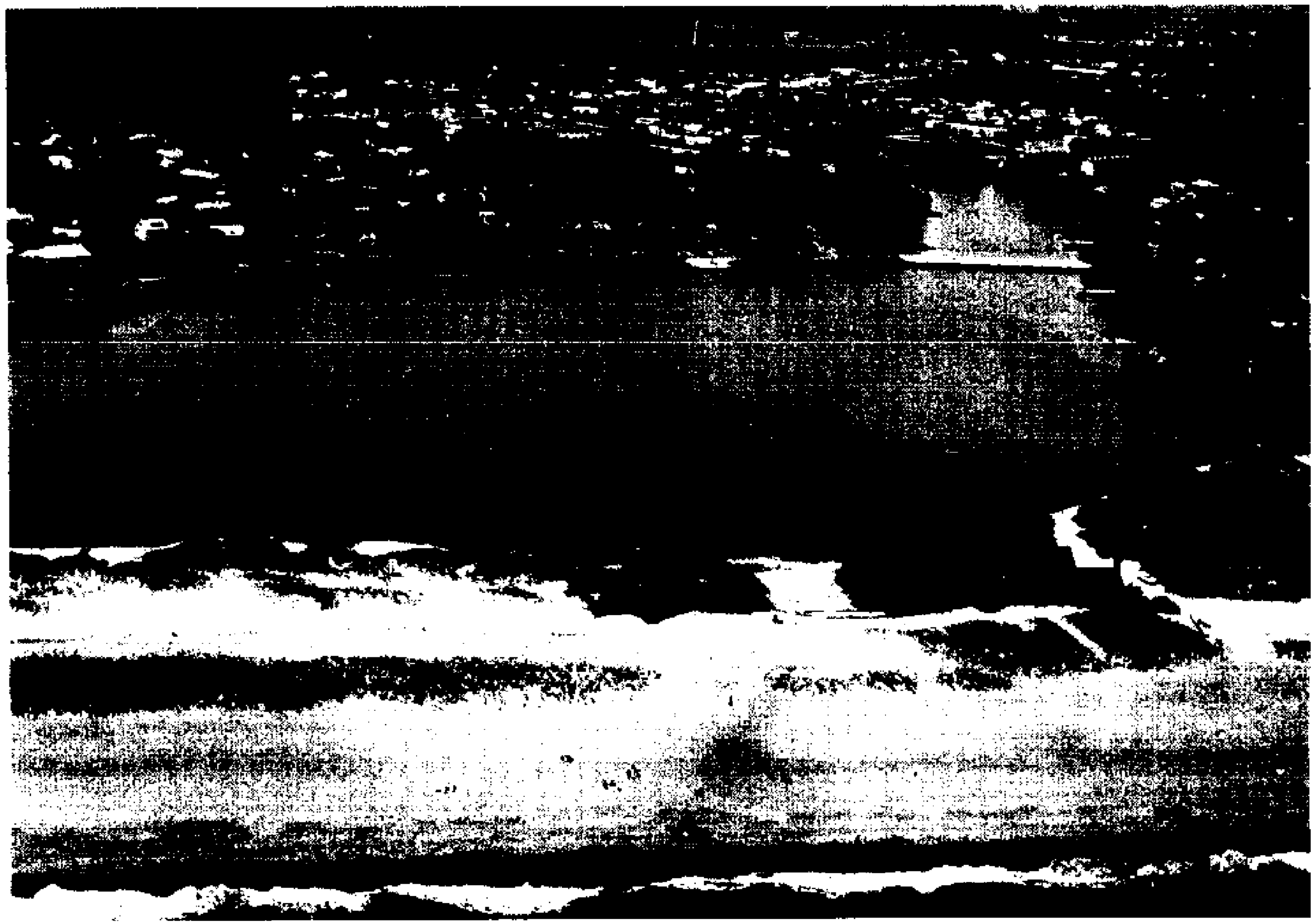


FIGURE 42. Aerial photograph of the beach lying in between the Atlantic Ocean and Silver Lake.

(5) The beach is characterized by seaward-dipping low-angle laminations which are parallel to the beach face. The back-beach area shows low-angle landward-dipping laminations parallel to the berm surface.

(6) The stratigraphic record of this beach is unlikely to be preserved.

(D) BARRIER-TIDAL DELTA-LAGOON (BAYMOUTH BARRIER)

This section of the coastal barrier complex, also known as a baymouth barrier, extends from the south of Rehoboth to Cottonpatch Hill in the southern part of the study area (Figures 14 and 15). It is therefore the longest section of the coastal barrier under investigation, and includes a linear barrier as well as a tidal delta sequence. The baymouth barrier is, as stated by Kraft (1971a), "a largely submerged sand body with only the smaller portion exposed above the tidal level." This section of the barrier complex also provides the best illustration of Walther's Law, discussed earlier in this report, as it shows a more or less complete vertical record of a transgressive coastal environmental sequence which can also be observed geographically at the present time. This section of the Holocene barrier complex, as in the case of the previous sections, unconformably overlies Pleistocene sediments.

The surficial transgressive sequence of the baymouth barrier, proceeding from land to sea, was described by Kraft (1971a) as follows:

> (1) The submerged Pleistocene highland with a trellis-dendritic drainage pattern; (2) the fringe of a marsh characterized by tree stumps, roots, and a marsh flora with a mixture of sand, clay, and silt; (3) typical lagoonal margin Spartina alterniflora and Spartina patens marshes; (4) thin, and possibly ephemeral, sand beaches on the westward sides of the coastal lagoons; (5) nearshore lagoonal sediments comprised of a mixture of sand and mud; (6) typical lagoonal clay-silts characterized by Elphidium sp. and Crassostrea virginica with abundant molluscan faunas; (7) submerged back barrier sand lobes; (8) on the eastern shorelines of the lagoon at the edge of the back barrier a Spartina patens and Spartina alterniflora marsh followed by pine forests developed on the slope of the back of the baymouth barrier; (9) linear dunes paralleling the coast; (10) the berm-washover area; (11) the beach face; (12) the submerged beach face at the edge of the presently eroding transgression; and finally (13) the shallow marine sands and shells forming a lag deposit as the transgression proceeds.

The baymouth barrier is backed by Rehoboth Bay and Indian River Bay which are connected with the ocean through the Indian River Inlet. The latter was artificially constructed in 1939 and is presently maintained by a pair of rock jetties. A natural inlet existed to the north of the present one (Figure 14) before it was closed by sedimentation. A flood and an ebb tidal delta are associated with the Indian River Inlet. This inlet has a history of migration north and south along the coast and is described by Thompson and Dalrymple (1976). The existence of old natural inlets is indicated by the fan-like shapes of former tidal deltas which have now been covered by Spartina marshes. As can be seen in Figure 14, the width of the barrier in the vicinity of these old tidal inlets and tidal deltas is greater than at other places along this section of the barrier complex.

The beach face of the baymouth barrier has a slope varying from 4° to 8°. This slope continues seaward to a depth of approximately 9 m (30 ft.). From this point onwards, up to a distance of about 8 km (5 miles) the depth varies from about 9m (30 ft.) to 18 m (59 ft.) (Kraft, 1971a). In general the beach and berm are composed of well sorted, medium to coarse sands. The most common sedimentary structures seen in trenches dug in the berm are horizontal laminations and truncated laminations, indicating building and erosion of the beach, respectively. Trenches in the intertidal area show horizontal laminations parallel to the beach face (Kraft, 1971a).

The baymouth barrier, like the other sections of this coastal area already described, is subject to severe erosion by waves produced by high intensity coastal storms. Eroded sediments are distributed over the submarine area immediately adjacent to the beach, and also carried north by littoral transport. The major portion of sands stored in the submarine area are later brought back again to the shore in the process of building up of the beach and berm when weather conditions have returned to normal. Washover lobes, some extending into the coastal lagoons behind the barrier, exist all along the baymouth barrier (Figure 14), and are partly covered by vegetation. Major erosion by storm waves also unearths stumps of trees of an ancient forest which are normally buried 2-3 m (6-8 ft.) under the beach-berm system. In some places along the barrier, tree stumps are also sometimes exposed at very low tide in the surf zone. According to Kraft (1971a, 1971b), an extensive back-barrier forest (mostly pine, but also cypress and white cedar) existed along the entire Delaware Atlantic coast when the barrier was more seaward (eastward) of its existing position. The exposed tree stumps provide conclusive proof of coastal transgression.

Figure 43 is a geologic cross section extending from the Pleistocene highlands, through the Lewes and Rehoboth canal, across the northeastern corner of Rehoboth Bay, across the baymouth barrier including Dewey Beach, and into the nearshore marine area. Whatever back-barrier marsh may have existed here has been covered by fill material for the purpose of housing and recreational facilities. The thickness of the barrier here is about

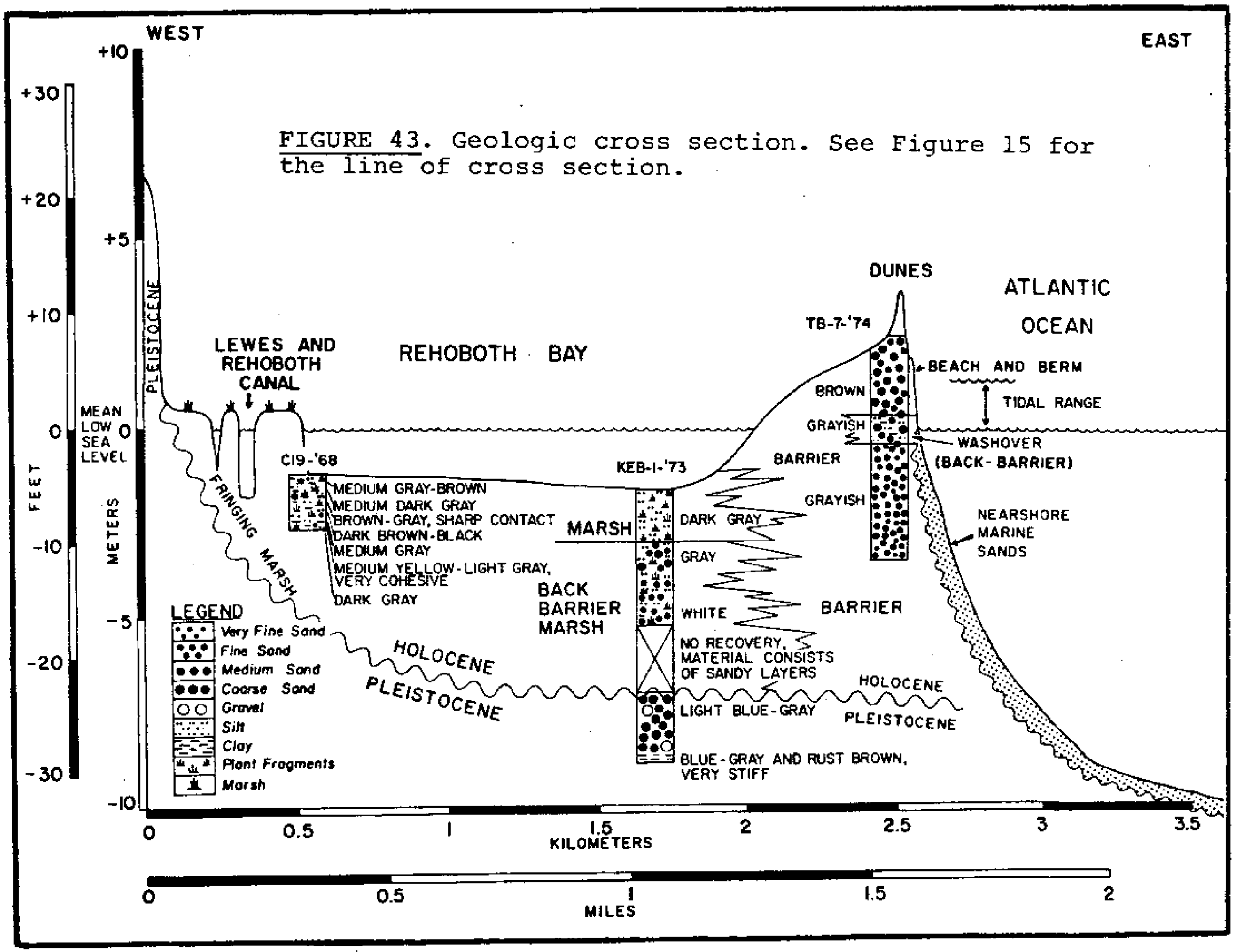


FIGURE 43. Geologic cross section. See Figure 15 for the line of cross section.

10 m (32.8 ft.), and it overlies Pleistocene lagoonal sediments characterized by a blue-gray color. The vertical sequence of the barrier has an interfingering relationship with the back-barrier marsh and the fringing marsh muds which have been inundated by the waters of Rehoboth Bay. Back-barrier marsh sediments are characterized by the presence of medium to coarse silty sand with abundant plant debris, the sand being derived from the barrier. Fringing marsh muds are composed of silt and plant material with little or no sand. In core TB-7-'74, the upper part of the barrier sequence is composed of fine to coarse sands, while the lower part is made up of fine to medium sands. The thin stratigraphic record of a washover deposit extending across the barrier into the back-barrier area is seen in core TB-7-'74. It is characterized by the presence of poorly sorted fine to coarse sands with silt and clay. The upper part of the stratigraphic record will be destroyed by the ongoing marine transgression, whereas the lower part may be preserved and will be overlain by shallow marine sediments. Figure 44 is an aerial photograph showing the area represented in the cross section (Figure 43). This photograph shows the general surface relationship of the barrier to the lagoon, the fringing lagoonal marsh, and the highlands, which is also illustrated in depth by the cross section.

FIGURE 44. Aerial photograph of the barrier near Dewey Beach, with Rehoboth Bay in the background.

Indian Beach is located south of Dewey Beach. A cross section extending from the Pleistocene hill at Thompson Island and passing successively through the marsh, Rehoboth Bay, the back-barrier marsh, the baymouth barrier including Indian Beach, and into the nearshore marine area is shown in Figure 45. The thickness of the barrier in this area in not exactly known, as the core TB-6-'74 did not penetrate through the barrier sediments into the underlying probably Pleistocene sediments. A part of the baymouth barrier in this area is submerged by the lagoon. A back-barrier marsh underlain by the sub-lagoonal barrier is present. Barrier sands are mostly medium grained. A washover has been preserved in the vertical sequence seen in core TB-6-'74. Sub-lagoonal sands of the barrier overlie Pleistocene lagoonal sediments in core R-4119. The latter are identified by their blue color. A veneer of Rehoboth Bay lagoonal sediments overlies a sequence of marsh muds with abundant plant material, which in turn unconformably overlies Pleistocene sediments. A fringing lagoonal marsh exists alongside the Pleistocene highland at Thompson Island. As in the previous cases, the upper part, that is, the beach-dune section of the baymouth barrier has a low potential for preservation in the stratigraphic record; the lower part of the barrier sediments has a much better chance for preservation.

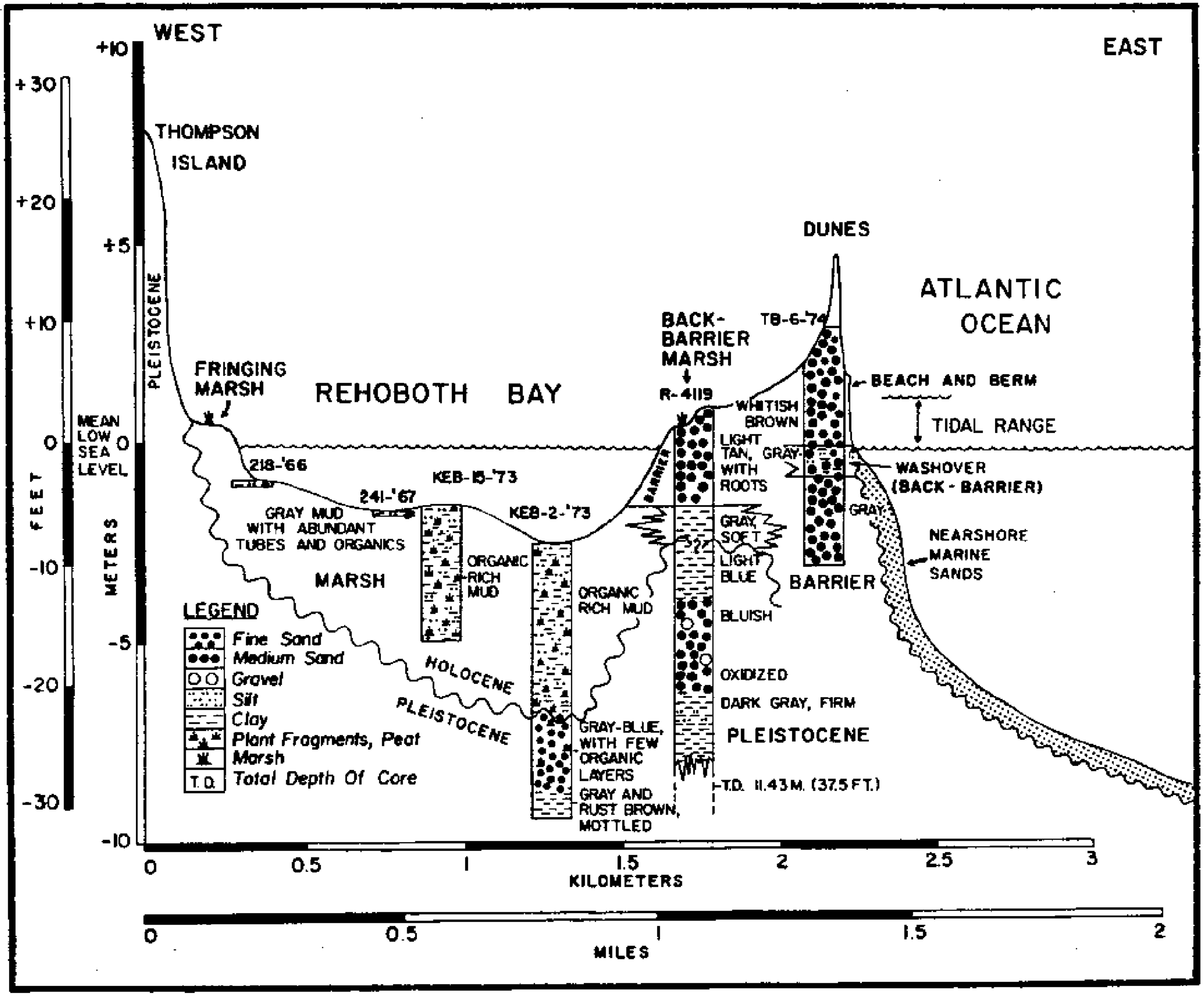


FIGURE 45

Geologic cross section. The line of cross section is shown in Figure 15.

In the geologic cross section shown in Figure 46 one can observe that a greater part of the linear baymouth barrier is submerged under the Rehoboth Bay than that seen in the area of the previous cross section (Figure 45). A well developed back-barrier marsh exists in this area, and pine tree stumps are exposed on the ocean side in the surf zone at very low tide. The barrier sediments are coarse grained, as can be observed from the record of them seen in core R-4118. Also, the record of thin back-barrier marshes is preserved in the vertical sequence of core R-4118. These marshes existed when the barrier was further seaward of its existing position. The sub-lagoonal portion of the baymouth barrier is composed of fine to medium sands with little silt and occasional shell fragments. In core KEB-4-'73, records of what may have been thin isolated marshes covering small islands, similar to the presently disappearing marsh which covers Big Piney Island in western Rehoboth Bay, have been preserved. Barrier sediments interfinger and grade laterally and with depth into lagoonal sediments. On the Atlantic Ocean side, the barrier sediments are covered by a thin veneer of shallow marine sands as the Holocene transgression continues. A transgressive vertical sequence of sediments is represented in this cross section (Figure 46).

In the geologic cross section shown in Figure 47,

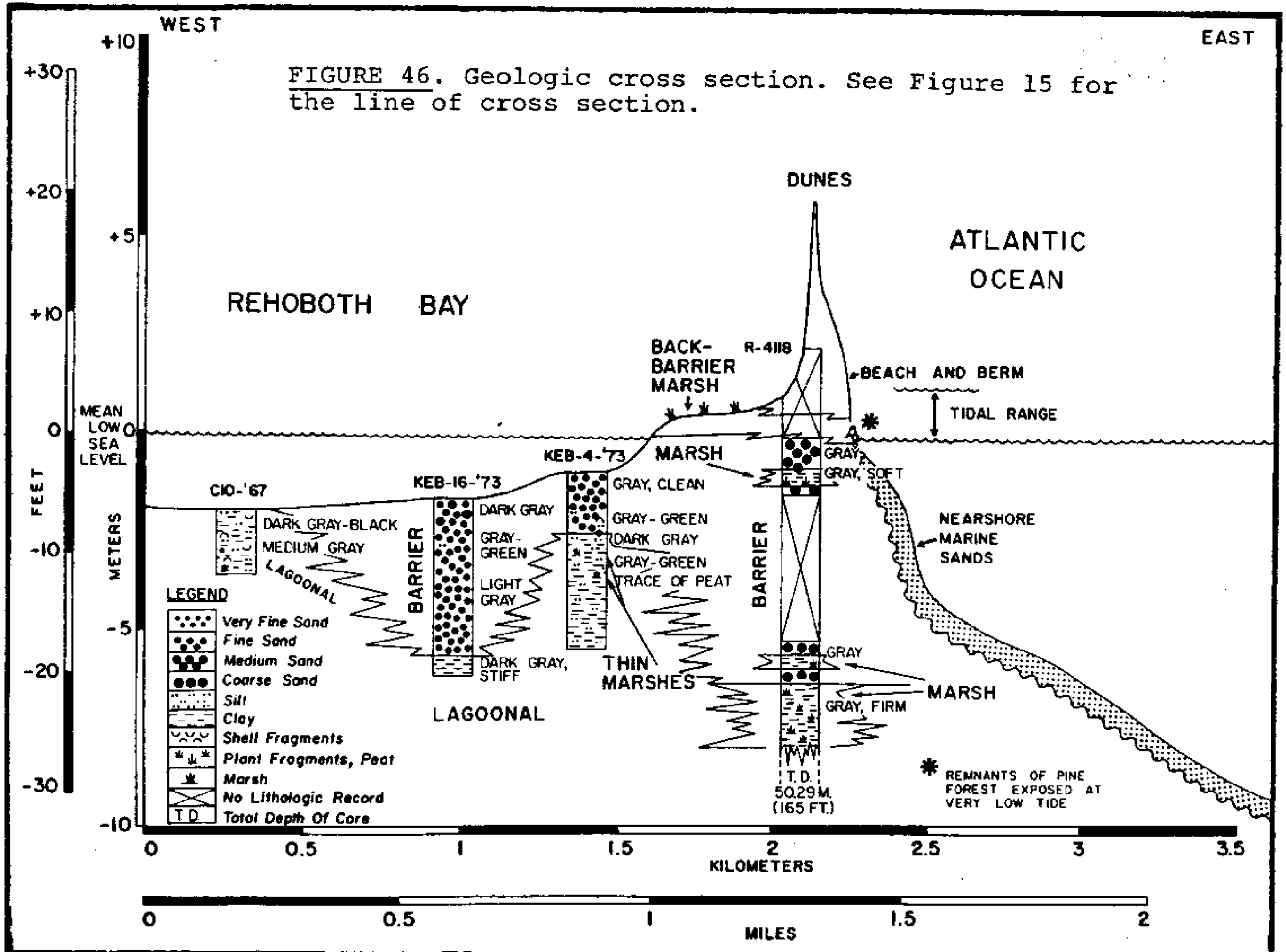


FIGURE 46. Geologic cross section. See Figure 15 for the line of cross section.

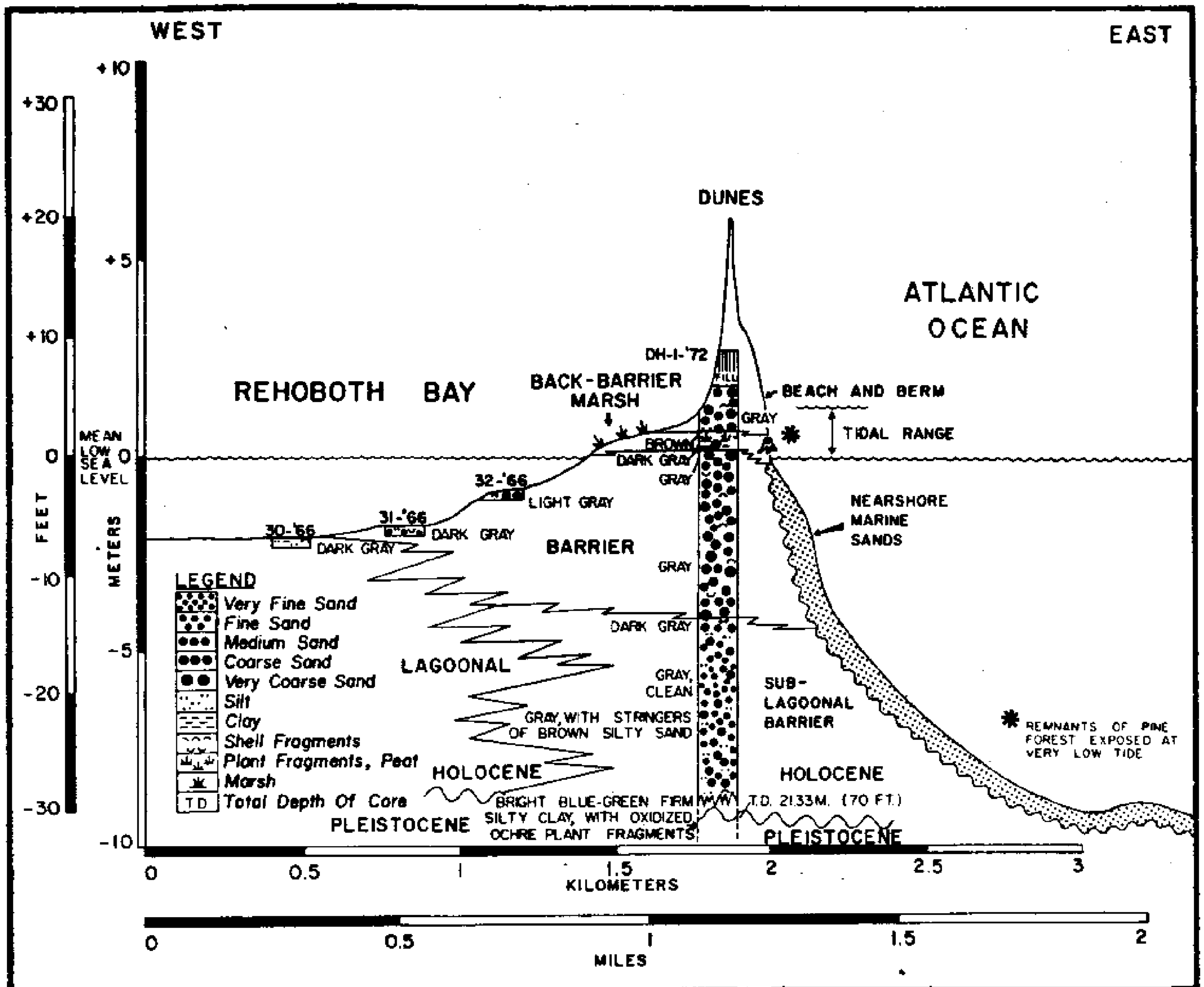


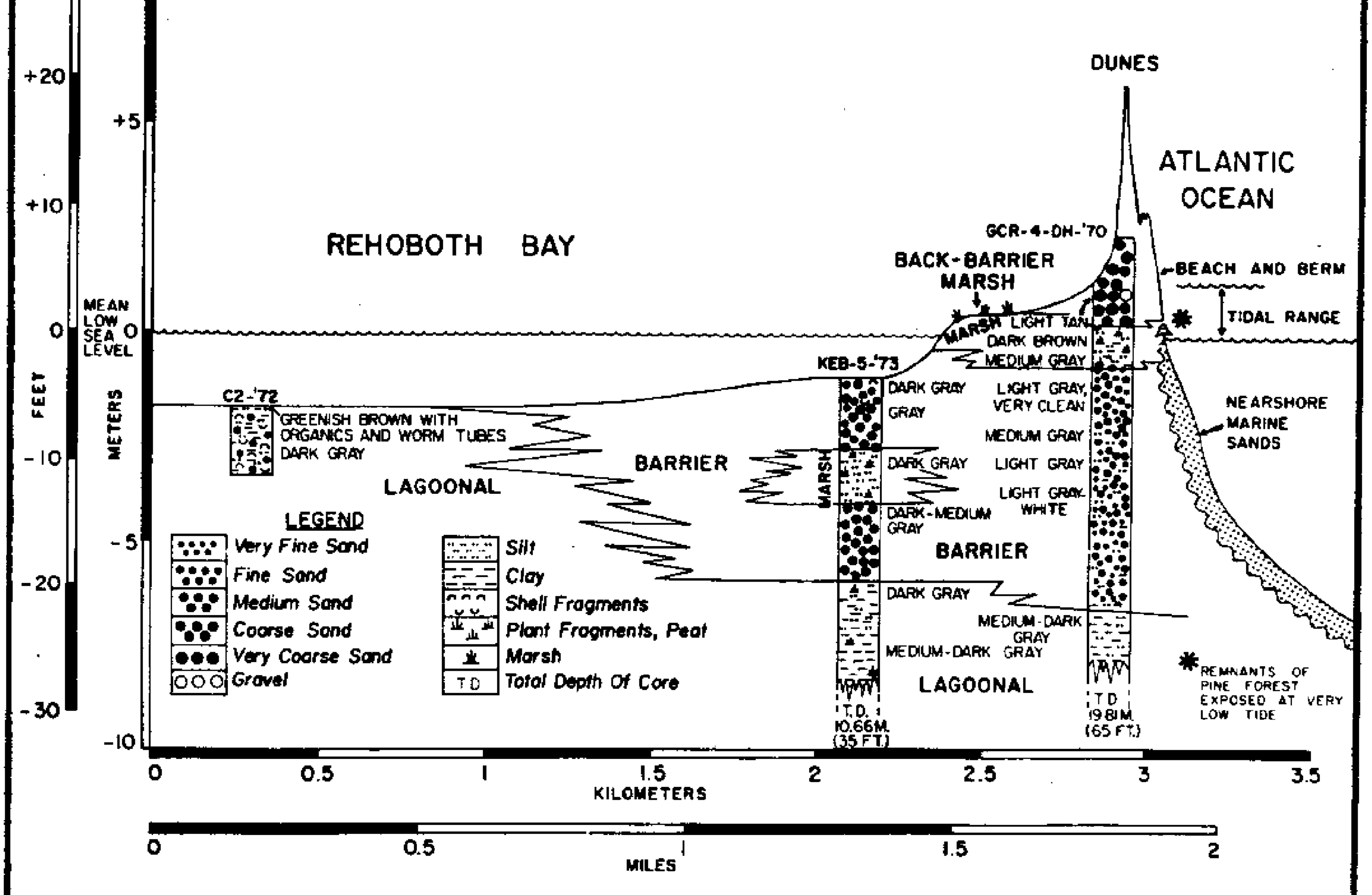
FIGURE 47

Geologic cross section. See Figure 15 for the line of cross section.

the barrier sediments are underlain by sub-lagoonal barrier sediments which were deposited when the present baymouth barrier was further eastward (seaward) of its existing position. The latter sediments unconformably overlie Pleistocene lagoonal blue-green silty clay containing oxidized ochre-colored plant fragments. A thin record of the back-barrier marsh which is again overlain by barrier sediments is seen in core DH-1-'72. Here again, as before, the remnants of a back-barrier pine forest, which existed when the barrier was further east, are exposed at very low tide, and after storms in the surf zone of the Atlantic Ocean beach. The barrier sands seen in core DH-1-'72 are medium to very coarse grained with shell fragments; sub-lagoonal barrier sands are fine to medium grained and contain shell detritus. The barrier thins westward into Rehoboth Bay where it grades laterally into lagoonal sediments with an intertonguing relationship. The back-barrier marsh represents part of the leading edge of the Holocene marine transgression, as the baymouth barrier migrates landward (westward) across Rehoboth Bay in response to relative sea level rise and coastal erosion.

Figure 48 is another cross section across the baymouth barrier in which the sub-lagoonal part of the barrier extends to about 1.6 km (1 mile) into Rehoboth Bay.

FIGURE 48. Geologic cross section. The line of cross section is shown in Figure 15.



The main barrier, including the dunes, has a maximum thickness of about 12 m (49.3 ft.), including a 1.5 m (5 ft.) thick section of back-barrier marsh sediments, as seen in core GCR-4-DH-'70. The upper part of the barrier sequence, that is, the part overlying the back-barrier marsh record, is made up of coarse to very coarse sands with little gravel. Below this section of marsh muds, the barrier sands are very fine to medium grained with silt, and rather poorly sorted. This suggests that the configuration of this portion of the barrier may have been such that at one time it was at the edge of or under a coastal lagoon which consequently resulted in the deposition of silts in the barrier sands. In core KEB-5-'73 the sub-lagoonal barrier sands are medium to coarse grained, with some shell fragments at the top of the sequence. The marsh muds in this core in all probability represent an old back-barrier marsh. Barrier sediments overlie and grade laterally into lagoonal sediments on the landward side, whereas they are covered by shallow marine sediments on the Atlantic Ocean side. A transgressive vertical sequence of sediments is represented in this cross section (Figure 48).

Sub-lagoonal sands of the baymouth barrier seen in the cross section shown in Figure 49 are well sorted, fine grained, and contain shell fragments. The barrier sediments

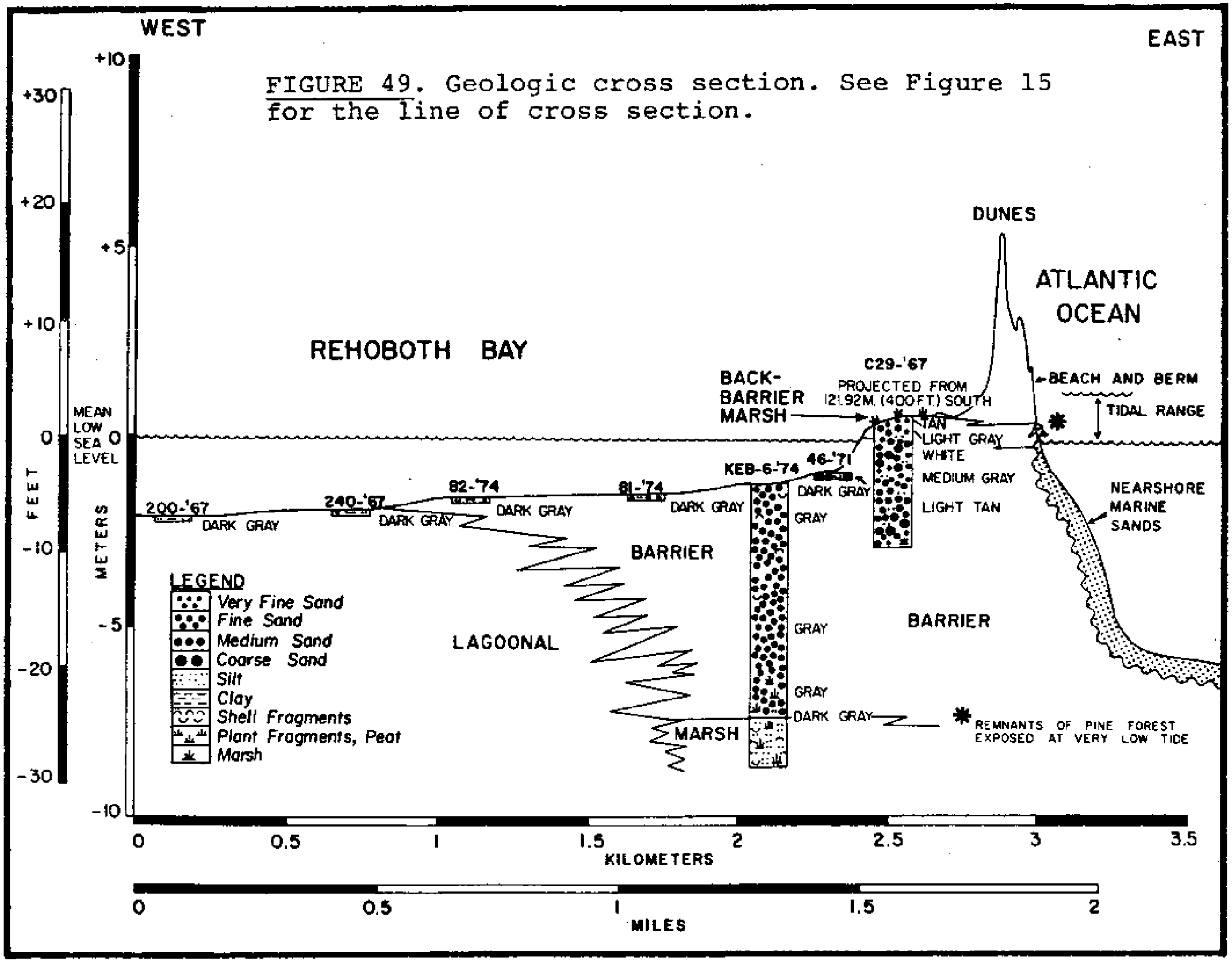


FIGURE 49. Geologic cross section. See Figure 15 for the line of cross section.

overlie marsh muds in core KEB-6-'74. Barrier sands underlying the back-barrier marsh (C29-'67) are poorly sorted and fine to coarse grained with silt. In the area represented by this cross section (Figure 49), the relationship of barrier sands to lagoonal and shallow marine sediments on the two sides of the barrier are similar to that described in the earlier cross sections.

Figure 50 is a detailed and typical cross section of the transgressive linear baymouth barrier, which also provides an excellent illustration of Walther's Law. Radiocarbon dates obtained using marsh muds are shown along the length of two cores. The different surficial environments represented in this cross section as one proceeds from west to east are (1) lagoonal; (2) sub-lagoonal barrier; (3) back-barrier marsh; (4) dunes; (5) berm and beach; and finally (6) the steep submarine shoreface. The total width of the barrier taken along its widest part in the cross section is approximately 3 km (1.8 miles), of which about 2 km (1.2 miles) constitutes the sub-lagoonal part. The total thickness of the barrier, including the dunes and the back-barrier marsh sequences, is about 10 m (30 ft.). Barrier sands are mostly medium to coarse grained, with decreasing grain size and introduction of silt, clay, and shell fragments towards the central portion of Rehoboth Bay. Records of back-barrier marshes

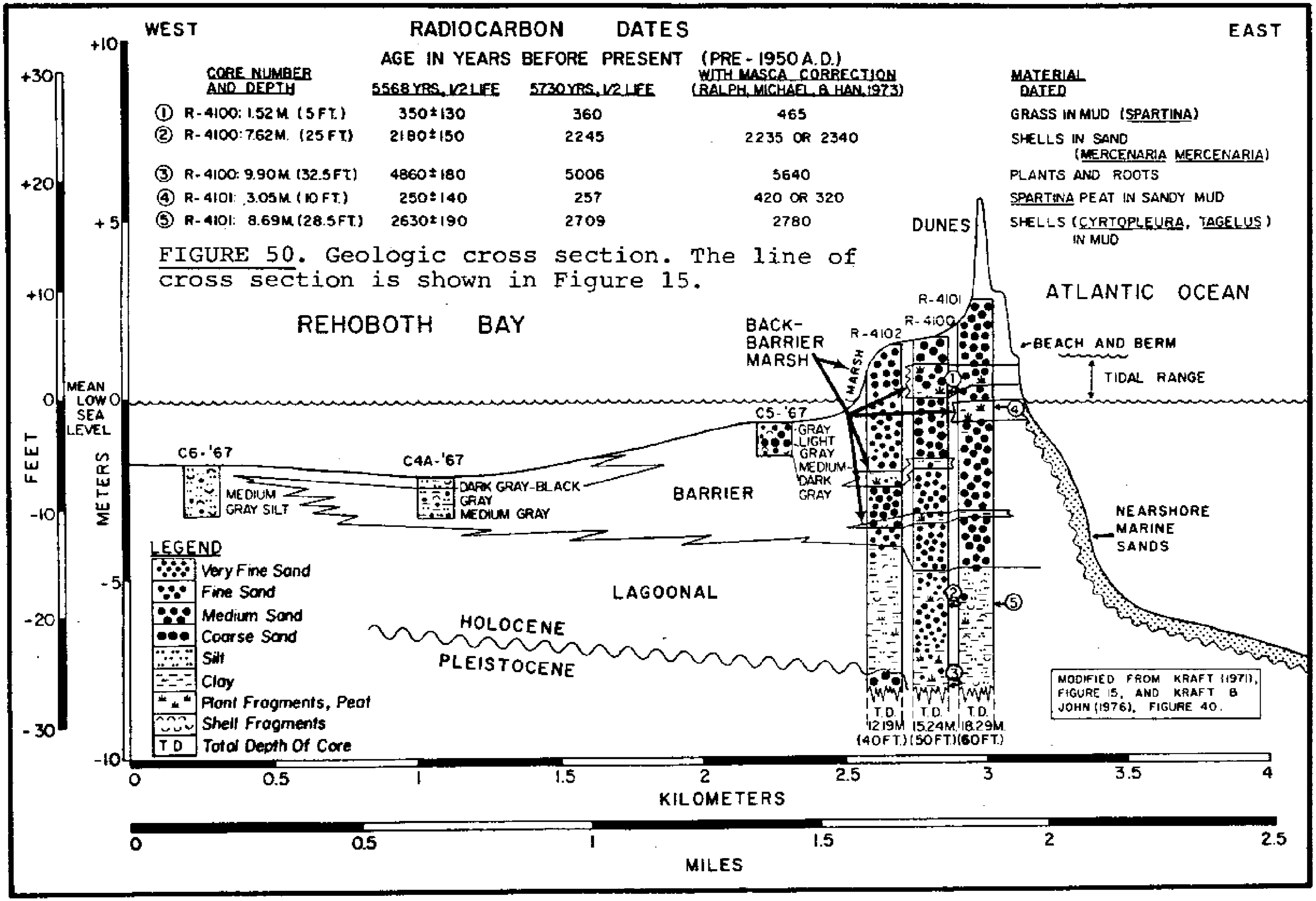


FIGURE 50. Geologic cross section. The line of cross section is shown in Figure 15.

are preserved in the vertical stratigraphic sequences of cores R-4102, R-4100, and R-4101. These back-barrier marshes existed at different times when the main part of the baymouth barrier was further eastward (seaward) of its present position, and relative sea level was lower. As the transgression progressed, Holocene lagoonal sediments at the lagoonal edge were partly covered by sub-lagoonal barrier sediments by washover deposition. A back-barrier *Spartina* marsh then developed at the edge of the lagoon over the back-barrier sands. Later, this marsh was wholly or partly buried by washover deposits resulting from storm overwash. At the same time, the lagoonal sediments were further transgressed by sands brought in by overwash. Then the back-barrier marsh grew back again. This whole process continued again and again as the barrier migrated landward and upward in space and time as the transgression continued, thus producing the vertical stratigraphic sequence seen in the cross section (Figure 50). The barrier sands lying between the back-barrier marsh sequences in the cores represent washover deposits. It can therefore be stated that washover deposition by overwash during storms constitutes the most important mechanism for the westward (landward) migration of the baymouth barrier, as ocean side erosion of the barrier continues.

Sediments eroded from the beach and foreshore zone are mostly stored in the adjacent submarine area. They are carried across the barrier and often into the eastern side of Rehoboth Bay as washover deposits during storm overwash. However, part of the eroded sediment will be carried north by littoral transport to be deposited finally at the Cape Henlopen spit tip, and part of it is lost by movement from the nearshore area further seaward as a result of wave action. As erosion continues, the barrier sediments are recycled, and the process is repeated endlessly. Barrier sands are underlain by lagoonal muds which are characterized by a Crassostrea virginica fauna. Lagoonal sediments overlie marsh sediments which unconformably overlie Pleistocene deposits. The radiocarbon date of 2,340 years before present obtained at a depth of 7.6 m (25 ft.) is the bottom of the vertical sedimentary sequence of the barrier, as seen in core R-4100 in Figure 50. This date indicates that the entire present Holocene barrier sequence was developed within the last 2,340 years. As observed in the previous cases, part of the stratigraphic record of the transgressive vertical sequence may be preserved under a cover of shallow marine sediments. Evidence presented by this cross section, and also earlier ones, indicates that this coastal barrier was not formed at its existing site, but migrated here from another position elsewhere on the Atlantic continental shelf.

Figures 51A and 51B, 52A and 52B, and 53A and 53B, are photographs of cores R-4100, R-4101, and R-4102 respectively, seen in the cross section (Figure 50). Sedimentary structures and differences in grain size and color of the sediments from different sedimentary environments represented in the core sequences can be observed in these photographs.

Figure 54 represents a detailed summary of the characteristics of core R-4100. The electric log curves do not show any distinctive patterns. Grain size indicates that the barrier sands preserved in core R-4100 are fine to medium grained. Trask sorting values are all less than 2.5, and this would place all sediments in the well sorted category in terms of Trask's verbal limits for sorting. According to graphic standard deviation values, barrier sediments are on the average moderately well sorted. As is to be expected, the barrier sands are negatively skewed. Burrows tend to be concentrated at the interface of barrier and marsh sediments. Horizontal laminations and concave and convex laminations are observed in different parts of the core. Between depths of 5 m (16.4 ft.) and 7 m (22.9 ft.), high-angle laminations and ripple laminations caused by washover deposition can be observed.

Figure 55 presents a detailed summary of the lithology, sedimentary structures, grain-size parameters,

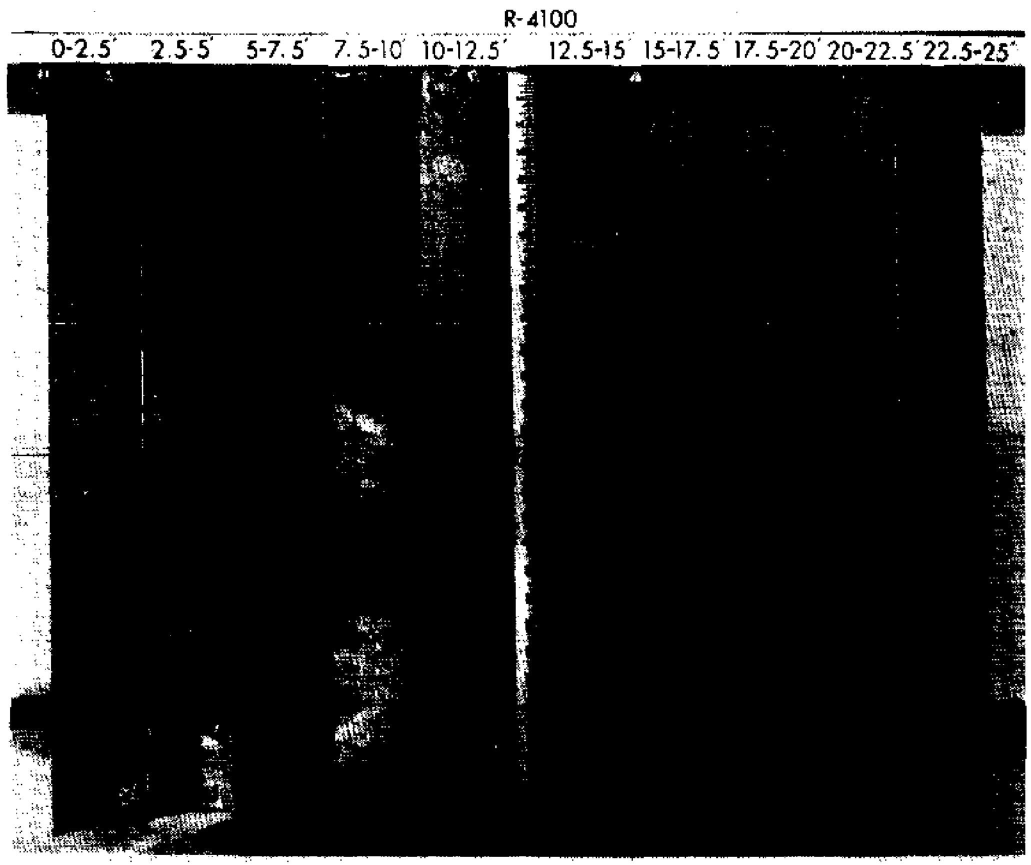


FIGURE 51A. Photograph of core R-4100 (0-25 ft.; 0-7.6 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

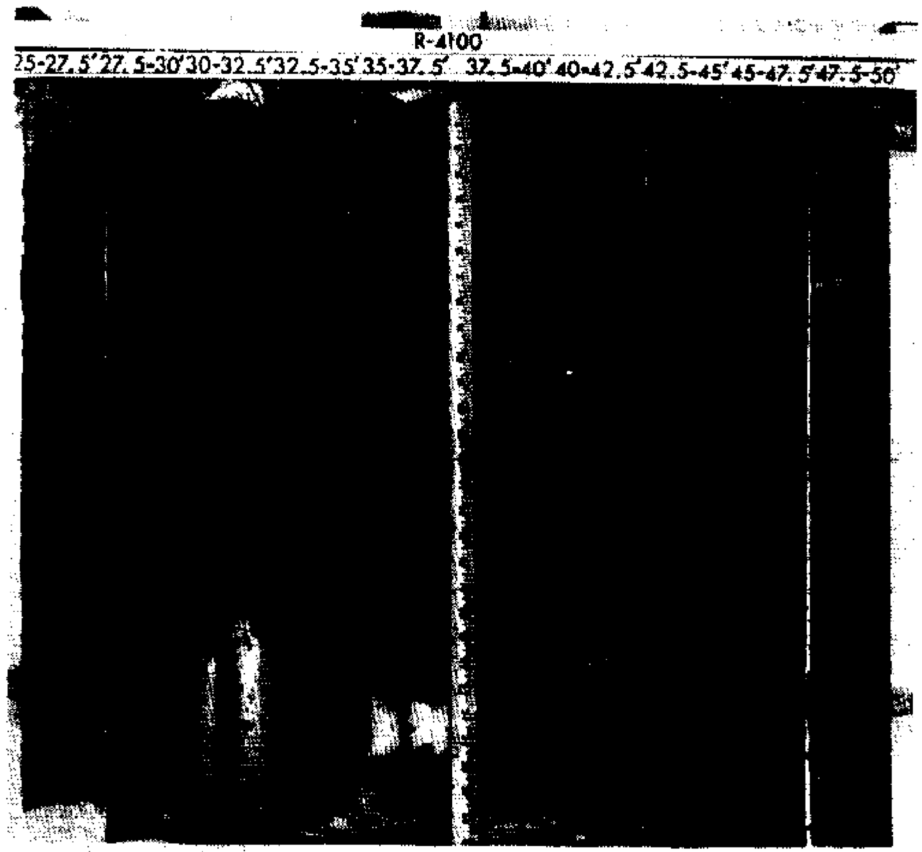


FIGURE 51B. Photograph of core R-4100 (25-50 ft.; 7.6-15.2 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

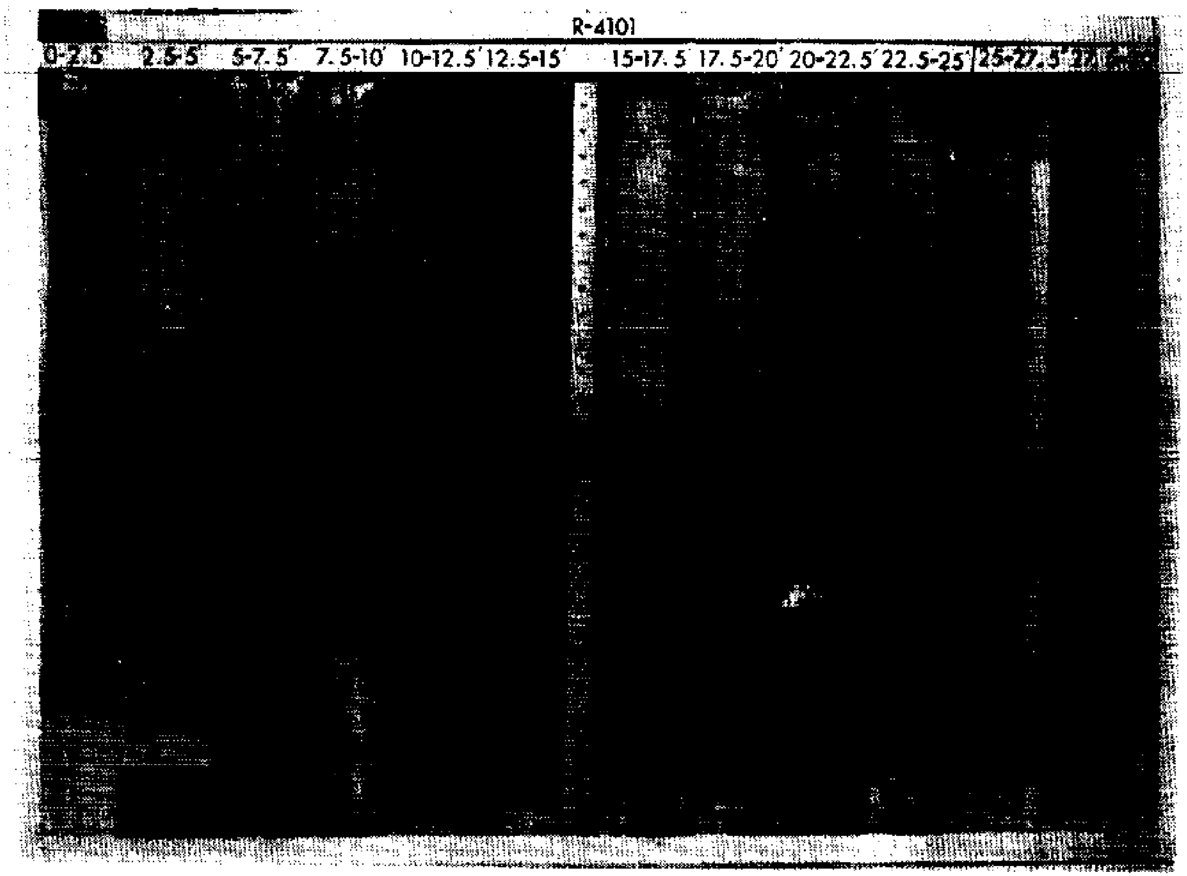


FIGURE 52A. Photograph of core R-4101 (0-30 ft.; 0-9.1 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

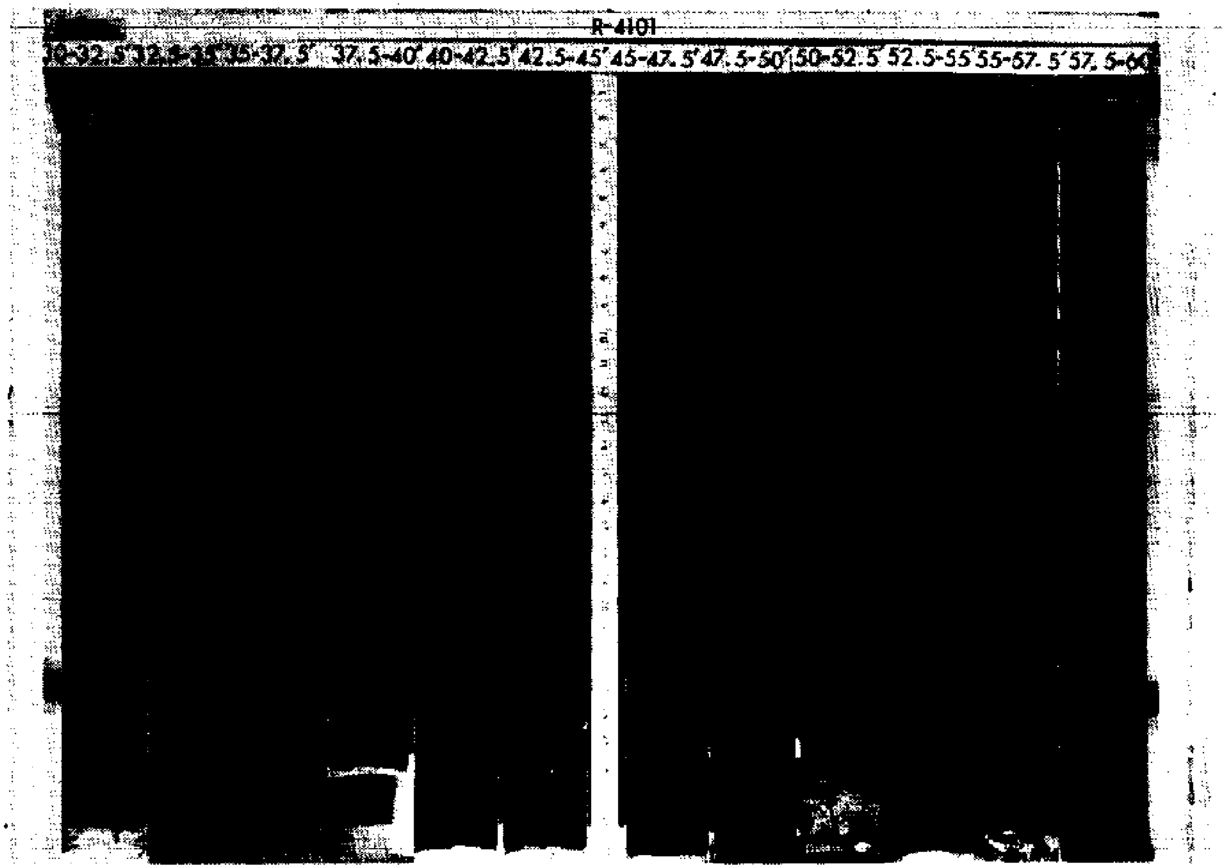


FIGURE 52B. Photograph of core R-4101 (30-60 ft.; 9.1-18.3 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

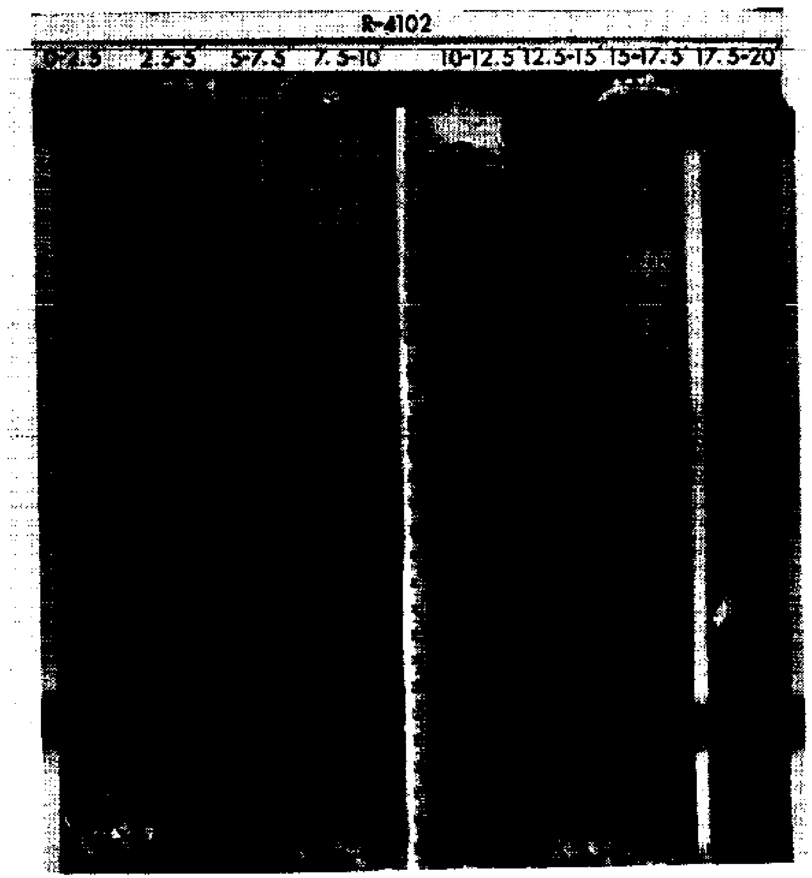


FIGURE 53A. Photograph of core R-4102 (0-20 ft.; 0-6.1 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

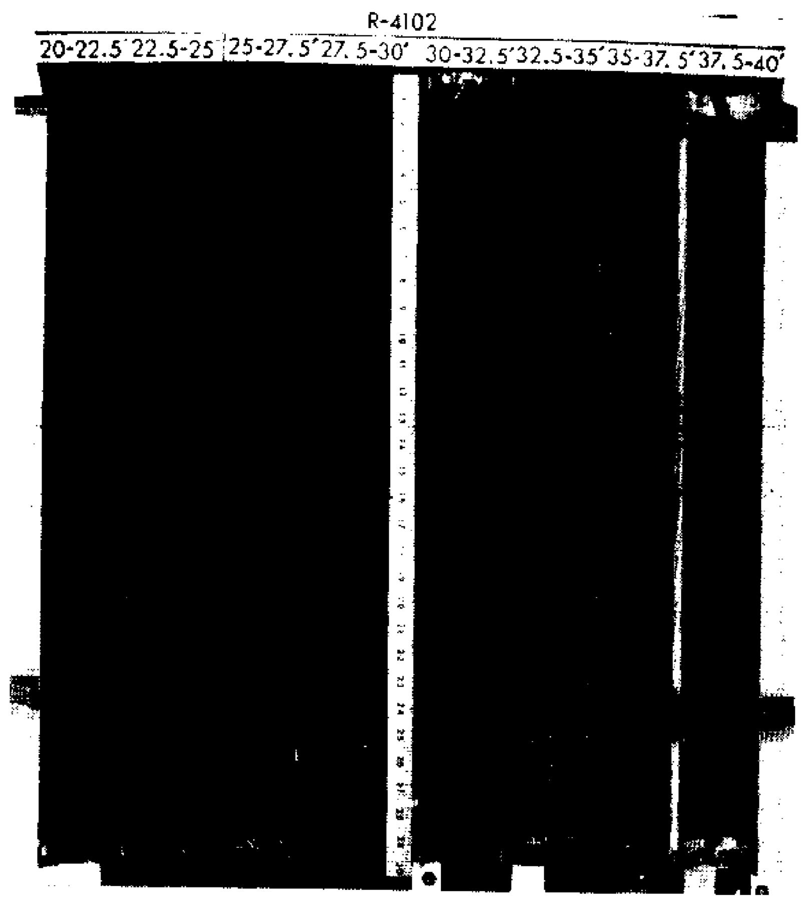


FIGURE 53B. Photograph of core R-4102 (20-40 ft.; 6.1-12.2 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

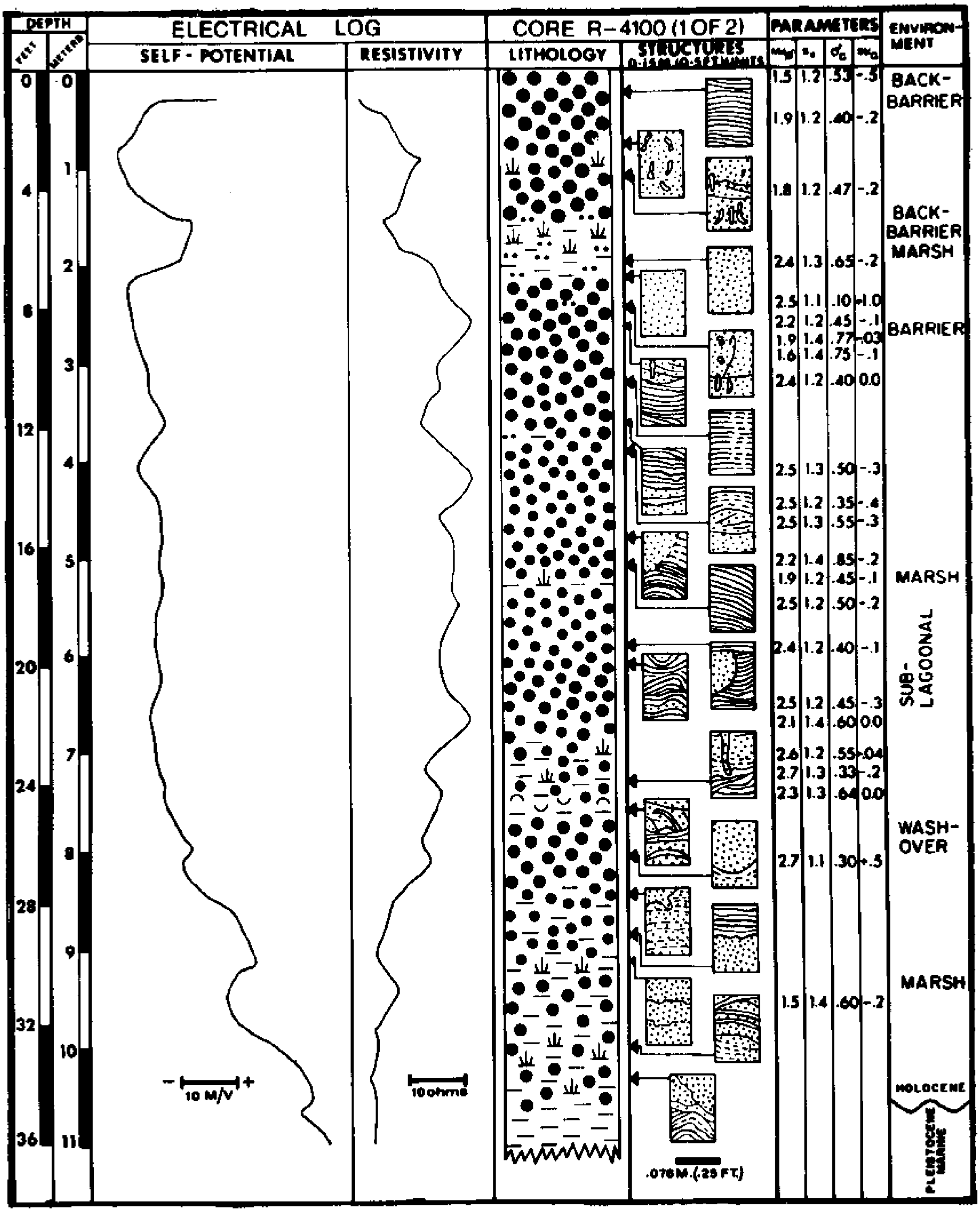


FIGURE 54. Geophysical, sedimentological, and sedimentary structure data for core R-4100. (cont.) →

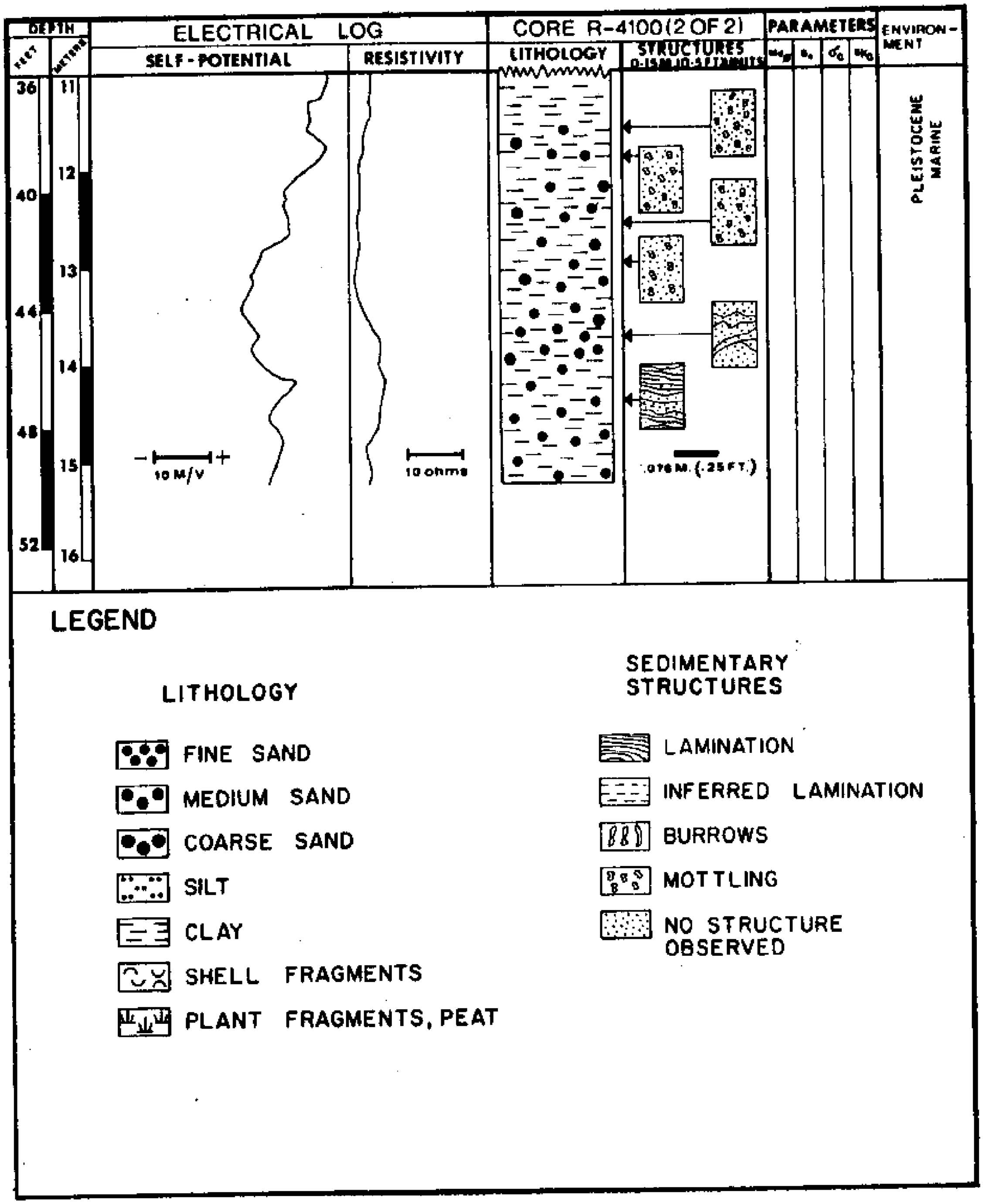


FIGURE 54 (cont.). Geophysical, sedimentological, and sedimentary structure data for core R-4100.

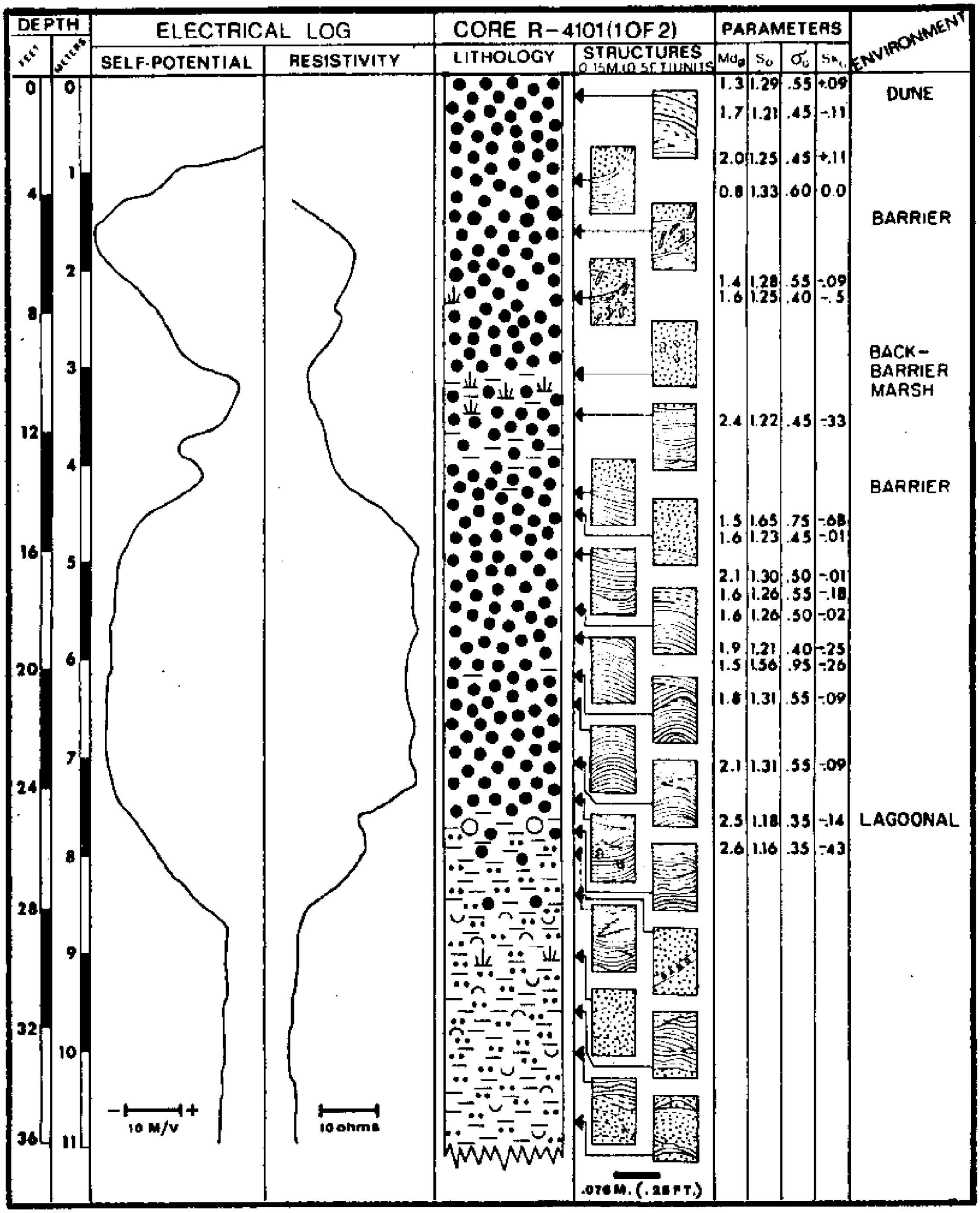


FIGURE 55. Geophysical, sedimentological, and sedimentary structure data for core R-4101. (cont.) →

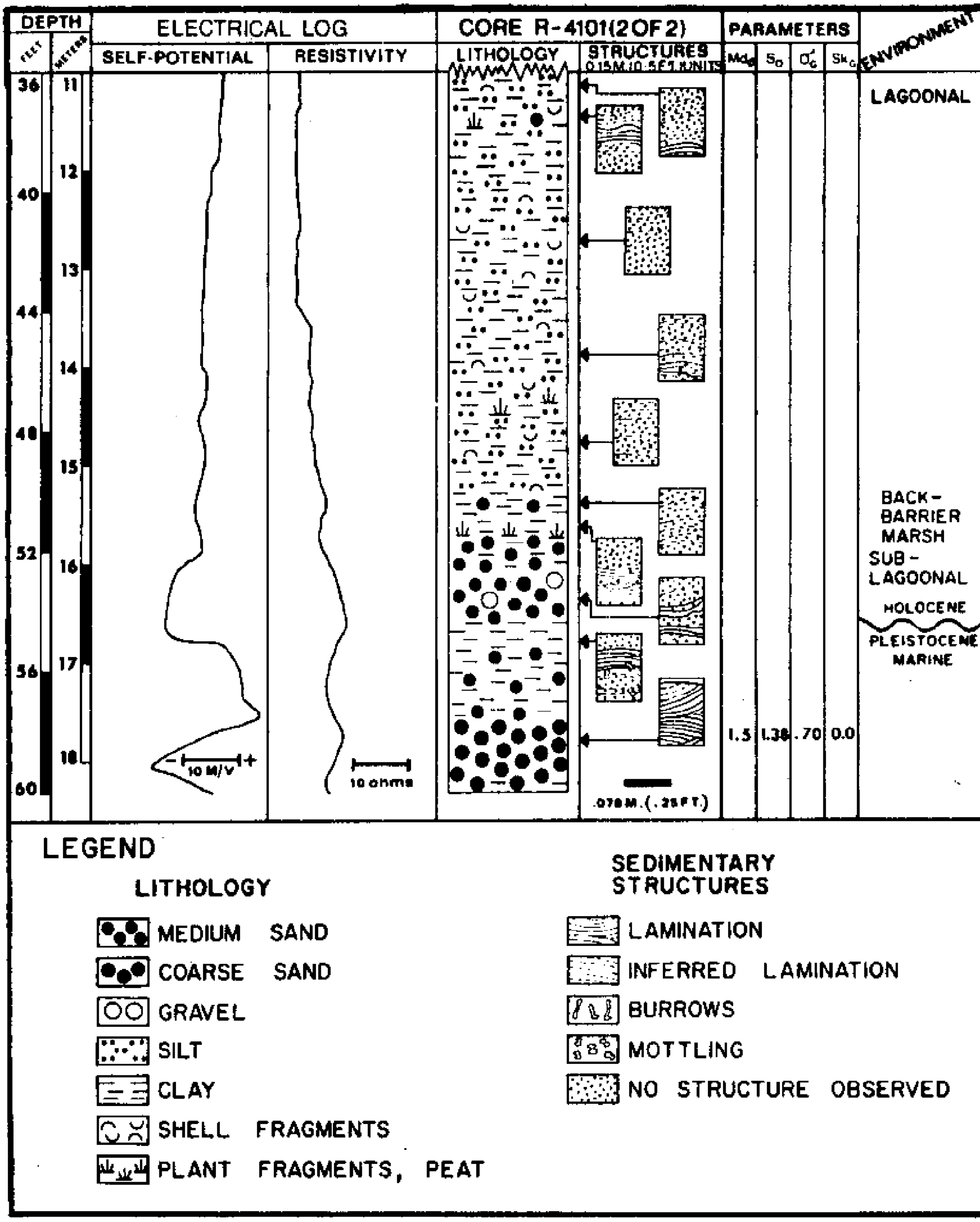


FIGURE 55 (cont.). Geophysical, sedimentological, and sedimentary structure data for core R-4101.

electric log patterns, and environments observed in core R-4101. The more or less bell-shaped SP curve pattern is characteristic of a transgressive sequence. The contact between barrier and lagoonal sediments is well defined. High-angle laminations below the back-barrier marsh at about a depth of 4 m (13.1 ft.) indicate that sediments in this part of the core are of washover origin. As seen in the core sequence, the washover deposits were later covered by a back-barrier marsh. Other sedimentary structures seen in the barrier sands include simple cross-laminations, convex laminations and burrows. Though according to the Trask coefficient of sorting values the barrier sands are well sorted, graphic standard deviation values put the barrier sands in the moderately well sorted category. Barrier sands in core R-4101 are medium grained. Dune sands show positive skewness, and barrier sands are negatively skewed. Sub-environments of the barrier cannot be distinguished on the basis of grain-size parameters as these are not distinctive.

Figure 56 is a summary of the characteristics of core R-4102. Electric log curve shapes do not show any distinctive patterns. As in the case of the other two cores described in the preceding paragraphs, barrier sands seen in core R-4102 are moderately well sorted, fine to medium grained, and negatively skewed. Dune and some wash-

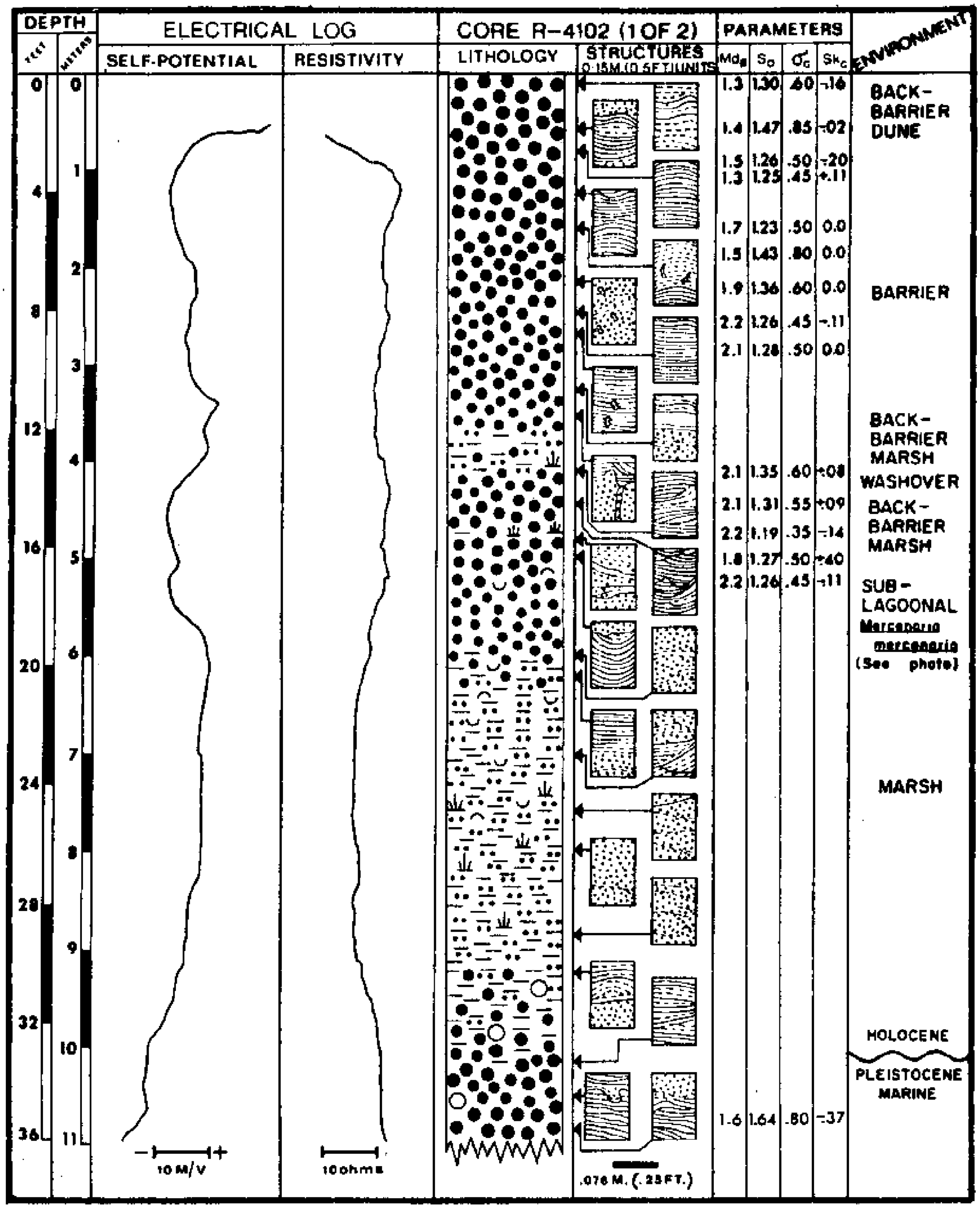


FIGURE 56. Geophysical, sedimentological, and sedimentary structure data for core R-4102. (cont.)→

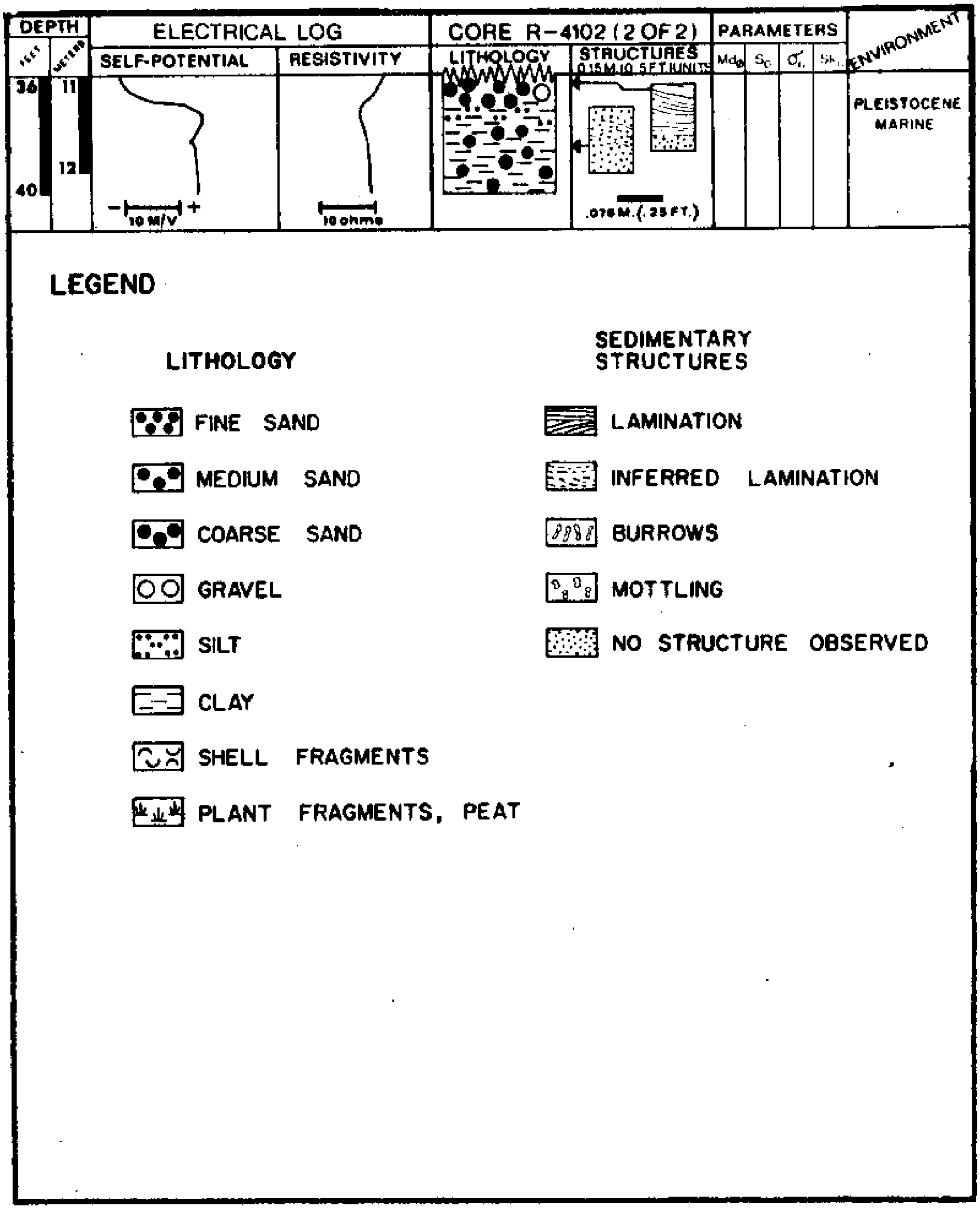


FIGURE 56 (cont.). Geophysical, sedimentological, and sedimentary structure data for core R-4102.

over sands show positive skewness. Horizontal laminations, concave laminations, and trough cross-laminations are observed in the barrier sands of core R-4102. A point to be noted here is the lower average grain size of barrier sands in this general area as compared to the Cape Henlopen spit area. This is due to the fact that the sediments involved here are repeatedly subject to re-cycling and resorting, unlike the sediments at the spit tip.

Core DH-2-'74 seen in Figure 57 passes through the barrier sands into the underlying lagoonal sediments. Thin records of two washovers which entered the lagoon are seen in this core preserved between silt and clay of the lagoon. This further emphasizes the importance of washovers in the process of barrier migration. Though a back-barrier marsh is present in this area and tree stumps are sometimes exposed in the surf zone of the Atlantic Ocean beach at very low tide, or after storm erosion, no record of the continuance of the back-barrier marsh under the barrier is seen in core DH-2-'74. Sands underlying the main part of the barrier are medium to coarse grained with gravel. Proceeding bayward, in core KEB-7-'73 the sands are fine grained with shell material, and directly overlie a sequence of marsh muds. In core KEB-13-'73 the barrier sands underlying the lagoon are of fine to medium grain

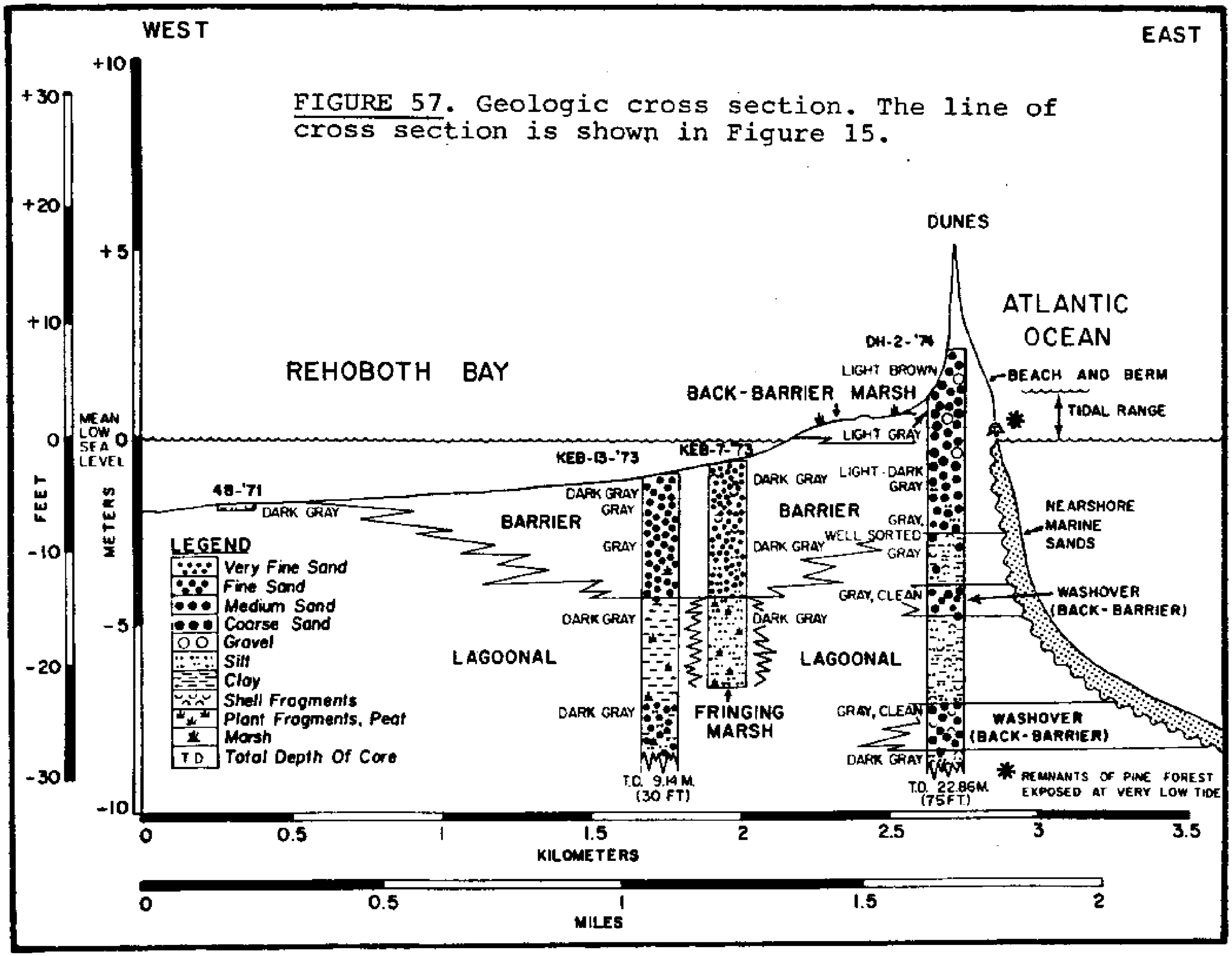


FIGURE 57. Geologic cross section. The line of cross section is shown in Figure 15.

size and overlie lagoonal clay. Further westward, these sub-lagoonal barrier sediments grade laterally into lagoonal sediments with an interfingering relationship.

The line of cross section for Figure 58 passes through the beginning of the area in which old tidal deltas once existed (Figure 14). As there is no core through the main barrier, the correct thickness of the barrier is not known, but can be estimated to be about 12 m (39.4 ft.), including the dunes overlying the barrier, on the basis of the cross section (Figure 58). Barrier sands immediately underlying the back-barrier marsh are coarse grained; they are mostly medium grained towards and under the lagoon. The thin marsh sequence seen in core KEB-12-'73 was probably deposited on a small marsh island, before again being buried by barrier sediments. The sub-lagoonal barrier sands overlie and grade laterally westward into lagoonal sediments. As erosion of the barrier continues on the ocean side, shallow marine sediments are being deposited over the transgressive barrier sediments, thus creating a path of the landward moving barrier under the submarine surface.

Figure 59 is a geologic cross section across a part of the presently marsh-covered old tidal delta area. A continuation of the existing back-barrier marsh is encountered in core DH-1-'74; outcrops of the marsh have

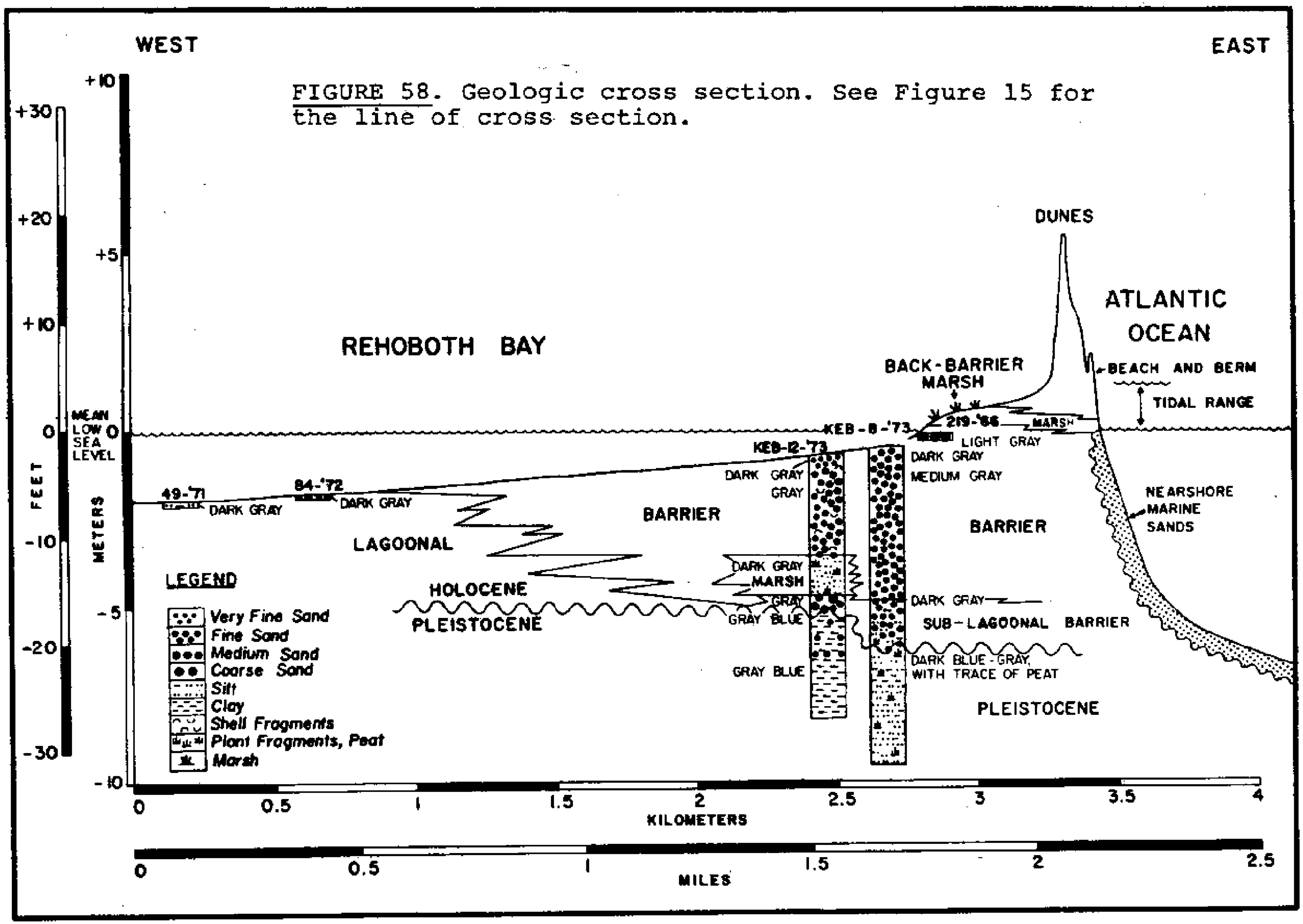


FIGURE 58. Geologic cross section. See Figure 15 for the line of cross section.

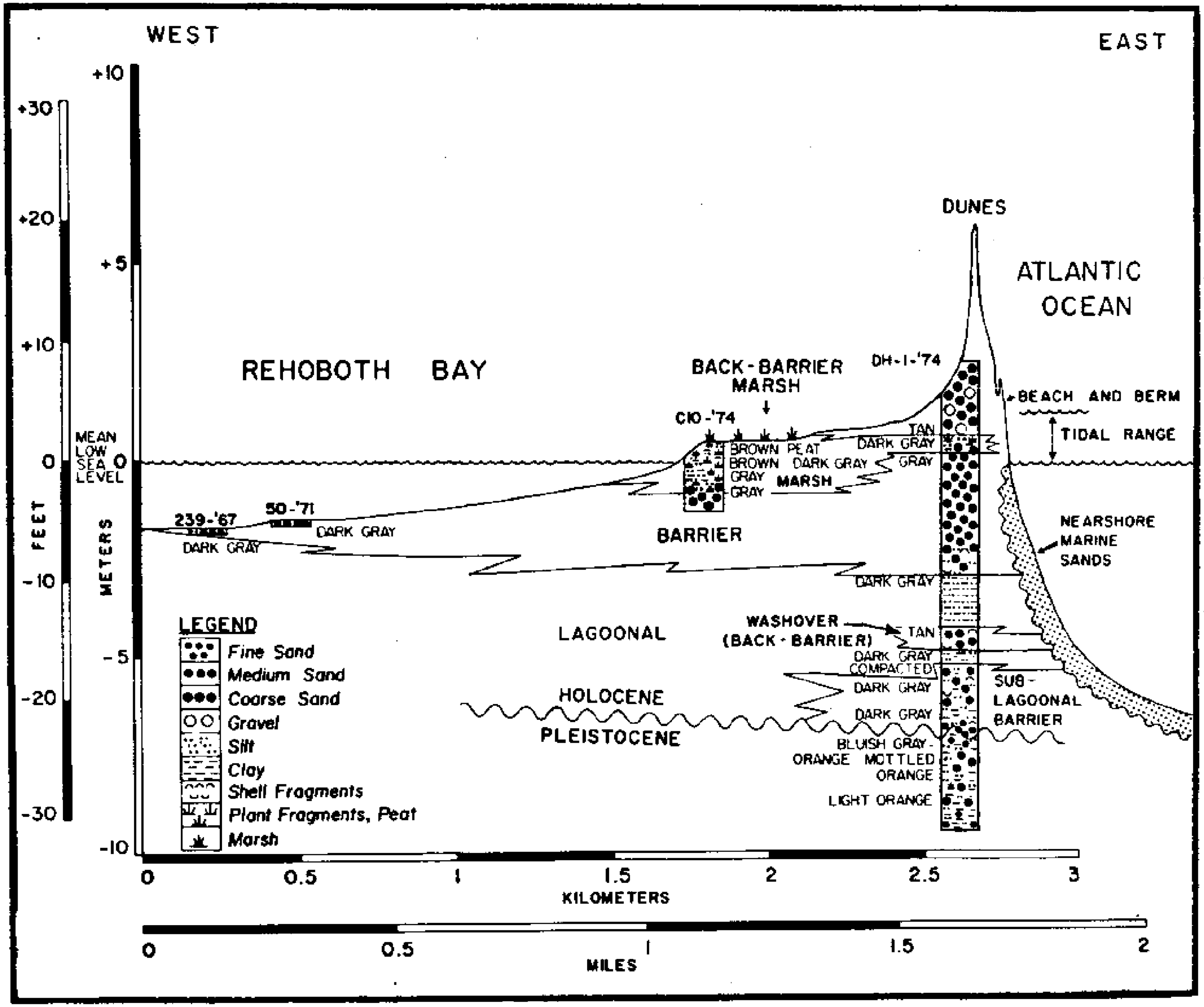


FIGURE 59

Geologic cross section. The line of cross section is shown in Figure 15.

been reported in the low tide surf zone on the Atlantic Ocean side. Barrier sands are medium to coarse grained with some gravel, and overlie lagoonal sediments. The record of a washover deposit is preserved in the form of a medium grained sand lens between lagoonal silt and clay, as observed in core DH-1-'74. As is usually the case, barrier sands submerged by lagoon waters grade laterally into lagoonal sediments in the westward direction.

Figure 60 is a detailed and typical cross section of the transgressive Atlantic coastal baymouth barrier across a part of it where tidal deltas existed previously. At that time the tidal inlet was located in the southern part of Rehoboth Bay, north of the present position of the Indian River Inlet. As a result of this, barrier sands and gravels were moved further into Rehoboth Bay than was the case towards the north of this area. These former tidal deltas which are fan-shaped as a result of tidal current action are now covered over by marshes. Radiocarbon dates obtained at different depths in the cores through the barrier are shown in the cross section (Figure 60). At the base of the section an erosional unconformity can be observed; Holocene sediments are truncated and lie against the Pleistocene surface, and the normally present lagoonal sequence is missing. This is the result of deep erosion by strong tidal currents in the inlet as it

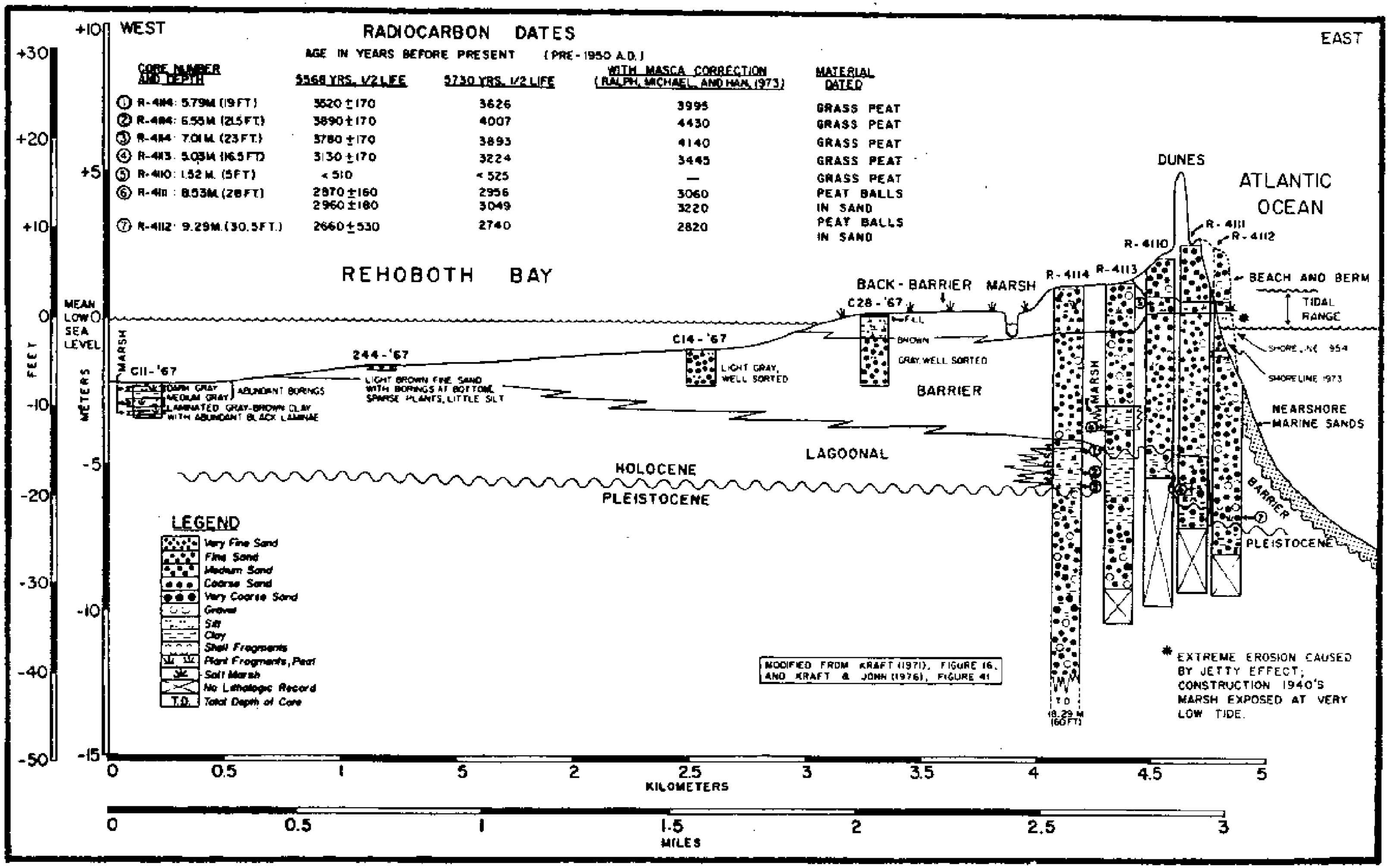


FIGURE 60. Geologic cross section. See Figure 15 for the line of cross section.

migrated back and forth in this area. A radiocarbon date of 525 years obtained for the back-barrier marsh sequence in core R-4110 at a depth of 1.5 m (5 ft.) indicates the young age of the barrier section overlying it. Also, based on radiocarbon dates it can be stated that the present Holocene barrier sequence was developed in about the last 3,000 years. Records of other back-barrier marshes have been encountered in different cores through the barrier, as can be observed in the cross section (Figure 60). Here again, as previously noted, washovers have played a vital role in the landward migration of the barrier. Sands of the main barrier are medium to coarse grained with some gravel and shell detritus; there is a decrease in sand size westward into Rehoboth Bay. Shoreline erosion in this area took place at a rate of approximately 3 m (10 ft.) per year between the years 1954 and 1973 as determined from topographic maps made in these years. This has resulted in the erosion of the upper barrier vertical sequence seen in core R-4112. A layer of shallow marine sediments covers the lower barrier record, as is clearly illustrated in the cross section (Figure 60). This section also illustrates destruction of the barrier as coastal erosion and the landward and upward migration of the bay-mouth barrier continues through space and time.

Figures 61, 62, 63A and 63B, 64, and 65A and 65B, are photographs of cores R-4110, R-4111, R-4112, R-4113, and R-4114 respectively. These four borings in the barrier are seen in Figure 60. The internal sedimentary structures, grain-size differences, and color variations in the sediment can be observed in these photographs.

Figure 66 is a summary of the characteristics of core R-4110. The uniform and somewhat straight nature of the SP curve indicates uniformity of depositional conditions and a more or less homogeneous internal structure. Grain-size parameters indicate that barrier sediments in core R-4110 are medium grained, moderately well sorted, and negatively skewed. Sedimentary structures observed in core R-4110 include convex and concave laminations, and planar cross-laminations.

The detailed lithology, sedimentary structures, grain-size parameters, electric log curves, and sedimentary environments of core R-4111 are shown in Figure 67. The electric log curve pattern does not show any distinctive shape although a slight funnel effect may be envisaged. Here again, the sands of the barrier are on the average medium grained, moderately well sorted to moderately sorted, and negatively skewed. Trask sorting coefficient values put all the sediments in the well sorted class. Horizontal laminations, concave laminations, high-

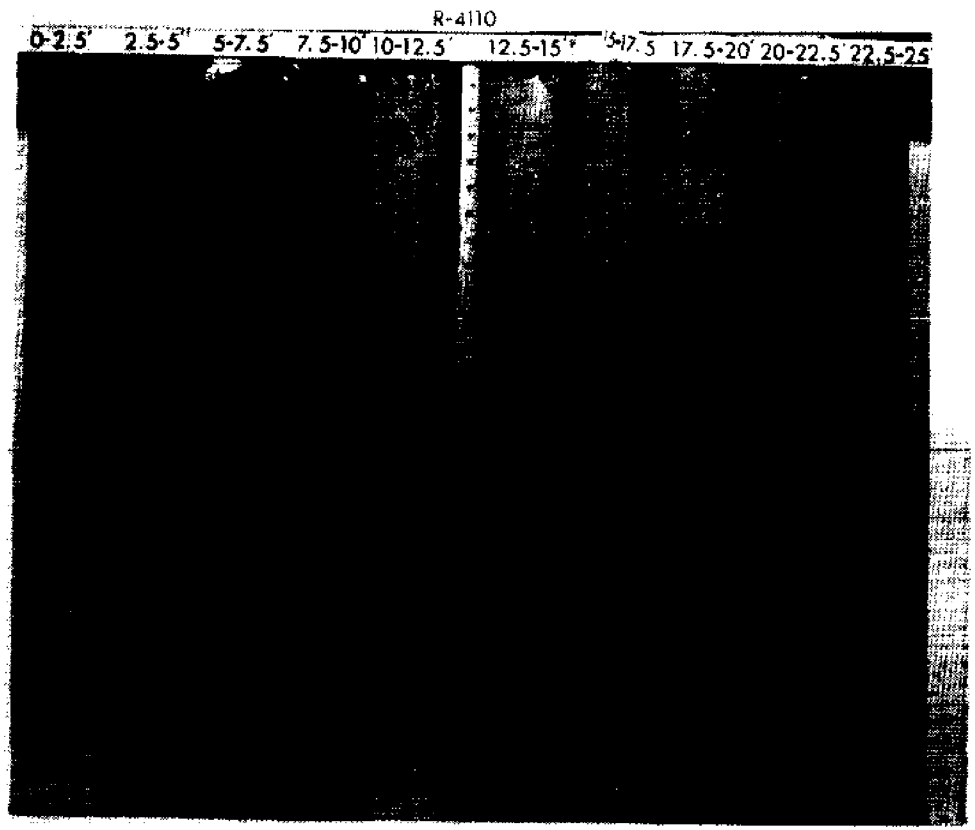


FIGURE 61. Photograph of core R-4110 (0-25 ft.; 0-7.6 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

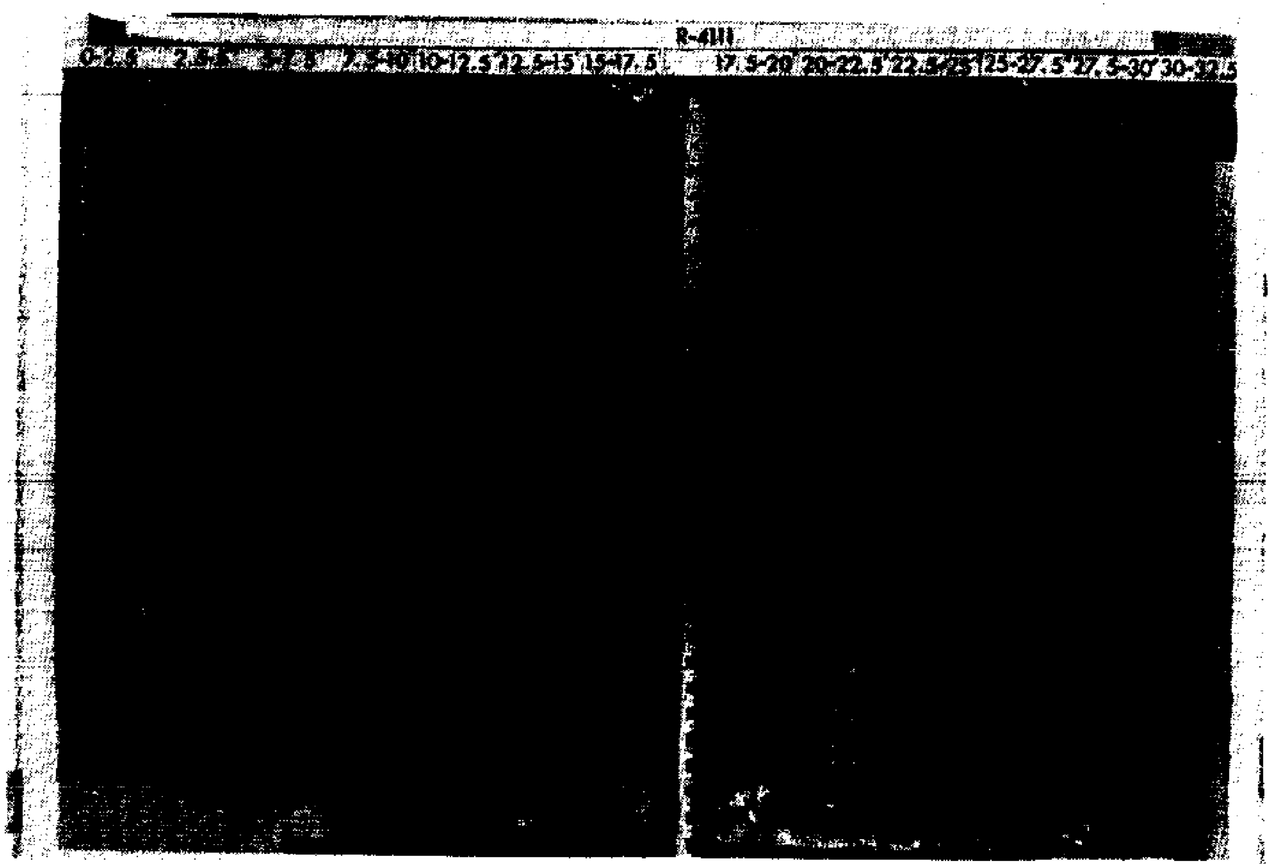


FIGURE 62. Photograph of core R-4111.(0-32.5 ft.; 0-9.9 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

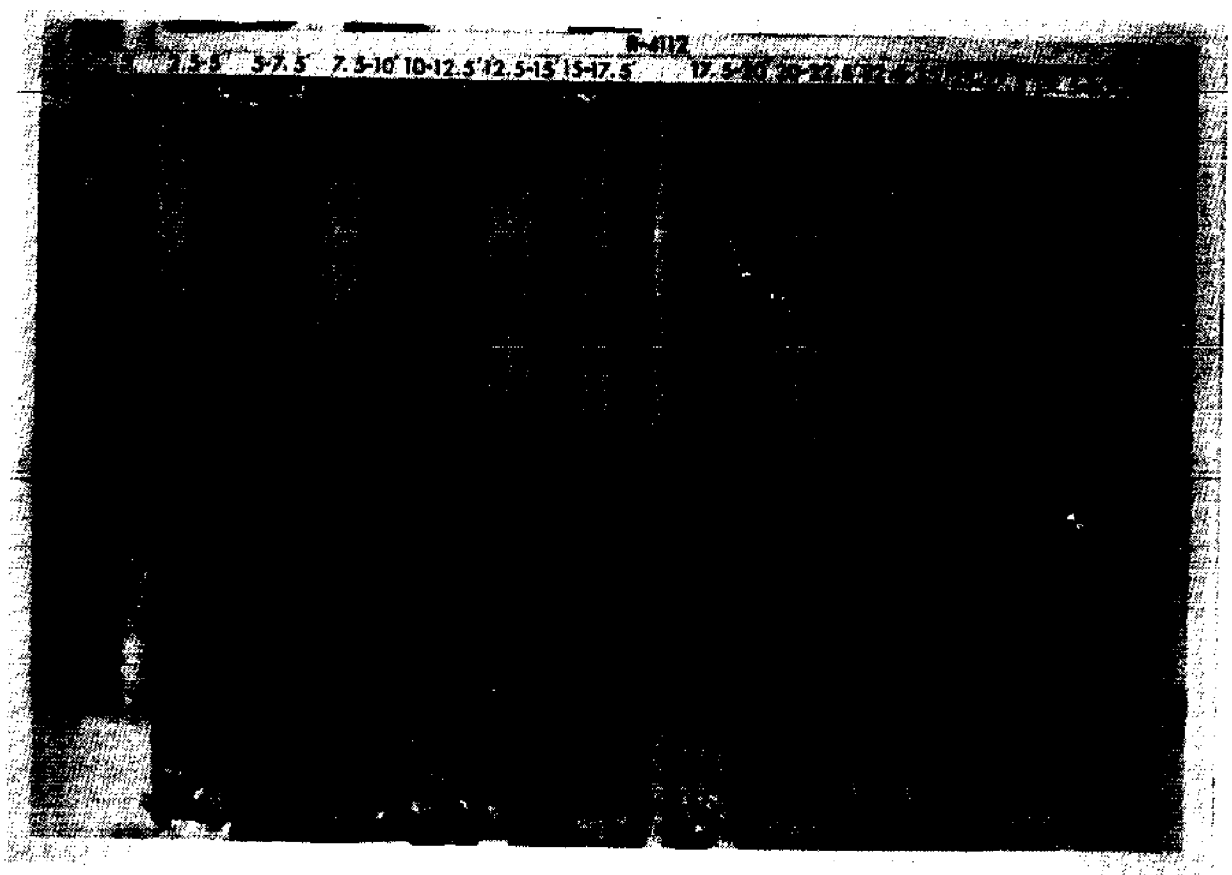


FIGURE 63A. Photograph of core R-4112 (0-32.5 ft.; 0-9.9 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

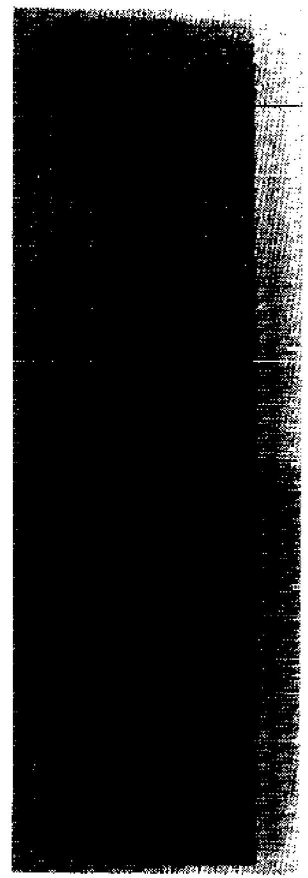


FIGURE 63B. Photograph of core R-4112 (32.5-37 ft.; 9.9-11.3 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

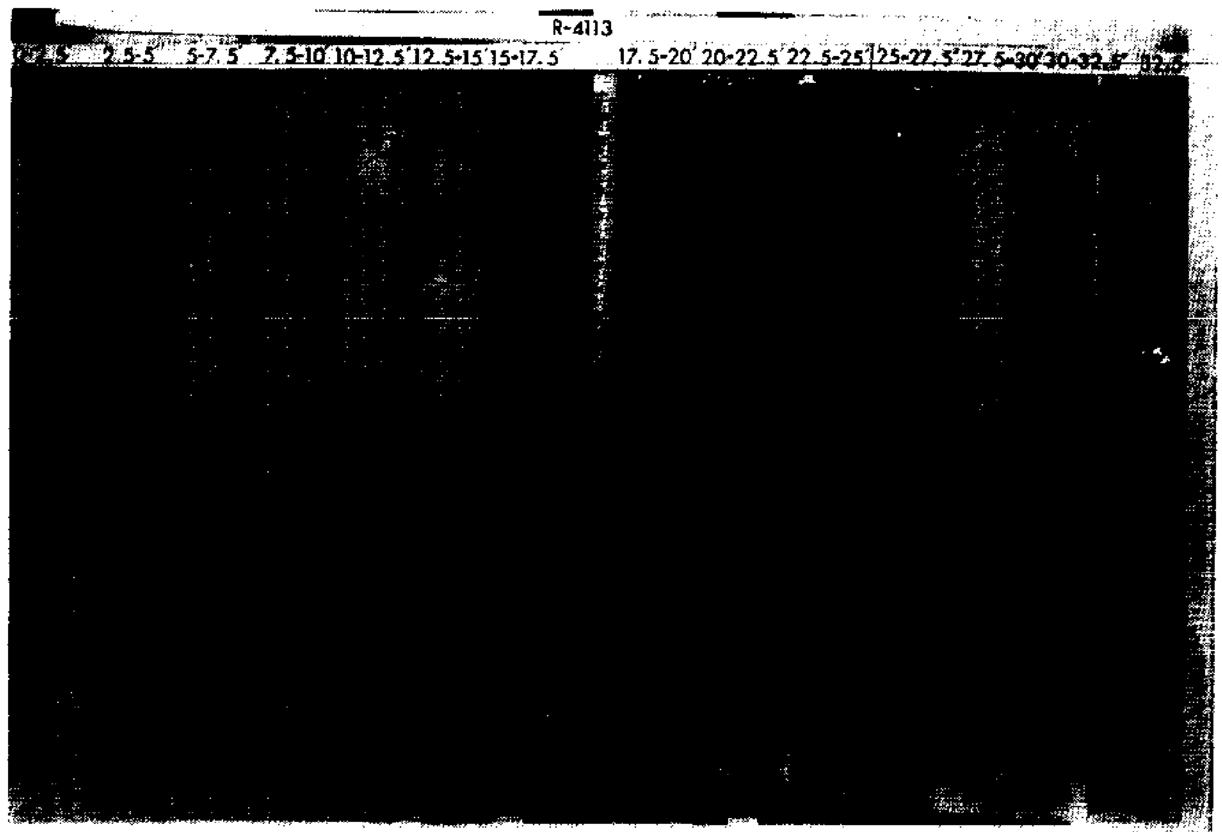


FIGURE 64. Photograph of core R-4113 (0-32.5 ft.; 0-9.9 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

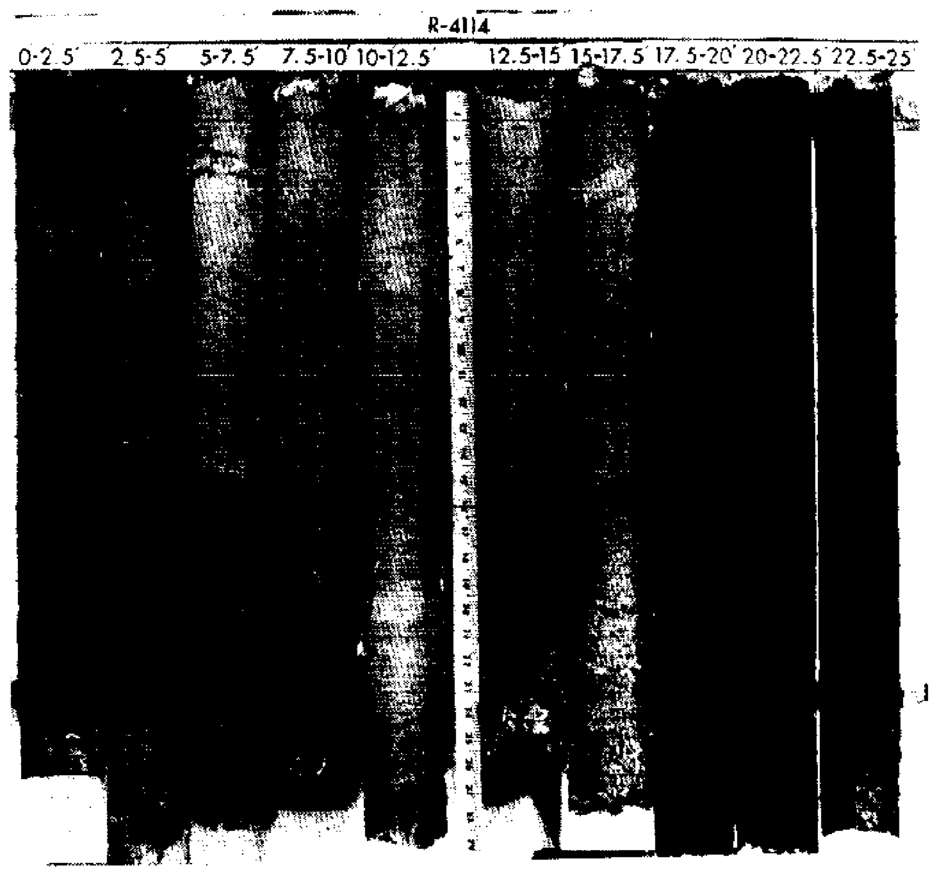


FIGURE 65A. Photograph of core R-4114 (0-25 ft.; 0-7.6 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

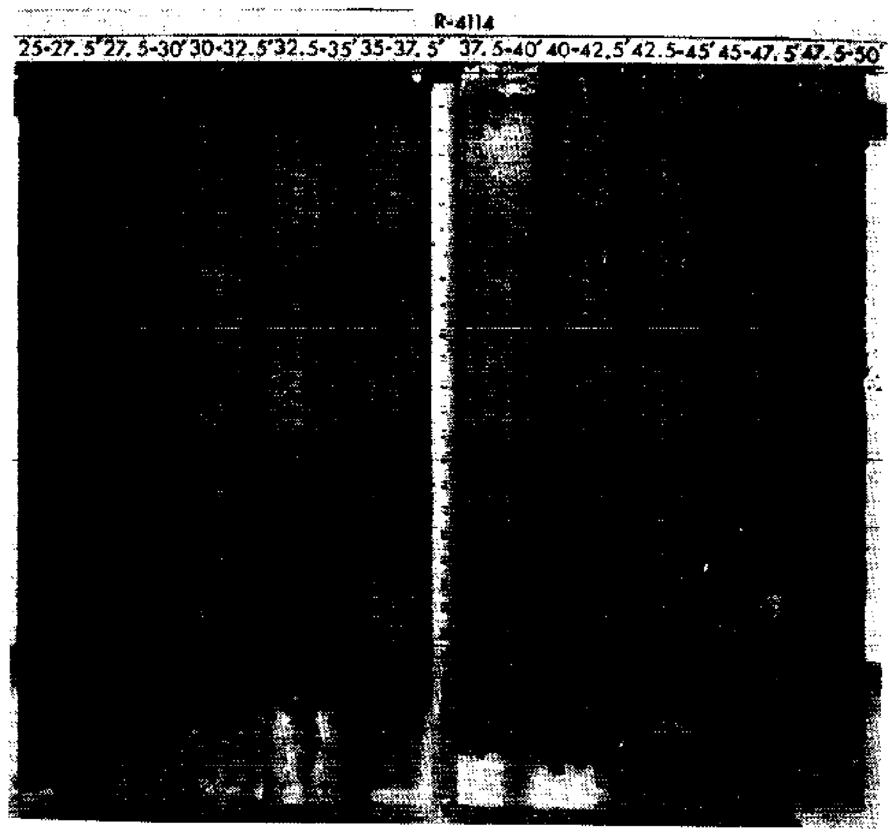


FIGURE 65B. Photograph of core R-4114 (25-50 ft.; 7.6-15.2 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

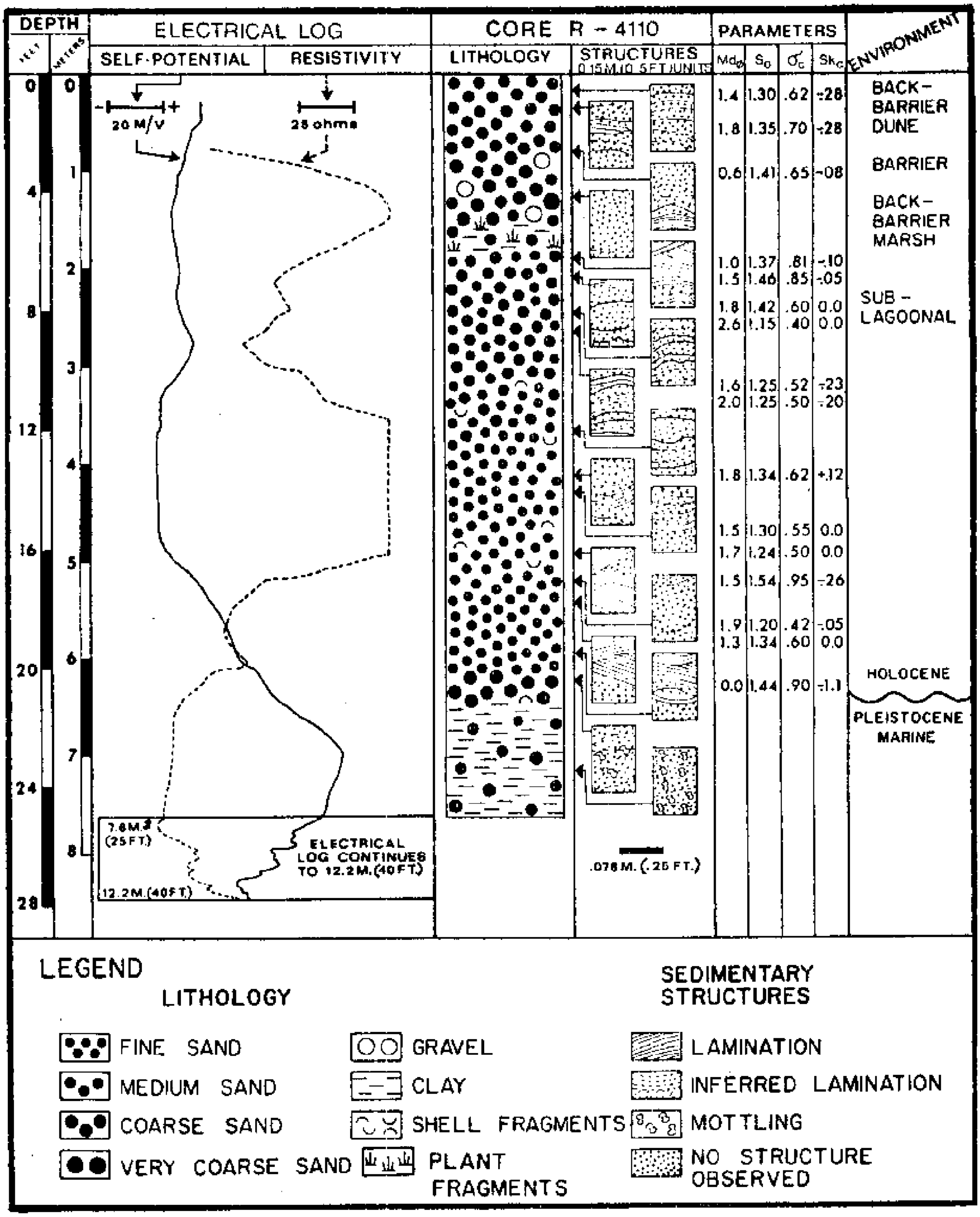


FIGURE 66. Geophysical, sedimentological, and sedimentary structure data for core R-4110.

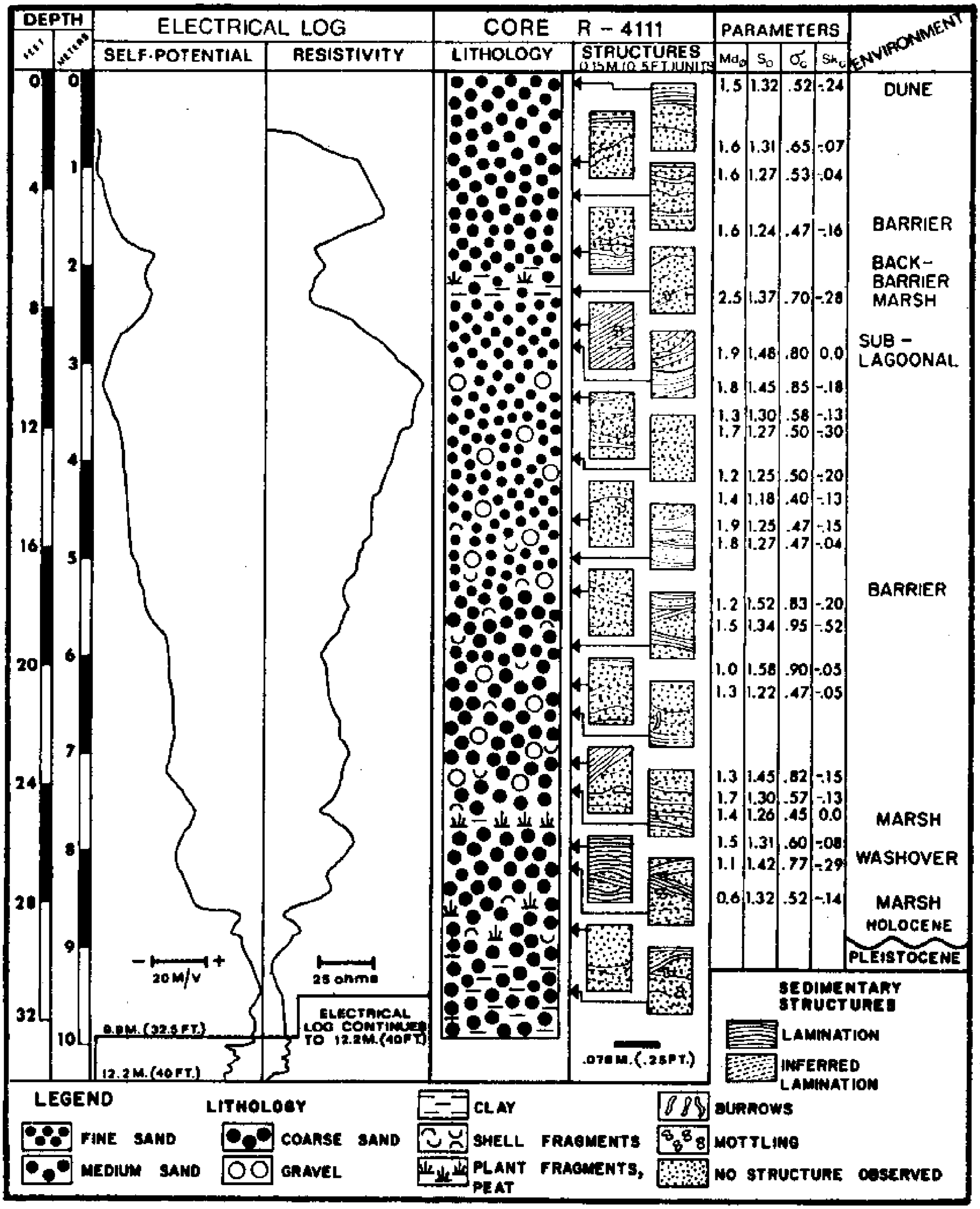


Figure 67. Geophysical, sedimentological, and sedimentary structure data for core R-4111.

angle laminations, and planar cross-laminations are observed in core R-4111. High-angle laminations are probably indicative of washover deposition. Grain-size parameters were not found to be distinctive for separating barrier sub-environments by plotting a combination of any two different parameters.

Figure 68 shows a summary of the different characteristics of core R-4112. Here again, the electric log curves are not characteristic of either transgression or regression, but the general straightness of a part of the SP curve indicates more or less uniform conditions of deposition and internal homogeneity of the sediments in that section of the core. Based on grain size-parameters, it can be stated that barrier sands in core R-4112 are on the average medium grained, moderately well sorted to moderately sorted, and negatively skewed. Positive skewness is indicated in parts of the core sequence where the barrier sands are mixed with washover sands and silts of the back-barrier area. As observed in Figure 68, high-angle laminations appear to be characteristically associated with washover deposits. Some burrows are observed in areas where marsh muds and barrier sands are intermixed. Other sedimentary structures seen in core R-4112 include concave and convex laminations, horizontal laminations, and planar cross-laminations.

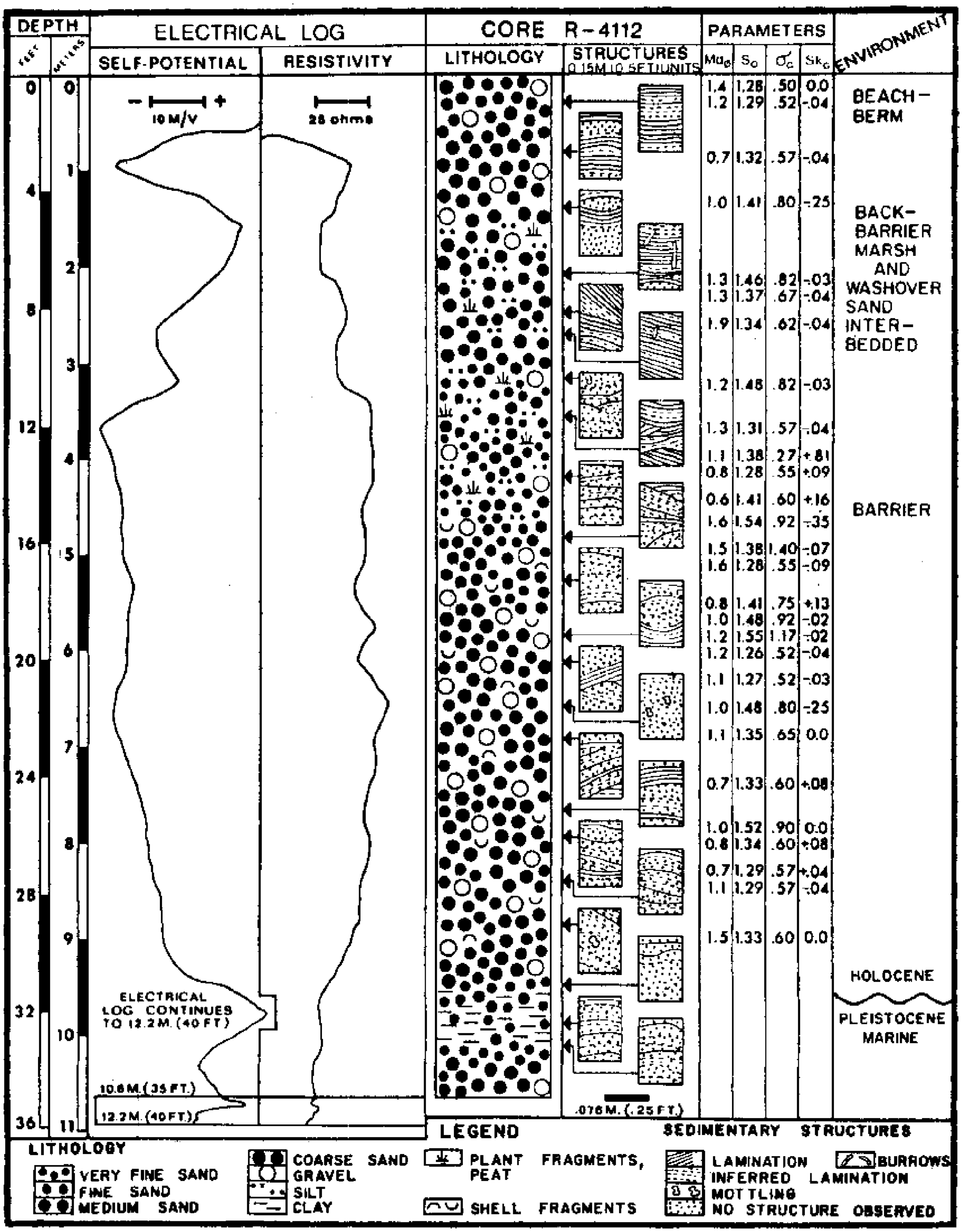


FIGURE 68. Geophysical, sedimentological, and sedimentary structure data for core R-4112.

The sedimentary characteristics of core R-4113 are summarized in detail in Figure 69. As before, the electric log patterns do not show any characteristic shapes but the changes in sediment composition are strikingly reflected. Washover deposits are well defined in the detailed lithology for core R-4113. Barrier sands are generally medium grained, moderately well sorted, and negatively skewed. Sedimentary structures seen in core R-4113 are convex and concave laminations, high-angle laminations, planar cross-laminations, and burrows.

The detailed characteristics of core R-4114 are shown in Figure 70. The general features seen here are similar to those observed in the other three cores described in the preceding paragraphs. The area represented by the cross sections shown in Figures 58, 59, and 60, can be observed in the aerial photograph shown in Figure 71. In this picture, the abandoned old tidal channels and the marsh-covered fan-shaped areas of former tidal deltas can be observed. The channels across the marshy areas are slowly being filled with silt. The main road passing through this section of the coast is situated in the middle of the barrier.

Figure 72 is a geologic cross section which goes across the channel-like area connecting Rehoboth Bay and Indian River Bay. The line of section extends from the

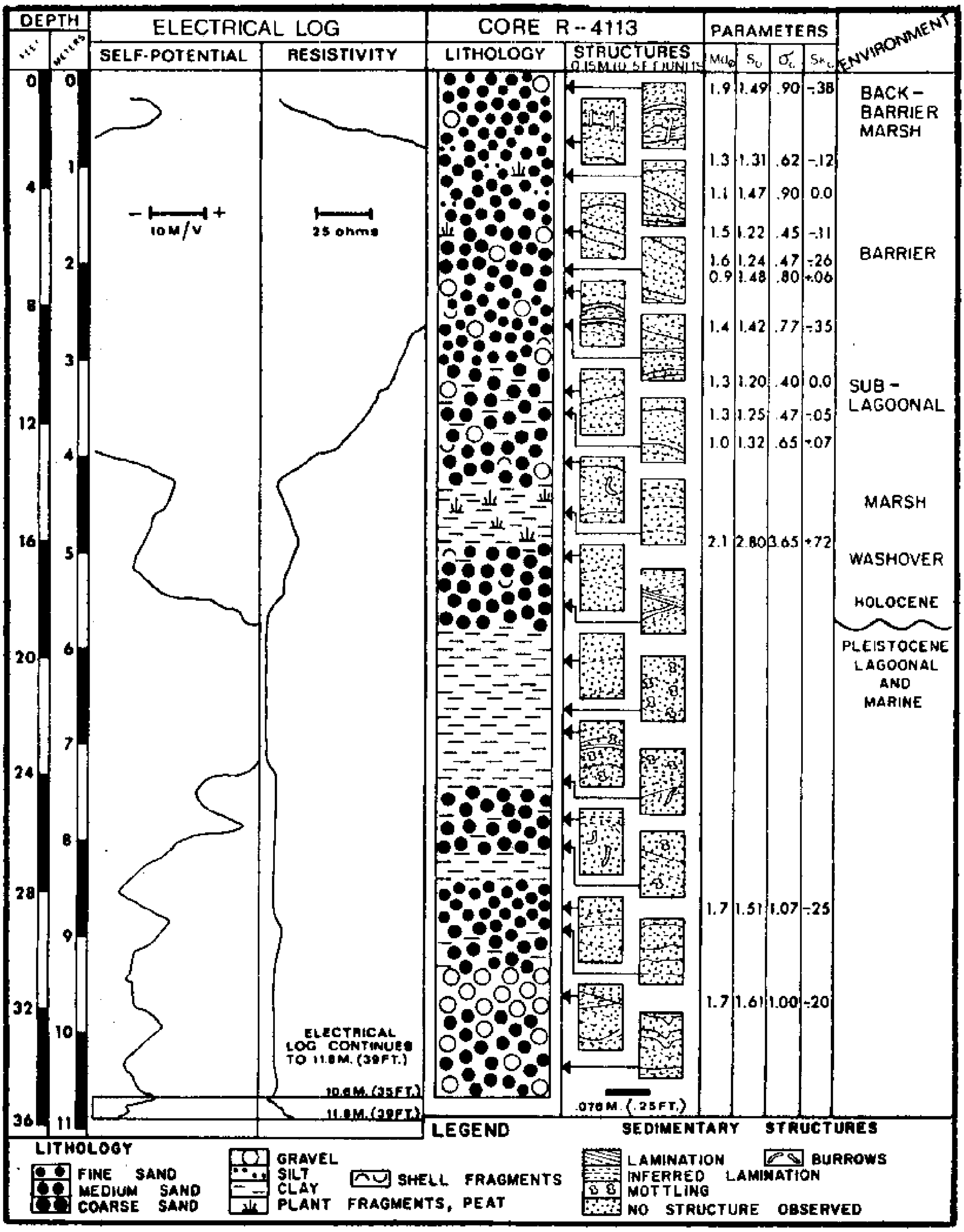


FIGURE 69. Geophysical, sedimentological, and sedimentary structure data for core R-4113.

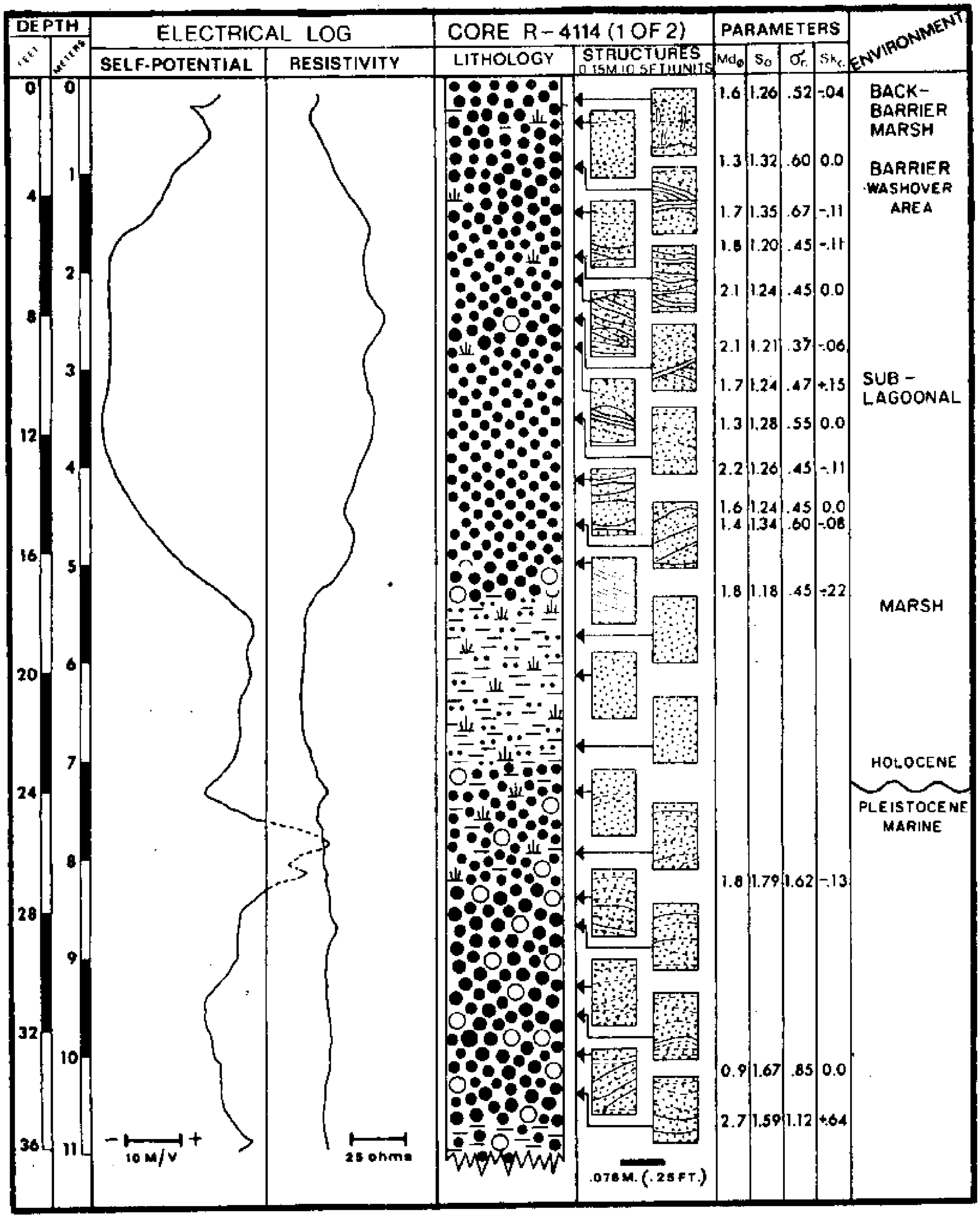


FIGURE 70. Geophysical, sedimentological, and sedimentary structure data for core R-4114. (cont.)→

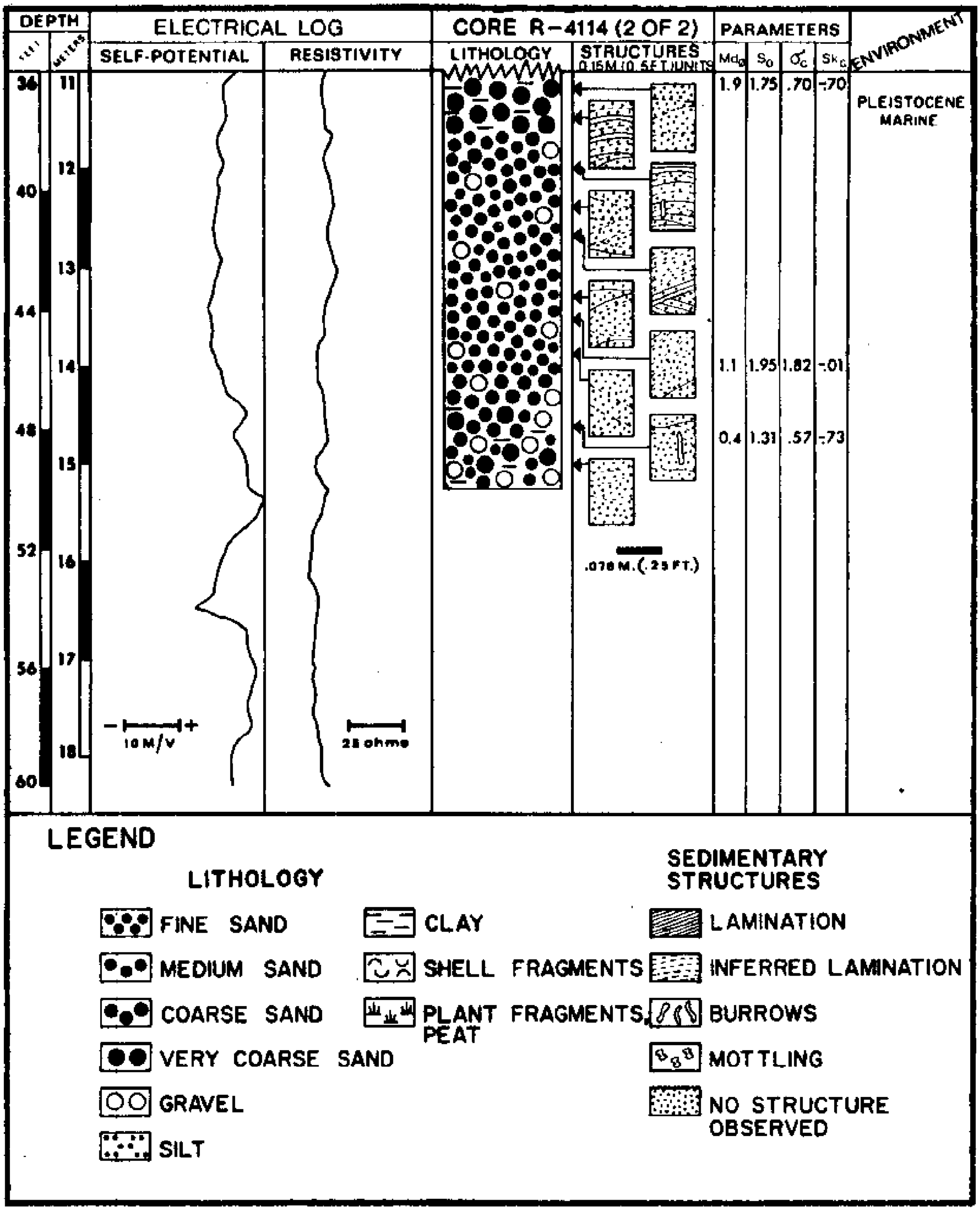


FIGURE 70 (cont.). Geophysical, sedimentological, and sedimentary structure data for core R-4114.

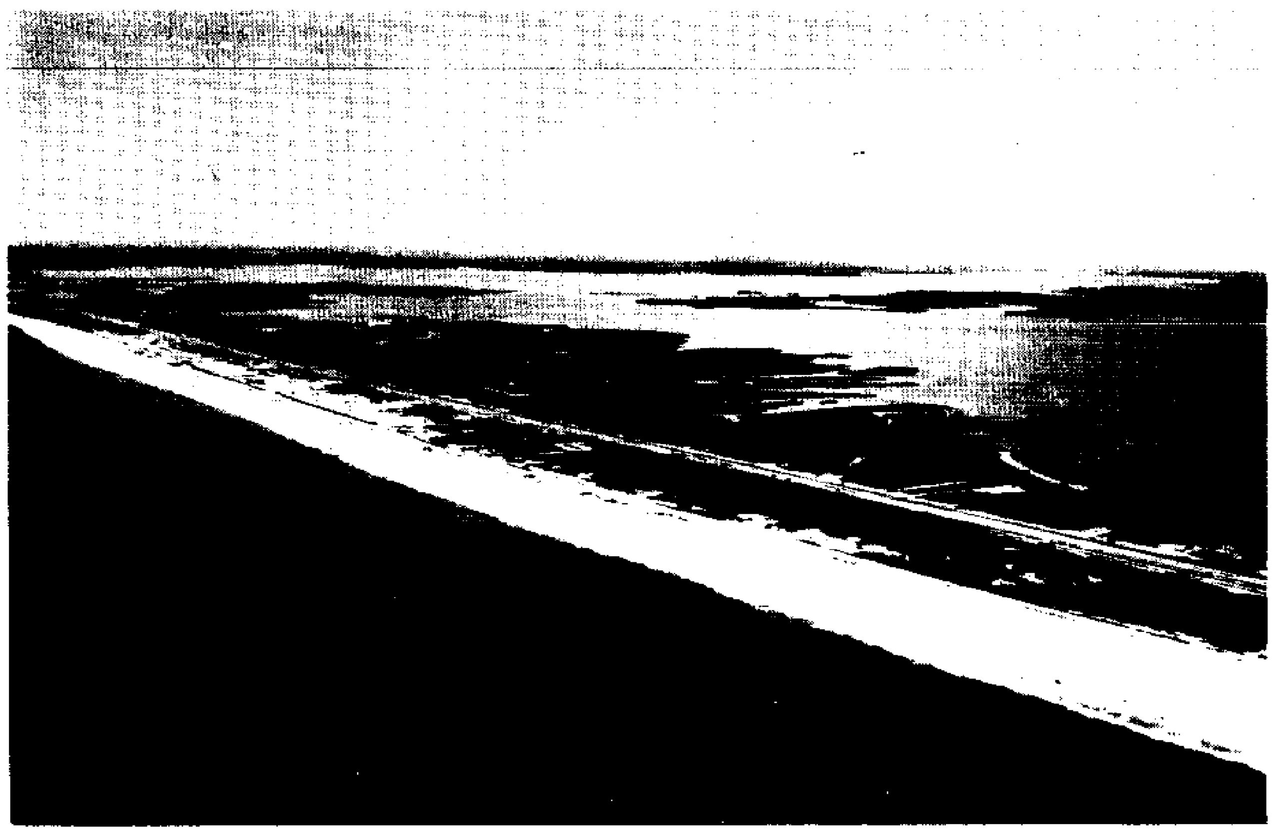


FIGURE 71. Aerial photograph of the baymouth barrier looking southwards. The Atlantic Ocean is seen in the foreground, and Rehoboth Bay in the background. Between the bay and the barrier is the old tidal delta-inlet complex presently covered with back-barrier marsh. (Courtesy of Dr. J. C. Kraft)

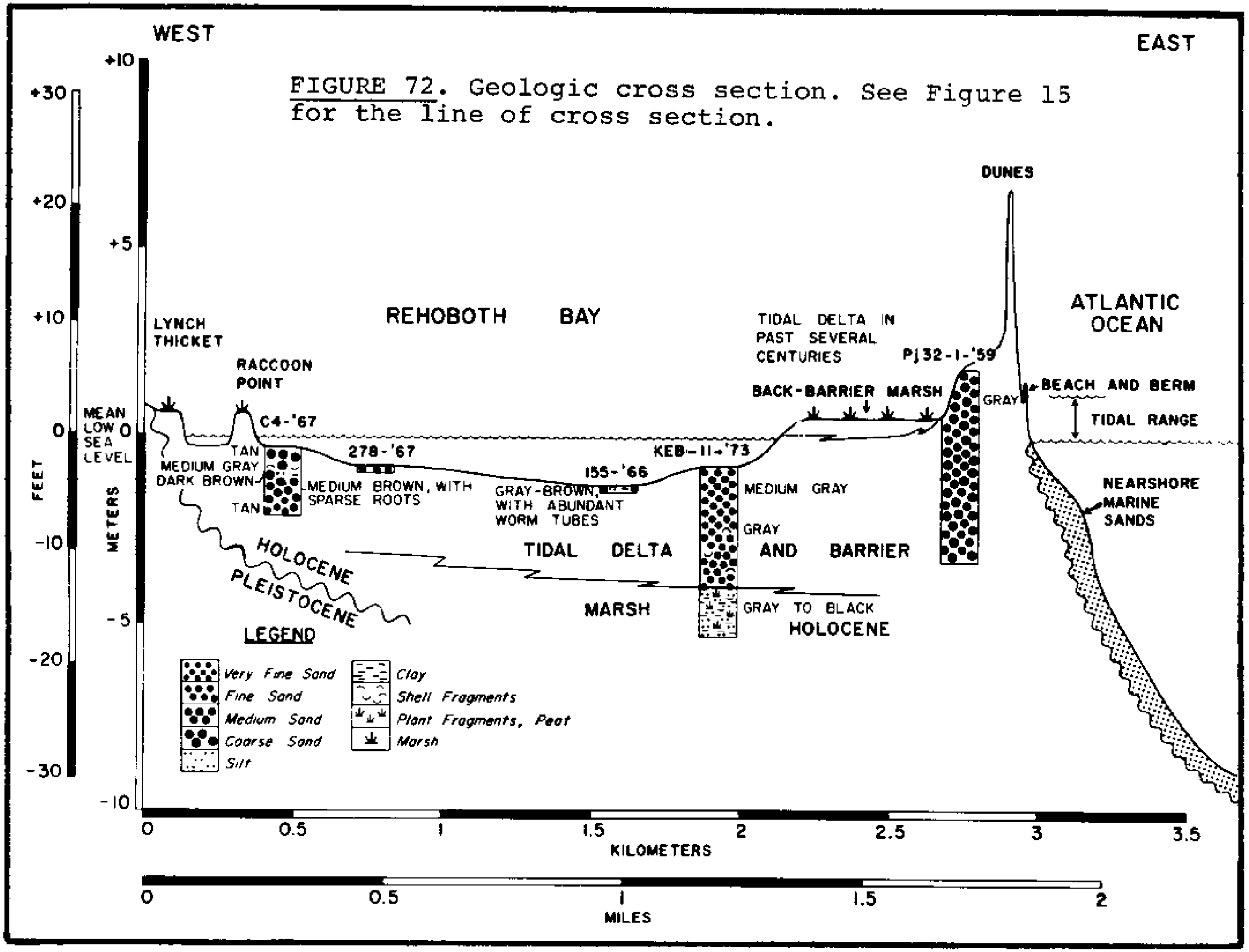


FIGURE 72. Geologic cross section. See Figure 15 for the line of cross section.

Pleistocene highlands at Lynch Thicket, across a small semi-enclosed part of Rehoboth Bay, a fringing marsh at Raccoon Point, Rehoboth Bay, a back-barrier marsh, the baymouth barrier with overlying dunes, and finally terminates in the nearshore Atlantic Ocean area. Sands underlying the main barrier are medium to coarse grained; they become fine to medium grained westward across the old tidal delta area. Tidal delta and barrier sands overlie a marsh sequence in core KEB-11-'73.

The line of cross section for Figure 73 extends from Indian River Bay to the Atlantic nearshore marine area. It passes through the two Pleistocene highlands at Burton Island and Bottom Hills, and goes across the old inlet area. Core TB-1-'74 is located at the edge of the present flood tidal delta of the Indian River Inlet and is also at the edge of the dredged inlet channel. Hence, only medium grained tidal-delta sands are observed in this core. The core did not penetrate deep enough to determine the type of sediments which underlie the tidal delta sequence. The old natural inlet was located in the close vicinity of core KEB-9-'73. Hence the medium grained sands of this core are representative of the barrier as well as the old inlet, provided of course that this area has not suffered from man's interference.

Tidal inlets are known to migrate naturally in the

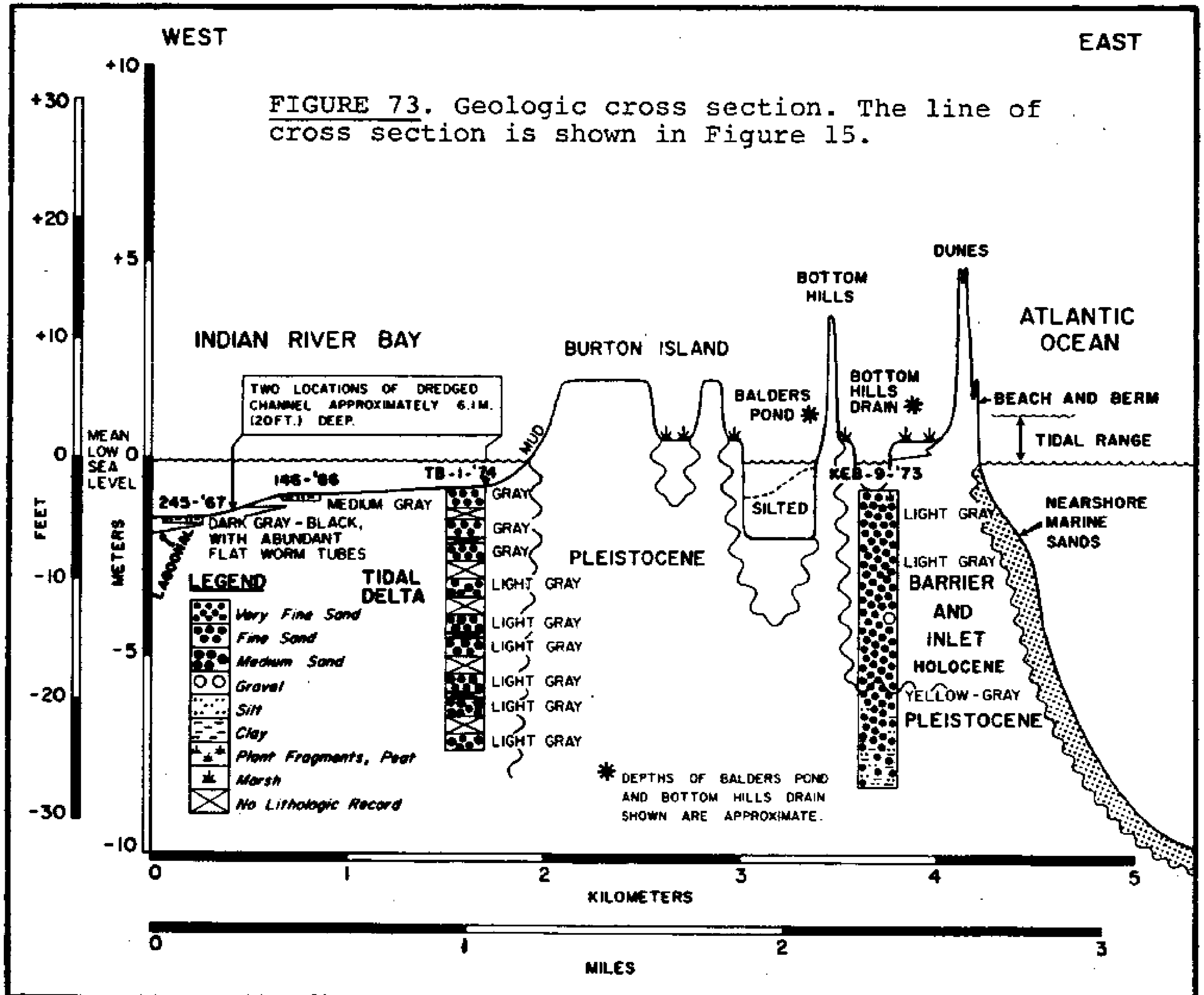


FIGURE 73. Geologic cross section. The line of cross section is shown in Figure 15.

downdrift direction in the absence of any obstructions, like jetties, to impede their movement. This is exactly what the Indian River Inlet did before it was stabilized at its present position by jetties. The deposition of sand by littoral transport on the updrift side of an inlet is accompanied by erosion on the downdrift side, which results in the lateral migration of the inlet. When the inlet migrates along the coast over a prolonged period of time, it reworks much of the barrier sediments in its path. The importance of inlet sedimentation lies in the fact that sediment deposition takes place at depths where reworking by waves is unlikely, thus increasing its potential for preservation in the geological record. Hubbard and Barwis (1976) presented models for a transgressive as well as a regressive inlet sequence. Their model of the transgressive sequence was based on the assumption of the existence of a ravinement surface. The inlet sequence formed by the migration of Fire Island Inlet, Long Island, New York, was the subject of discussion by Kumar and Sanders (1970, 1972, 1974, 1975), and Kumar (1973). A large number of papers dealing with the various geologic as well as the engineering aspects of tidal inlets are available in the literature. Some of the more significant of the former include Price (1963a), Hoyt and Henry (1965, 1967), El-Ashry and Wanless (1965), Dolan and Glassen (1972), and Pierce (1970). Barwis (1976) presented an annotated bibliography on the subject.

Figure 74 shows a detailed and typical cross section in the area of the Indian River Inlet. The line of cross section extending from the Indian River Bay goes across the dredged channel of the Indian River Inlet, the Pleistocene highland at Burton Island, the Indian River Yacht Basin channel, another Pleistocene highland area, across the dunes and barrier, and terminates in the near-shore marine area passing through the ebb tidal delta of the Indian River Inlet. Core R-4115 passes through a deep channel cut through the barrier representing the ancestral Indian River channel at the time it flowed further seaward as a major tributary of the ancestral Delaware River. The total thickness of the Holocene stratigraphic sequence in core R-4115 is 30 m (98.4 ft.), including a 12.5-m (41 ft.) thick section of barrier sands. Medium to coarse sands of the barrier overlie lagoonal silt and clay containing oysters (Crassostrea virginica), Elphidium sp., and other lagoonal fauna. Below the lagoonal sediments is a sequence of marsh muds with abundant plant debris, which unconformably overlies medium to very coarse grained Pleistocene sands. Thus here we have a situation in which a deep river channel was steadily infilled with sediment with the gradual rise in relative sea level since 11,000

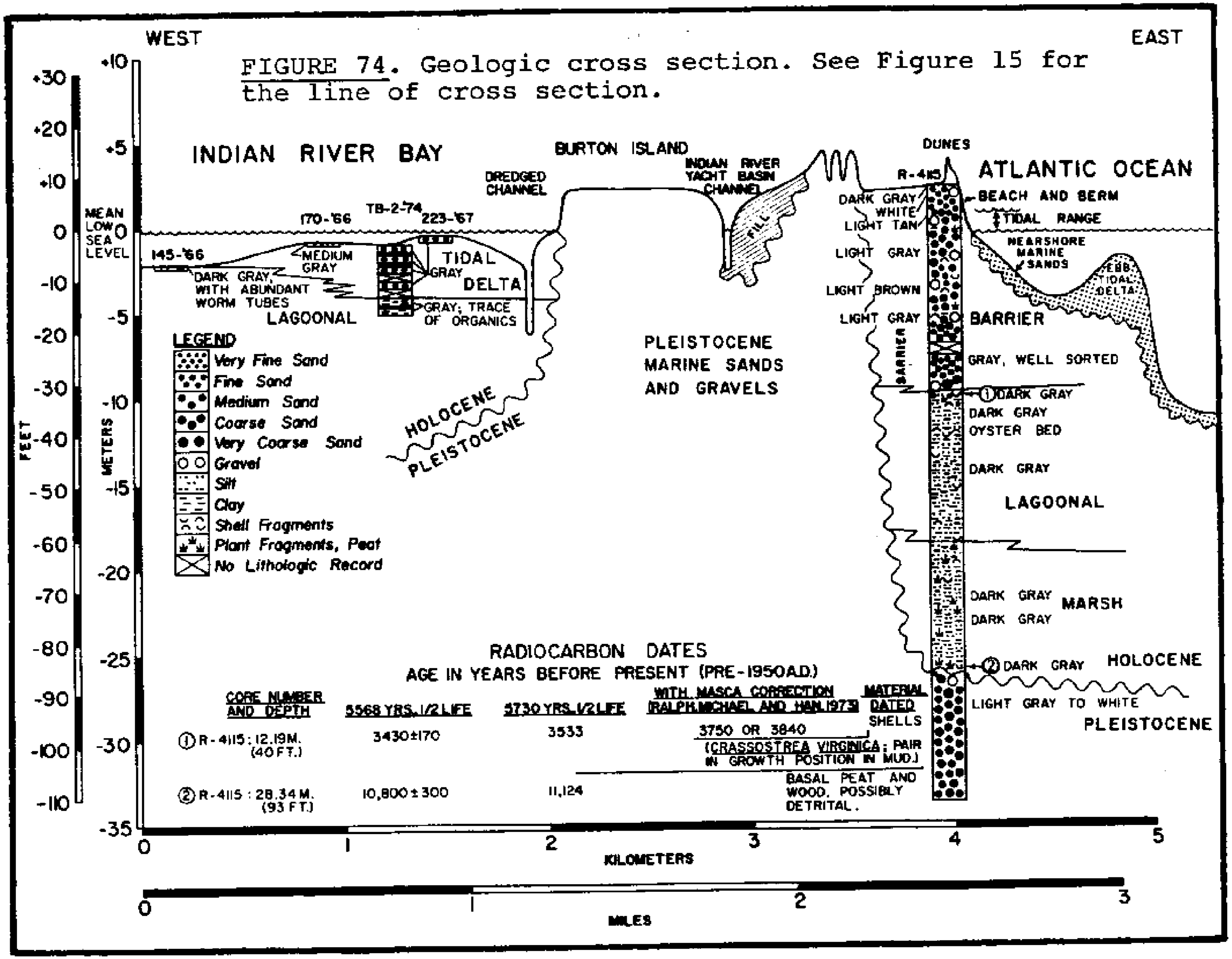
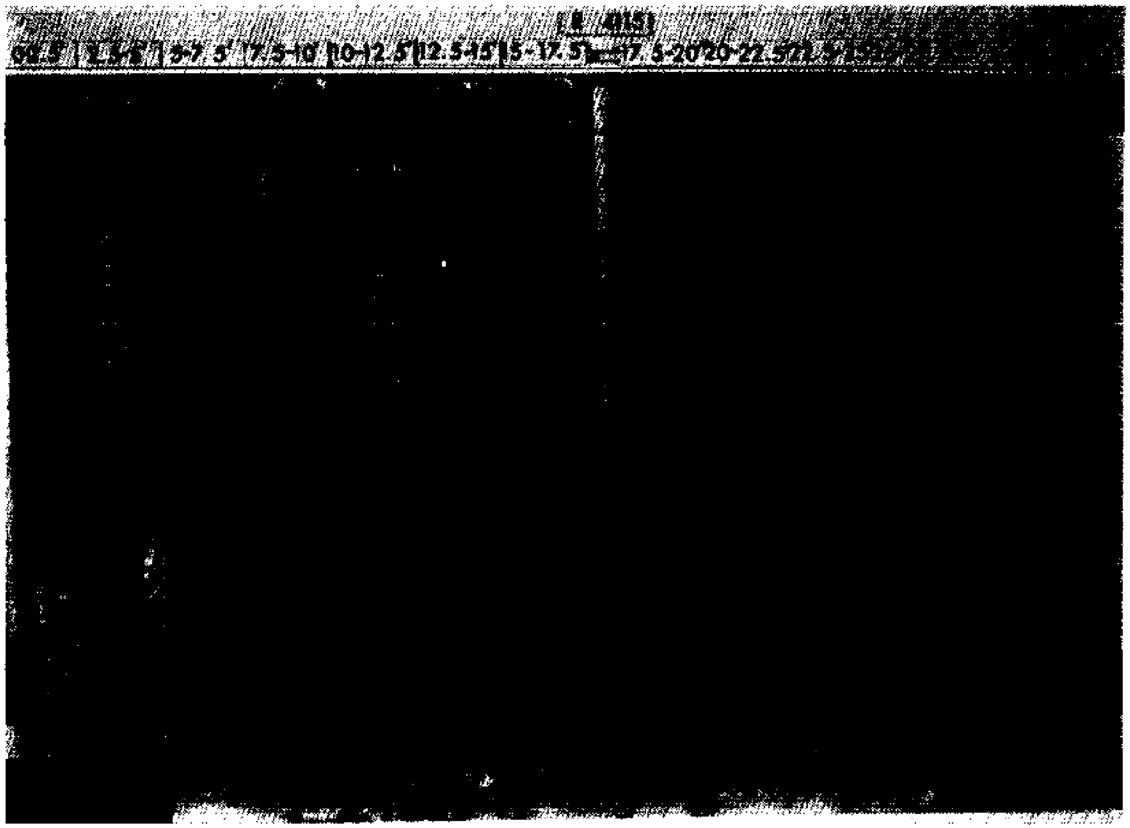


FIGURE 74. Geologic cross section. See Figure 15 for the line of cross section.

years before present, as indicated by the radiocarbon date from a basal peat at the base of the Holocene sedimentary sequence in core R-4115. Also, the radiocarbon shell date of 3,840 years before present obtained at the bottom of the barrier sand sequence shows that the barrier was developed within this time. Medium grained sands of the flood tidal delta associated with the Indian River Inlet overlie lagoonal sediments in core TB-2-'74. As discussed in the preceding paragraph, the transgressive sequence in this area has a greater potential for preservation in the stratigraphic record under a cover of marine sediments, than those in other sections of this coastal barrier complex.

Figures 75A, 75B, and 75C are photographs of core R-4115 seen in the cross section shown in Figure 74. The sedimentary structures, grain-size changes, and color changes in the sediments from the barrier, lagoon, marsh, and Pleistocene environments can be clearly observed in these photographs. A pair of Crassostrea virginica shells in place is found in the lagoonal core sediments shown in Figure 75B; a basal peat lies against the Pleistocene surface (Figure 75C).

Detailed characteristics of core R-4115 are presented in Figure 76. Changes in sediment composition downwards along the core are clearly reflected in the electric log curve patterns. The abrupt decrease in



<u>FIGURE 75A</u>. Photograph of core R-4115 (0-35 ft.; 0-10.7 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

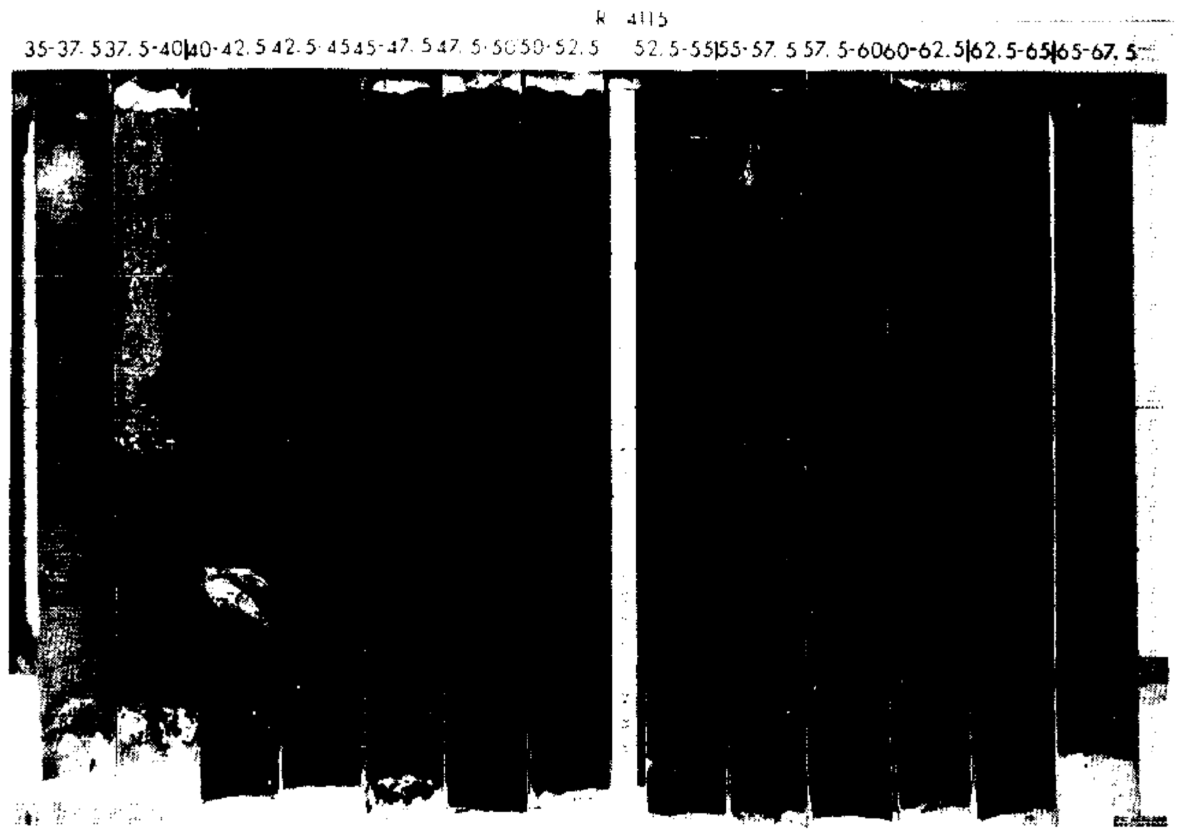


FIGURE 75B. Photograph of core R-4115 (35-67.5 ft.; 10.7-20.6 m). See Figure 15 for the core location (Courtesy of Shell Development Company)

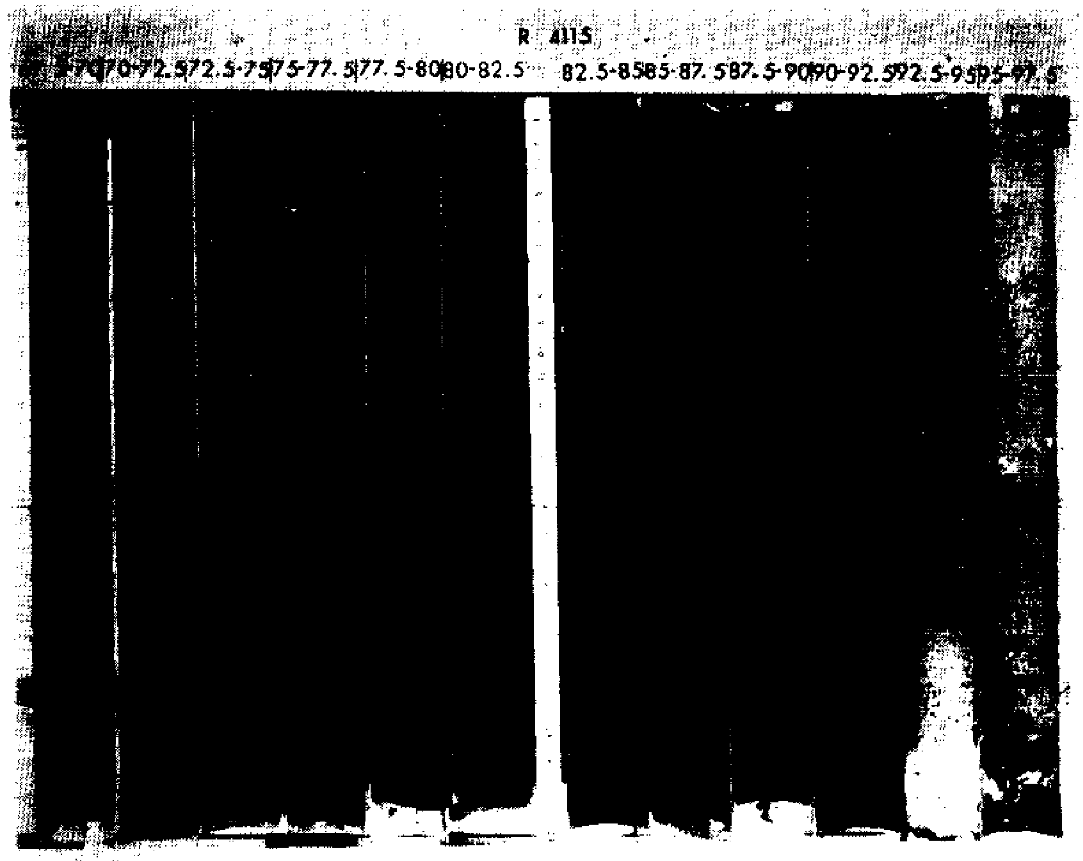


FIGURE 75C. Photograph of core R-4115 (67.5-97.5 ft.; 20.6-29.7 m). See Figure 15 for the core location. (Courtesy of Shell Development Company)

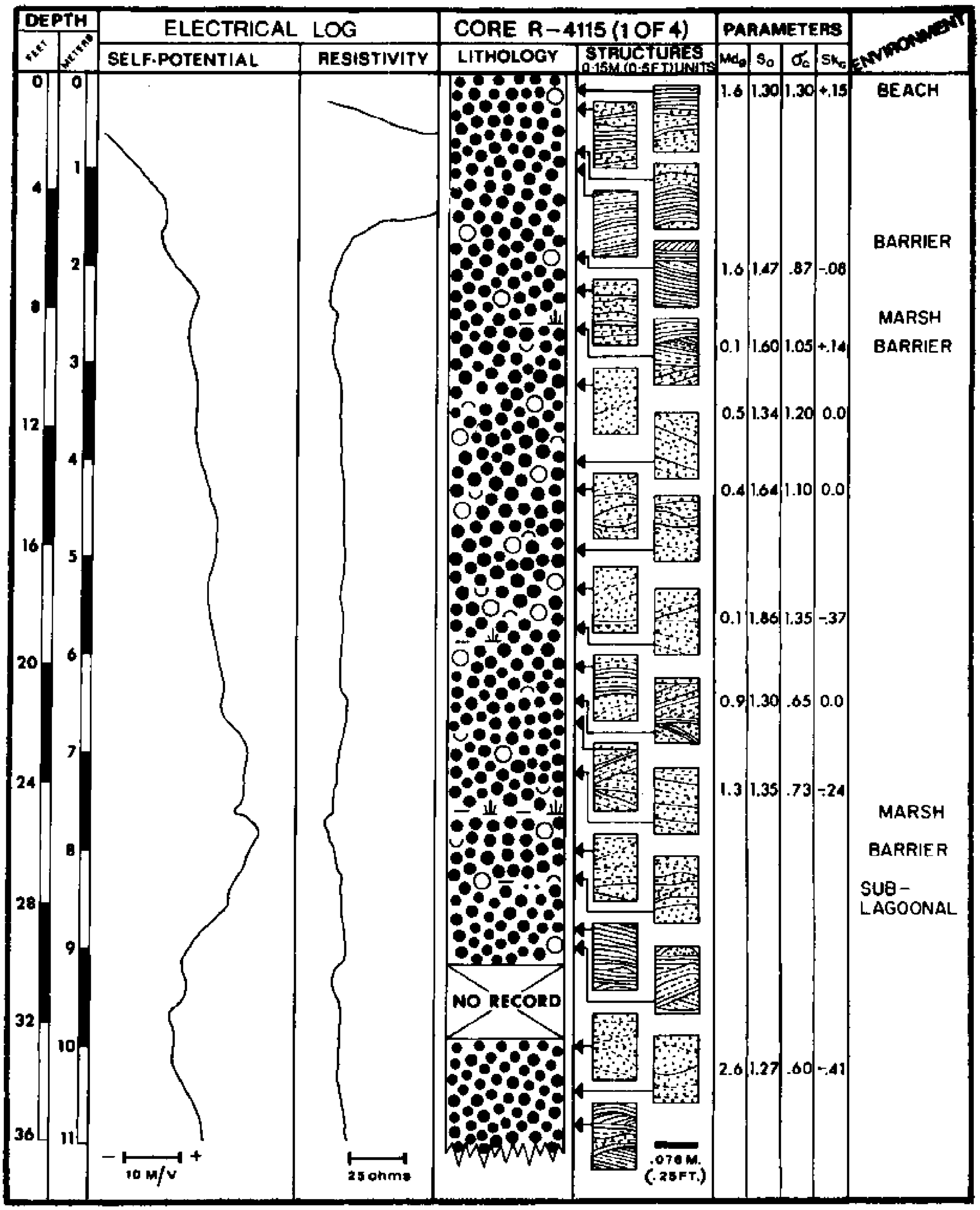


FIGURE 76. Geophysical, sedimentological, and sedimentary structure data for core R-4115. (cont.) →

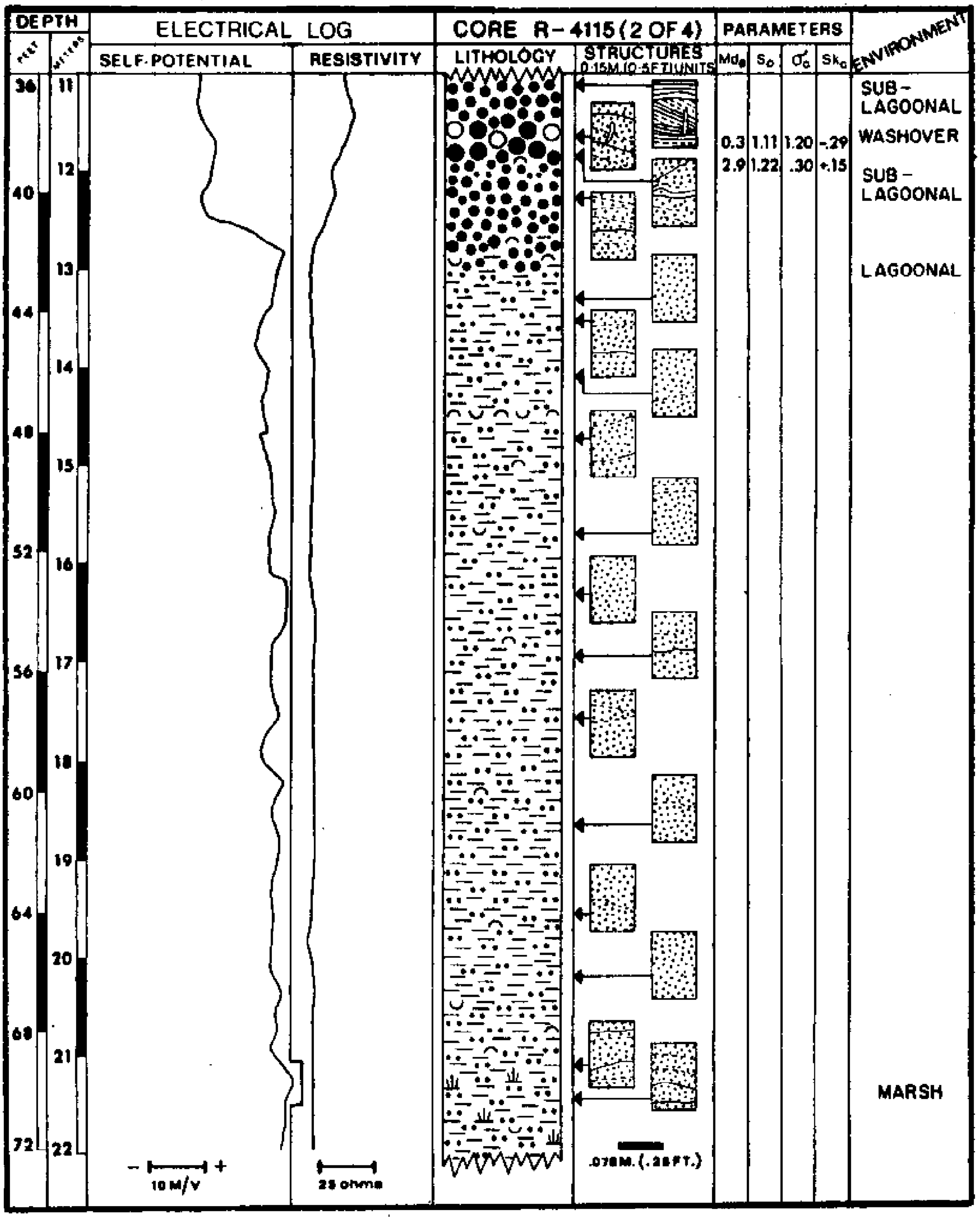


FIGURE 76 (cont.). Geophysical, sedimentological, and sedimentary structure data for core R-4115. (cont.)→

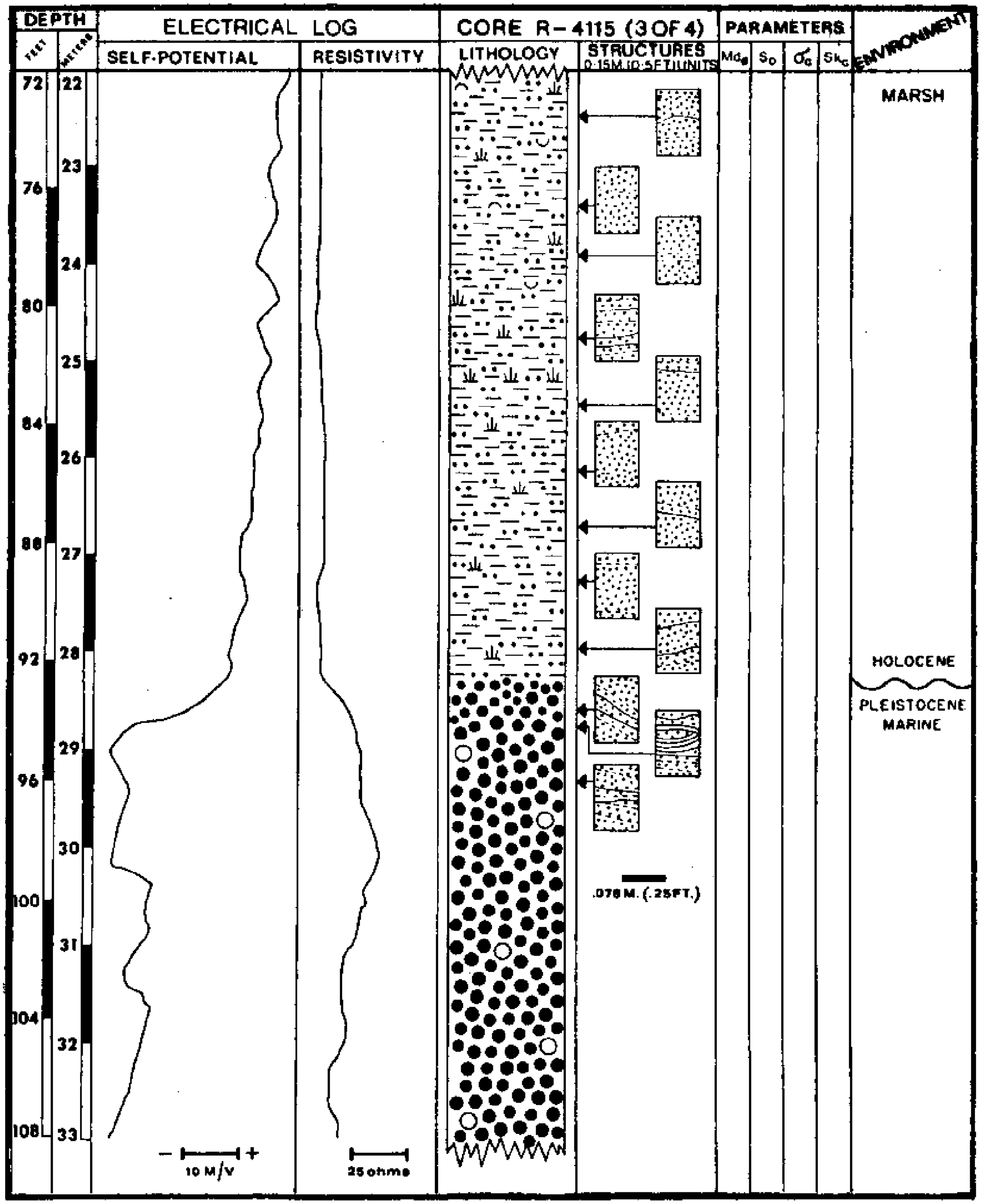


FIGURE 76 (cont.). Geophysical, sedimentological, and sedimentary structure data for core R-4115. (cont.)→

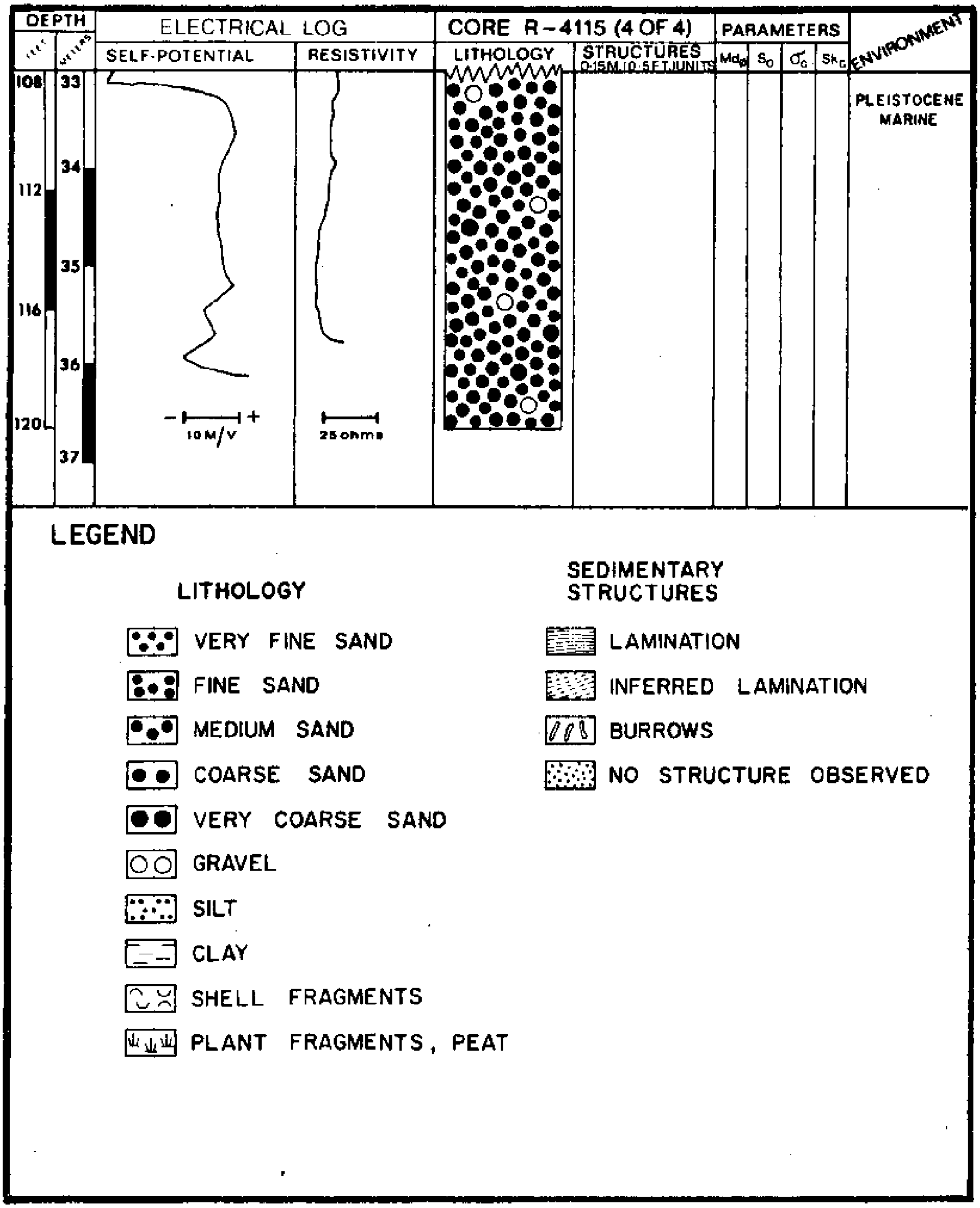


FIGURE 76 (cont.). Geophysical and sedimentological data for core R-4115.

amplitude of the SP curve pattern at the base of the Holocene section is indicative of a transgressive environment, as is also the more or less bell-shaped curve at this point. Grain-size parameters indicate that the mean grain size of barrier sands ranges from fine to coarse. This may be considered as a characteristic of channel sedimentation, as variations in channel configuration produces several energy levels within the channel resulting in the deposition of sediments of varying grain sizes. All Trask coefficients of sorting values are less than 2.5; therefore all sediments in core R-4115 come under the well sorted class. This parameter does not seem to be of much use in this case, or in any of the previous cases, because the verbal limits set for sorting categories are extremely high. Considering graphic standard deviation values, barrier sands are moderately to poorly sorted, and this is more true of the actual case, as can be judged from the detailed lithology presented. Most of the barrier sediments seen in core R-4115 are negatively skewed, but parts of the barrier sequence show positive skewness as well. A washover deposit is preserved a little above the contact of the barrier sands with the underlying lagoonal silt and clay. Sedimentary structures seen in core R-4115 include horizontal laminations, convex laminations, high-angle laminations, planar cross-laminations, and burrows near the interface with lagoonal sediments. Grain-size parameters are not sufficiently different to permit differentiation of sub-environments of the barrier-inlet sequence.

The general relationship of the Indian River Inlet to the baymouth barrier, the lagoon, and the back-barrier marsh can be observed in the aerial photograph shown in Figure 77. The line of cross section for Figure 74, and for the cross sections on the southern side of the Indian River Inlet to be discussed next, passes through the area seen in this aerial photograph (Figure 77). Severe erosion on the northern side of the inlet is caused by the building of the jetty, and constitutes a major hazard to the main highway.

Figure 78 is a geologic cross section of the baymouth barrier across the southern side of the Indian River Inlet. Unfortunately, the record of an old boring in this area made in connection with the construction of the bridge over the inlet could not be located for inclusion in this cross section. Tidal delta sands in the Indian River Bay are fine to medium grained, and overlie lagoonal silt and clay. The ebb tidal delta on the ocean side of the inlet is shown in this cross section.

The geologic cross section shown in Figure 79 is

FIGURE 77. Aerial photograph of Indian River Inlet showing the "jetty effect." Littoral transport is towards the front of the picture. This causes sand accretion on the southern side and erosion on the northern side of the inlet. (Courtesy of Dr. J. C. Kraft)

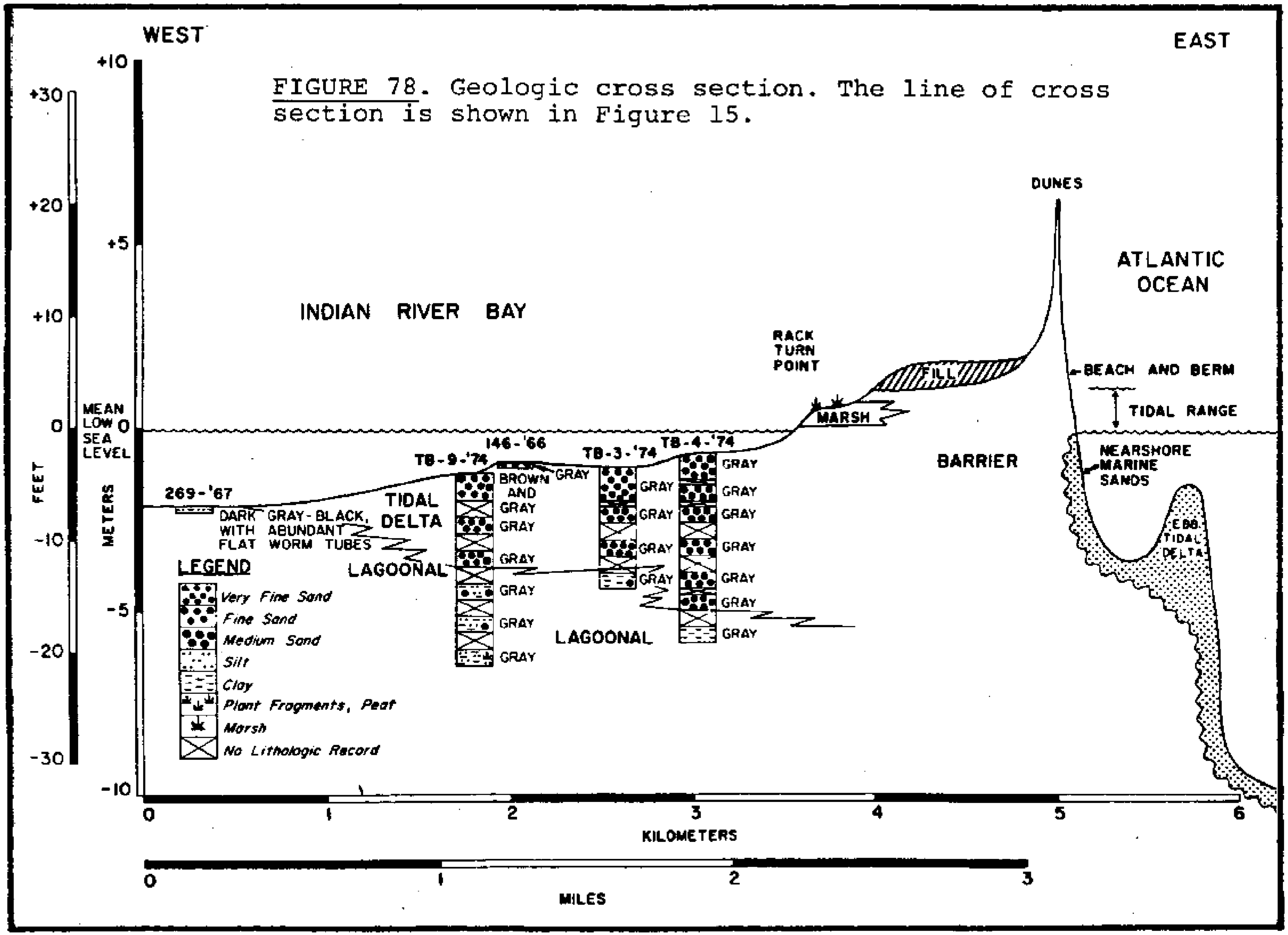
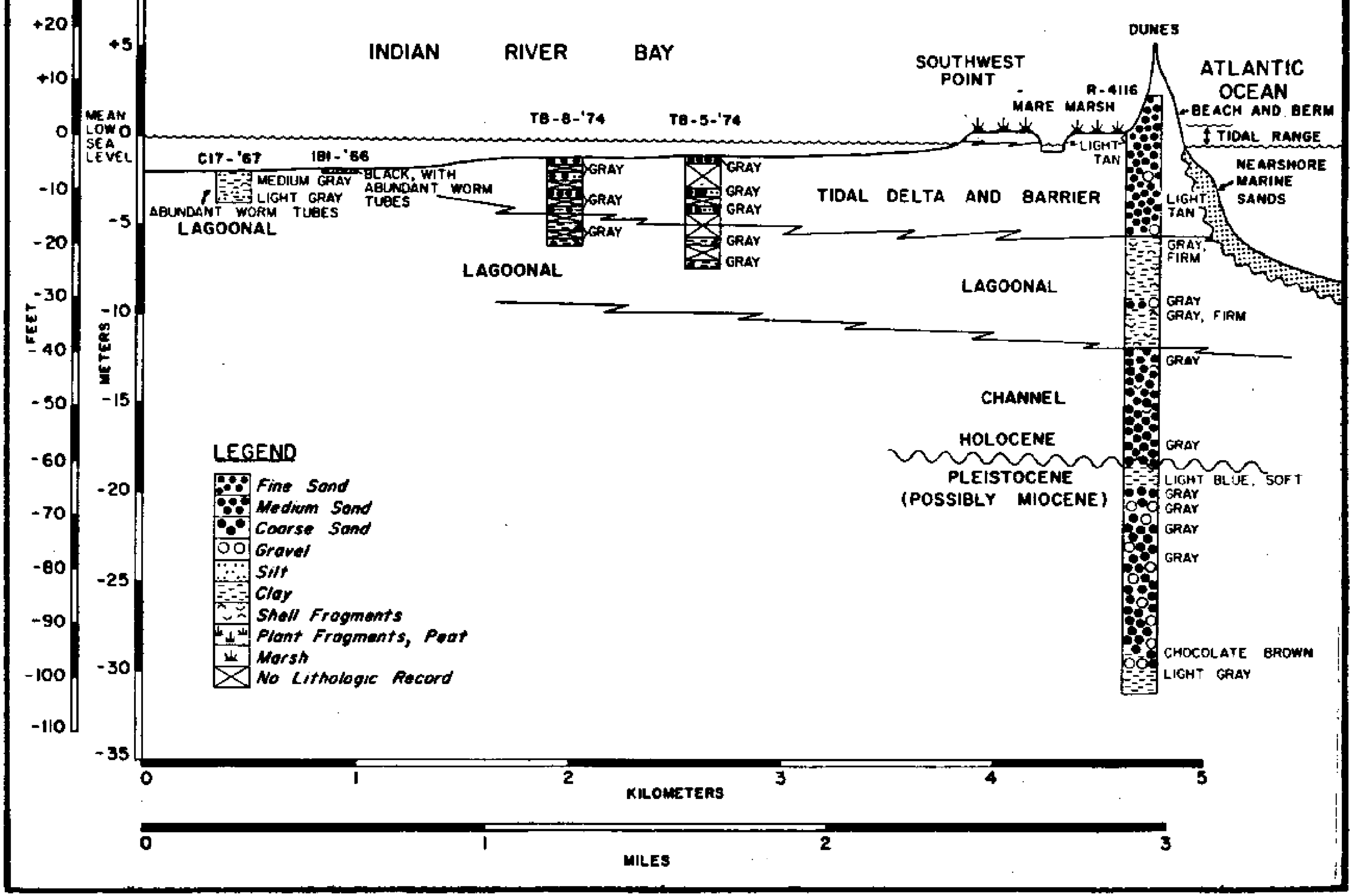


FIGURE 78. Geologic cross section. The line of cross section is shown in Figure 15.

FIGURE 79. Geologic cross section. See Figure 15 for the line of cross section.



somewhat similar to that shown in Figure 74 in that we are observing the infilling of another part of the ancestral Indian River channel. The total thickness of the Holocene section, including dunes, is 25 m (82 ft.) of which 10 m (32.8 ft.) constitutes the barrier and dune sequence. Medium to coarse barrier sands overlie lagoonal clays with Crassostrea virginica and Elphidium fauna, in addition to other species. Lagoonal sediments are underlain by medium to coarse channel sands which unconformably overlie pre-Holocene sediments. A large back-barrier marsh is developed in this area. Fine to medium grained tidal delta sands overlie and grade laterally into lagoonal sediments. The tidal delta area is very shallow, as can be observed in Figure 79, and may in the near future become a site for the growth of a new marsh.

Figure 80 is a geologic cross section starting from the Pleistocene highland at White Neck, going across the southern part of Indian River Bay and the edge of the tidal delta, the back-barrier marsh, the baymouth barrier with overlying dunes, and terminating in the nearshore Atlantic marine area. As there is no core through the main barrier, the thickness of the barrier sediments is not known. However, as one draws nearer to the Pleistocene highlands to the south of this area, the thickness of the barrier sequence would tend to decrease. Barrier sediments

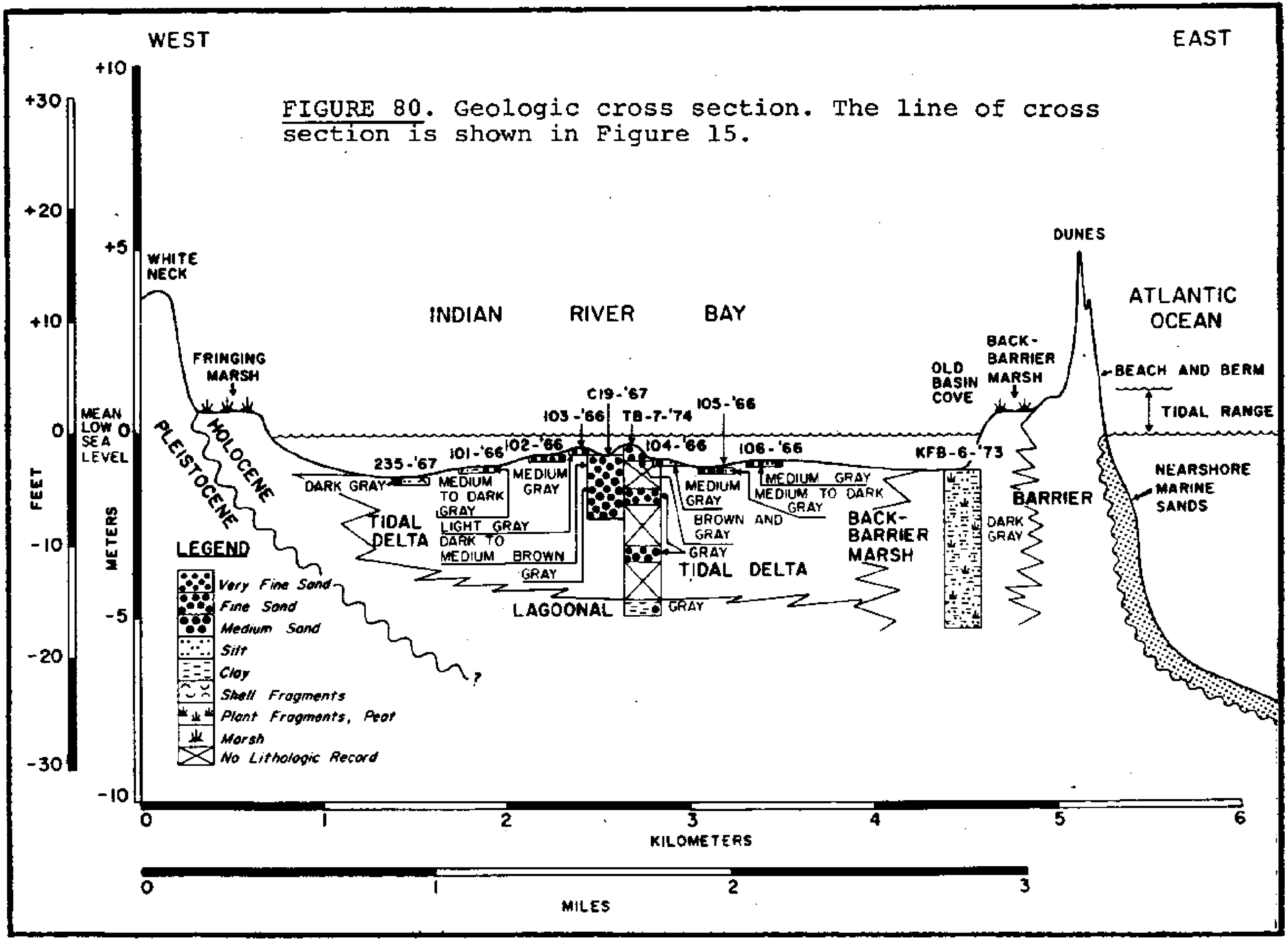


FIGURE 80. Geologic cross section. The line of cross section is shown in Figure 15.

here grade laterally into an at least 5-m (16.4 ft.) thick sequence of back-barrier marsh muds. The lagoon in this area is very shallow. Fine to medium tidal delta sands overlie lagoonal sediments, as seen in the cross section (Figure 80).

Approaching closer to the Pleistocene highlands, the thickness as well as the width of the barrier decreases, as can be observed in Figure 81. Here the thickness of the main barrier, including the dunes, is approximately 6.5 m (21.3 ft.). In core R-4117 medium sands of the barrier overlie a back-barrier marsh section. The latter is underlain by what is probably a thin sequence of channel sands, which unconformably overlie Pleistocene sediments. Sub-lagoonal barrier sands, as well as the lagoonal sands, are very fine grained and also overlie back-barrier marsh deposits. This indicates that the area occupied by Beach Cove was once a large back-barrier marsh before it was submerged by the waters of the Indian River Bay. As the barrier migrated, barrier sands transgressed into the Bay causing the formation of the sub-lagoonal barrier. Cedar Neck is believed by Kraft (oral communication) to be a Pleistocene epoch or mid-Wisconsin age barrier, and work is presently being done to corroborate this view. Figure 81 is the last cross section of the baymouth barrier studied in this report.

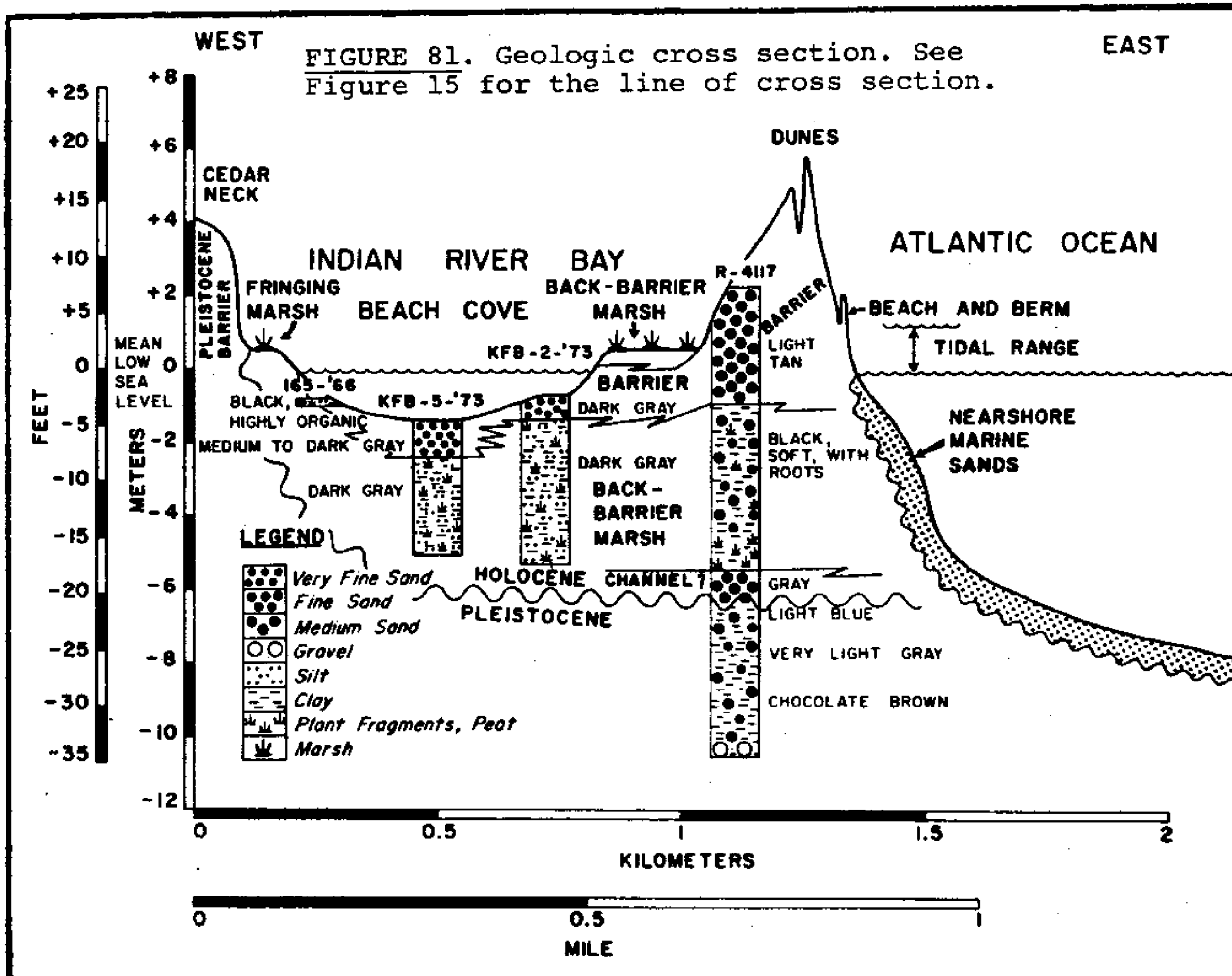


FIGURE 81. Geologic cross section. See Figure 15 for the line of cross section.

In the cross section shown in Figure 82, the beach-berm and dunes are seen abutting against a Pleistocene highland at Cottonpatch Hill. This situation is therefore similar to the case of the beach being built against Rehoboth highland, which has already been described in detail in section (B) of this chapter. The thin barrier and dune sequence here directly and unconformably overlies Pleistocene sands and gravels.

Concluding this discussion on the barrier-tidal delta-lagoon section of Delaware's Atlantic transgressive coastal barrier complex, the following statements can be made with regard to this area:

(1) This section of the transgressive coastal barrier complex includes a linear baymouth barrier as well as a tidal delta-inlet sequence. A flood and an ebb tidal delta are associated with the Indian River Inlet. The baymouth barrier is widest near the areas of the fan-shaped marsh-covered old tidal deltas. The greater part of this barrier is submerged. Back-barrier marshes are presently developed all along the length of the baymouth barrier.

(2) Barrier sands are generally medium grained, moderately well sorted, and negatively skewed. Sub-lagoonal barrier sands are fine to medium grained. Barrier sands deposited in the ancestral Indian River channel near the present Indian River Inlet are poorly sorted, with grain size

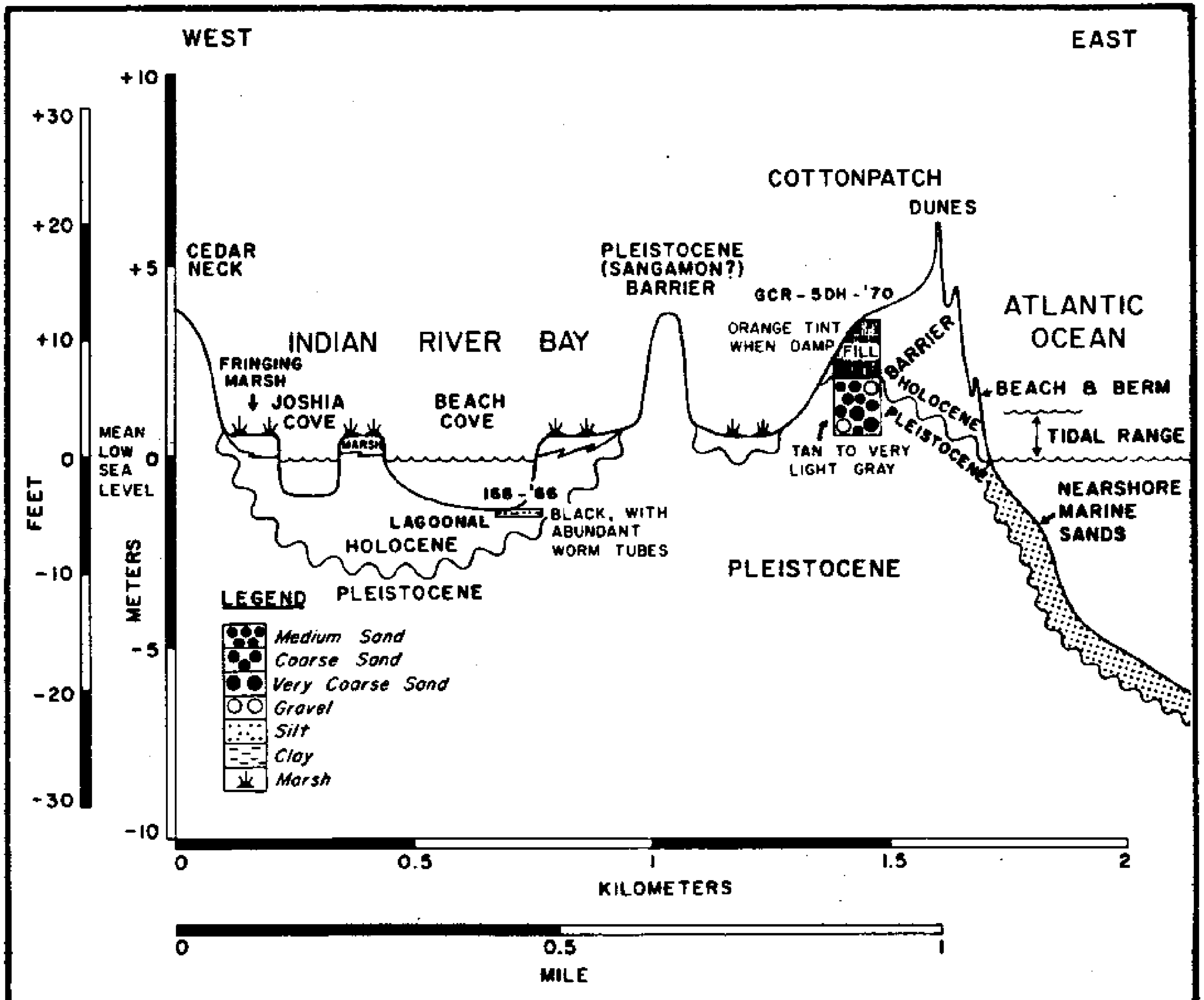


FIGURE 82

Geologic cross section. See Figure 15 for the line of cross section.

varying from fine to very coarse. Barrier and tidal delta-inlet sands can therefore be distinguished from each other on the basis of sorting.

(3) The vertical stratigraphic sequence of the baymouth barrier is similar to the present day lateral sedimentary environments in the direction of migration (landward). Hence, the cross sections of this area provide excellent illustrations of Walther's Law.

(4) Radiocarbon dates indicate that the present barrier sequence was developed within approximately the last 3,750 years.

(5) Exposure of pine tree stumps and back-barrier marsh muds in the low tide zone of the Atlantic Ocean beach, especially after storms, provides conclusive proof of continuing marine transgression and coastal erosion, resulting from relative sea level rise and massive storm-generated wave erosion.

(6) Baymouth barrier sediments released by coastal erosion are mostly stored in the adjacent submarine area. While part of it is lost by further seaward movement by wave action, another part of it is carried north by littoral transport and deposited at the Cape Henlopen spit tip. Storm overwash carries most of the submarine-stored barrier sediments, together with more beach and dune sediments, across the barrier and sometimes into the

lagoons forming washover fans. Continuing coastal erosion results in repeated recycling of barrier sediments. This accounts for the smaller average grain size of the baymouth barrier sediments, as compared to the sediments of the Cape Henlopen area.

(7) Washover fans can be presently seen on the surface of the baymouth barrier all along its length. Records of washover sands have been preserved in the vertical stratigraphic sequences observed in cores through the barrier. In many cases they lie between lagoonal clays and silts or back-barrier marsh sediments. Washovers help to widen the barrier. Hence washover deposition by storm-related overwash is the dominant mechanism for the landward migration of the baymouth barrier. The washover fans and back-barrier marshes constitute part of the edge of the ongoing Holocene transgression along the Atlantic coast of Delaware.

(8) As the vertical transgressive sequence in the Indian River Inlet area is thicker than in other areas, it has a better preservation potential. The lower parts of the transgressive sequences below mean low sea level may be preserved under a cover of marine sediments as the transgression proceeds landwards.

(9) Sedimentary structures most commonly observed in cores are horizontal laminations, convex and concave laminations,

planar cross-laminations, high-angle laminations, and ripple laminations. The latter two types appear to be more characteristic of washover deposits. Burrows are mostly found at the interface of barrier sands with marsh or lagoonal sediments.

(10) Baymouth barrier sequences in most cases overlie lagoonal sediments, the contact being fairly sharp and well defined. In some cases interfingering of sediment facies of the barrier and lagoon produces a slight funnel-shaped effect on geophysical logs near the base of the barrier. In the area of old tidal channels the scouring action of tidal currents has destroyed the stratigraphic records of underlying sedimentary environments, and the barrier sands truncate against the Pleistocene surface.

(11) The study of all characteristics of the vertical sedimentary core sequence, aided by a comparison with surficial environmental characteristics, provides the best basis for environmental interpretation. Grain-size parameters of the baymouth barrier sediments are not sufficiently distinctive to enable identification of barrier sub-environments.

(12) The transgressive vertical sequence of the baymouth barrier shows barrier sediments transgressing over older highland or lagoonal sediments. Back-barrier marsh sequences are also preserved in the vertical sedimentary

sequences studied in cores through the barrier. Hence this evidence suggests that this baymouth barrier is a landward migrating barrier which did not originate at its existing position. It has migrated to its existing site from a position further seaward on the Atlantic continental shelf.

A geologic cross section parallel to the transgressive Atlantic coastal barrier complex and extending along the entire length of the study area is shown in Figure 83. As can be observed in this cross section, the barrier varies greatly in thickness, and as discussed earlier, also in width. The thickest sequence is found at the Cape Henlopen spit. Other thick sequences are to be found in areas where ancestral streams tributary to the ancestral Delaware River have incised deep valleys through the pre-Holocene sediments. Proceeding from north to south we come across the ancestral valleys of Broadkill River, Wolfe Glade, Holland Glade, Love Creek, Herring Creek, and finally Indian River. South of the Rehoboth Pleistocene highland many of these ancestral valleys are filled with tidal marsh muds and lagoonal sediments, whereas north of the Rehoboth highland they are filled with shallow marine-estuarine sediments overlain by transgressive lagoon, marsh, and barrier sequences. The greater thicknesses of transgressive sedimentary sequences

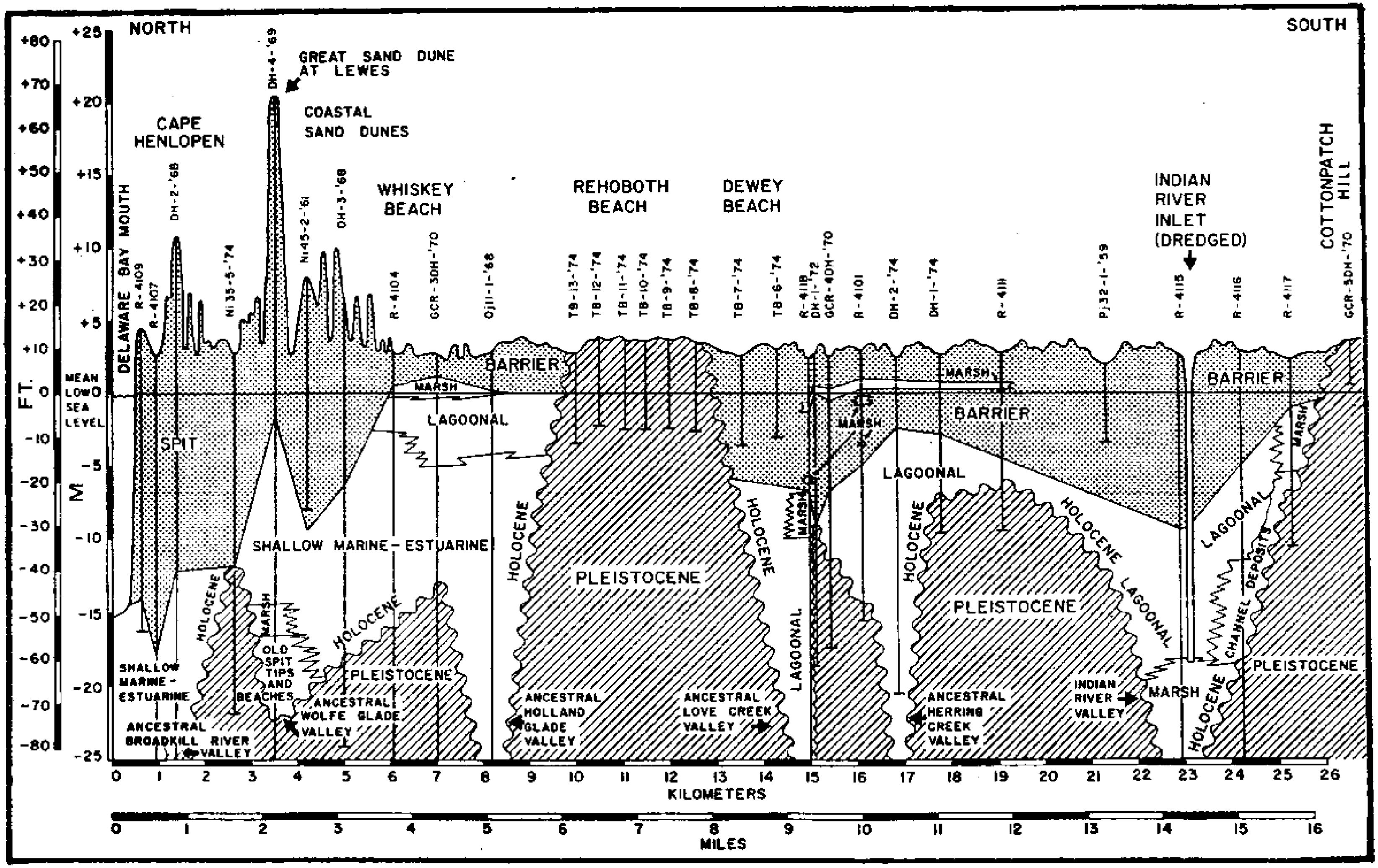


FIGURE 83. Geologic cross section parallel to the barrier complex. The line of cross section is shown in Figure 15.

in such areas results in their having a greater potential for preservation in the stratigraphic record. Large dune fields cover the Cape Henlopen area. South of the Rehoboth highland only a coast-parallel line of dunes has developed. The general topography of the Pleistocene surface being transgressed is very irregular, as can be seen in Figure 83. Pre-Holocene highlands are found abutting against the beach at Rehoboth Beach and Cottonpatch Hill. The beach in these areas, as noted previously, is extremely thin and narrow, and therefore stands little chance for preservation in the stratigraphic record; however, such sequences are found preserved in the subsurface in ancestral Wolfe Glade valley to the north.

Figure 84 represents a graphic summary of the vertical stratigraphic-environmental sequences of the four major variations in the transgressive Atlantic coastal barrier complex. Depending upon the area of study, some units in the sequences illustrated may be missing.

****

STRATIGRAPHIC, ENVIRONMENTAL SEQUENCE	GEOMORPHIC VARIATIONS			
	SPIT	BARRIER–MARSH	BEACH–HIGHLAND	BAYMOUTH BARRIER
DUNE	■	■	■	■
BEACH, BERM, WASHOVER	■	■	■	■
SPIT PLATFORM AND SLOPE	■	□	□	□
BACK-BARRIER MARSH	□	■	□	■
BARRIER, SUB-LAGOONAL PORTION	□	□	□	■
LAGOON	□	■	□	■
WASHOVER	□	□	□	■
LAGOON	□	□	□	■
MARSH	□	□	□	■
NEARSHORE MARINE, ESTUARINE	■	■	□	□
BEACH	■	□	□	□
PRE HOLOCENE	■	■	■	■

■ ENVIRONMENTS PRESENT □ ENVIRONMENTS ABSENT

FIGURE 84. Geomorphic variations and their respective stratigraphic-environmental sequences in the study area.

CONCLUSIONS

1. A 27-km (16.8 miles) long stretch of the transgressive Atlantic coastal barrier complex of Delaware extending from Cape Henlopen in the north to Cottonpatch Hill in the south was thoroughly investigated in this study. Within this length of the barrier complex, four major variations are found. These are (a) Cape Henlopen spit-beach-dune complex (Cape Henlopen to Whiskey Beach); (b) barrier against marsh (Whiskey Beach to Rehoboth); (c) beach against pre-Holocene highland (Rehoboth and Cottonpatch Hill); and (d) barrier-tidal delta-lagoon, that is, the baymouth barrier (South Rehoboth to Cotton-patch Hill). Each of these variations has been discussed separately in this report and conclusions about each of them are presented at the end of each discussion. Though this barrier complex is predominantly transgressive in nature, a regressive situation exists at the Cape Henlopen spit.

2. Sand for the barrier complex is mainly derived from coastal erosion of the Atlantic shore, especially the Pleistocene highland areas, and from offshore by wave

action. Eroded sand is carried from south to north along the coastline by littoral transport. Marsh and lagoonal muds and tree stumps exposed at very low tide in the surf zone at many sites along the Atlantic shoreline, especially after storm erosion, constitute vivid proof of continuing coastal erosion related to relative sea level rise and marine transgression.

3. Vertical stratigraphic-environmental sequences found in the four major variations of the coastal transgressive barrier complex of this study area are shown in Figure 84. These sequences, especially that of the baymouth barrier section, provide illustrations and proof of Walther's Law.

4. Transgressive sequences deposited in ancestral stream valleys crossing the barrier complex are thicker than in other sections of the barrier complex. Therefore they have a better potential for preservation in the stratigraphic record. Thin beach sequences found along the pre-Holocene highland areas at Rehoboth and Cottonpatch Hill stand little chance for preservation in view of the ongoing marine transgression. Upper parts of transgressive sequences representing the beach-berm and dune sediments are likely to be déstroyed by transgression. However, the lower parts of the vertical stratigraphic sequences below mean low sea level may be preserved under a cover of marine

sediments.

5. Washover deposition by storm overwash is the dominant mechanism for landward migration of transgressive coastal barrier complexes.

6. Washover fans and back-barrier marshes constitute part of the leading edge of the ongoing Holocene marine transgression on the Atlantic coast of Delaware, as the barrier complex migrates landward and upward through space and time.

7. Barrier sands are medium to coarse grained, moderately well sorted, and negatively skewed. Dune sands are fine to medium grained, well sorted, and mostly positively skewed. Barrier sands at the Cape Henlopen spit are of slightly coarser grain size and contain more gravel than the sands in other parts of the barrier complex. Spit sediments brought by littoral transport are derived from coastal erosion of pre-Holocene highlands to the south. Hence they are not as subject to repeated recycling as is the case with the sands along the rest of this barrier complex. Grain-size parameter variations in the sands of the barrier complex are not significantly variable to enable differentiation of barrier sub-environments. However, dune and barrier sands may be separated on the basis of skewness and sorting. Tidal delta-inlet sands can be distinguished from the barrier complex sands on the basis

of sorting. Trask's coefficient of sorting is not a useful parameter, unless the presently set verbal limits for sorting are redefined.

8. Detailed internal sedimentary structures are helpful in delineating environments, but they cannot be so used by themselves, especially since similar structures are observed in different environments identified in the subsurface. When the geophysical, sedimentological, and sedimentary structure data are studied together and compared with the characteristics of present day observed sedimentary environments, a reliable environmental interpretation can be made.

9. Based on radiocarbon dates from marsh peats and shell fragments, it can be stated that the barrier at the existing location was developed within approximately the last 3,750 years.

10. Evidence provided by the vertical stratigraphic sequences of this transgressive coastal barrier complex suggests that it is a landward migrating barrier which originated elsewhere further seaward on the Atlantic continental shelf. It has migrated to its present site from that seaward position.

11. Vertical sedimentary sequences of coarse sediments over fine sediments occur in both transgressive and regressive coastal environmental sequences. Hence the

aspect of geophysical logs may be funnel-shaped, columnar-shaped, and/or bell-shaped in an overall transgressive coastal environmental setting.

12. It is hoped that the detailed cross sections, vertical stratigraphic sequences, and internal sedimentary structures of Delaware's transgressive Atlantic coastal barrier complex presented in this report will serve as useful models for identification of similar sequences in the stratigraphic record, and also for paleogeographic and paleoenvironmental reconstructions.

Before finally concluding this report, one is reminded of some pertinent words of wisdom by Henry Clifton Sorby, who is known as the "Father of Sedimentary Petrology", who when describing the application of "current structures" for interpreting the origin of terraces in the Valley of Tay in 1856 (Summerson, 1976) wrote as follows:

> It must not be supposed that I wish to make it appear that the terraces in all other valleys are due to the same cause,--one set of circumstances may have formed some, and another set, others. Nothing, in my opinion, can be a greater obstacle to a correct interpretation of such phenomena, than to conclude that all things which appear <u>similar</u> are <u>identical</u>, and have had a similar origin; for each case should be investigated and judged from its own peculiar conditions.

The above statement remains true today and should caution us us when we try to use modern examples as models for interpreting ancient stratigraphic sequences.

****

REFERENCES CITED

Adams, R. D., and B. G. Thom, 1968, Relationship between coastal landforms and size distribution of surficial sediments, Horry and Marion Counties, South Carolina: Southeastern Geology, v. 9, p. 39-56.

Allen, D. R., 1975, Identification of sediments - their depositional environment and degree of compaction from well logs, p. 349-401, in G. V. Chilingarian and K. H. Wolf, eds., Compaction of Coarse Grained Sediments - I: Developments in Sedimentology, v. 18A, Elsevier Scientific Publishing Co., New York, 552p.

Allen, E. A., E. M. Maurmeyer, and J. C. Kraft, 1971, Three-dimensional characteristics of a rapidly transgressing estuarine washover barrier (abst.): Geol. Soc. America Abst. with Programs, Northeastern section, v. 9, No. 3, p. 234-235.

Allen, J. R. L., 1963, The classification of cross-stratified units, with notes on their origin: Sedimentology, v. 2, p. 93-114.

Allen, J. R. L., 1965a, Coastal Geomorphology of Eastern Nigeria; beach ridge barrier islands and vegetated tidal flats: Geologie En Mijnbouw, v. 44, p. 1-21.

Allen, J. R. L., 1965b, Late Quaternary Niger delta and adjacent areas; sedimentary environments and lithofacies: Am. Assoc. Petroleum Geologists Bull., v. 49, p. 547-600.

Allen, J. R. L., 1965c, The classification of cross-stratified units; further discussion: Sedimentology, v. 5, p. 252-254.

Anan, F. S., 1969, Grain size parameters of the beach and dune sands, Northeastern Massachusetts and New Hampshire coasts, p. 266-280, in Coastal Research Group, Coastal Environments of Northeastern Massachusetts and New Hampshire: Contr. No. 1-CRG, Geology Dept., Univ. of Massachusetts, Amherst, Mass., 462p.

Anderson, E. J., 1972, Sedimentary structure assemblages in transgressive and regressive calcarenites: 24th. Int. Geol. Congr., Montreal, Sec. 6, Stratigraphy and Sedimentology, p. 369-377.

Andrews, P. B., and G. J. van der Lingen, 1969, Environmentally significant sedimentologic characteristics of beach sands: New Zealand Jour. Geol. Geophys., v. 12, p. 119-137.

Andrews, P. B., 1970, Facies and genesis of a hurricane washover fan, St. Joseph Island, Central Texas coast: Rept. of Invest. No. 67, Bureau of Econ. Geology, Univ. of Texas at Austin, Austin, Texas, 147p.

Ball, M. W., T. J. Weaver, H. H. Crider, and D. S. Ball, 1941, Shoestring gas fields of Michigan, p. 237-266, in A. I. Levorsen, ed., Stratigraphic Type Oilfields: Am. Assoc. Petroleum Geologists, Tulsa, Oklahoma, 902p.

Ball, M. M., E. A. Shinn, and K. W. Stockman, 1967, The geological effects of hurricane Donna in South Florida: Jour. Geology, v. 75, p. 583-597.

Barwis, J. H., 1976, Annotated Bibliography on the Geologic, Hydraulic, and Engineering Aspects of Tidal Inlets: GITI Rept. No. 4, Dept. of the Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Virginia, 333p.

Barwis, J. H., 1976, Internal geometry of Kiawah Island beach ridges, p. II.115-II.125, in M. O. Hayes and T. W. Kana, eds., Terrigenous Clastic Depositional Environments; some modern examples: Tech. Rept. No. 11-CRD, Coastal Research Division, Dept. of Geology, Univ. of South Carolina, Columbia, South Carolina, 302p.

Bascom, W. N., 1951, The relationship between sand size and beach face slope: Amer. Geophys. Union, Trans., v. 32, p. 866-874.

Bascom, W. N., 1954, Characteristics of natural beaches: Proc. 4th. Conf. on Coastal Engineering, p. 163-180.

Bass, N. W., 1934, Origin of Bartlesville shoestring sands, Greenwood and Butler Counties, Kansas: Am. Assoc. Petroleum Geologists Bull., v. 18, p. 1313-1345.

Bass, N. W., 1939, Verden sandstone of Oklahoma, an exposed shoestring sand of Permean age: Am. Assoc. Petroleum Geologists Bull., v. 23, p. 559-581.

Belknap, D. F., 1975, Dating of Late Pleistocene and Holocene relative sea levels in coastal Delaware: Master of Science thesis, Dept. of Geology, Univ. of Delaware, Newark, Delaware, 95p.

Berg, R. R., and D. K. Davies, 1968, Origin of Lower Cretaceous Muddy sandstone at Bell Creek field, Montana: Am. Assoc. Petroleum Geologists Bull., v. 52, p. 1888-1898.

Bernard, H. A., C. F. Major, and B. S. Parrott, 1959, The Galveston barrier isalnd and environs; a model for predicting reservoir occurrence and trend: Gulf Coast Assoc. Geol. Soc., Trans., v. 9, p. 221-224.

Bernard, H. A., R. J. LeBlanc, and C. F. Major, 1962, Recent and Pleistocene geology of Southeast Texas, p. 175-224, in E. H. Rainwater and R. P. Zingula, eds., Geology of the Gulf Coast and Central Texas: Guidebook of excursions, 1962 Ann. Mtg. Geol. Soc. America, Houston, Texas. Reprinted, Bureau of Econ. Geology, Univ. of Texas, Guidebook No. 5, April, 1963.

Bernard, H. A., C. F. Major, B. S. Parrott, and R. J. LeBlanc, 1970, Recent Sediments of Southeast Texas: Guidebook No. 11, Bureau of Econ. Geology, Univ. of Texas, Austin, Texas.

Berryhill, H. L. Jr., K. A. Dickinson, and C. W. Holmes, 1969, Criteria for recognizing ancient barrier coastlines (abst.): Am. Assoc. Petroleum Geologists Bull., v. 53, p. 706-707.

Biederman, E. W. Jr., 1962, Distinction of shoreline environments in New Jersey: Jour. Sed. Petrology, v. 32, p. 181-200.

Bird, E. C. F., 1961, The coastal barriers of East Gippsland, Australia: Geographical Journal, v. 127, p. 460-468.

Bird, E. C. F., 1969, Coasts: M. I. T. Press, Cambridge, Massachusetts, 246p.

Bird, E. C. F., 1971, The evolution of sandy barrier formations on the East Gippsland coast, p. 45-63, in J. A. Steers, ed., Applied Coastal Geomorphology: M. I. T. Press, Cambridge, Massachusetts, 227p.

Blatt, H., G. Middleton, and R. Murray, 1972, Origin of Sedimentary Rocks: Prentice Hall Inc., Englewood Cliffs, New Jersey, 634p.

Boyd, D. R., and B. F. Dyer, 1966, Frio barrier bar system of South Texas: Am. Assoc. Petroleum Geologists Bull., v. 50, p. 170-178.

Boyd, H. W., 1971, Depositional environments within a beach: Elisha Mitchell Sci. Soc. Jour., v. 87, No. 4, p.162.

Bradley, J. S., 1957, Differentiation of marine and subaerial sedimentary environments by volume percentage of heavy minerals, Mustang Island, Texas: Jour. Sed. Petrology, v. 27, p. 116-125.

Brickman, E., L. A. Merrill, D. F. Belknap, E. M. Maurmeyer, and J. C. Kraft, 1977, Short term changes at Cape Henlopen, Delaware (abst.): Geol. Soc. America Abst. with Programs, Southeastern section, v. 9, No. 2, p. 121-122.

Bridges, P. H., 1976, Lower Silurian transgressive barrier islands, Southwest Wales: Sedimentology, v. 23, p. 347-362.

Briggs, G., 1966, Primary sedimentary structures in the search for petroleum (abst.): Gulf Coast Assoc. Geol. Soc., Trans., v. 16, p. 297.

Bruun, P., 1962, Sea level rise as a cause of shore erosion: Am. Soc. Civil Engineers Proc., Jour. Waterways and Harbors Div., v. 88, p. 117-130.

Busch, D. A., 1959, Prospecting for stratigraphic traps: Am. Assoc. Petroleum Geologists Bull., v. 43, p. 2829-2843.

Caldwell, J. M., 1959, Shore erosion by storm waves: Misc. Paper 1-59, Coastal Engineering Research Center, U. S. Army Corps of Engineers, Fort Belvoir, Va., 17p.

Caldwell, J. M., 1966, Coastal processes and beach erosion: Jour. Soc. Civil Engineers, v. 53, No. 2, p. 142-157.

Campbell, C. V., 1967, Lamina, laminaset, bed, and bedset: Sedimentology, v. 8, p. 7-26.

Campbell, C. V., 1971, Depositional model - Upper Cretaceous Gallup beach shoreline, Ship Rock area, New Mexico: Jour. Sed. Petrology, v. 41, p. 395-409.

Chappel, J., 1967, Recognizing fossil strand lines from grain size analysis: Jour. Sed. Petrology, v. 37, p. 157-165.

Clifton, H. E., R. E. Hunter, and R. L. Phillips, 1971, Depositional structures and processes in the non-barred high energy nearshore: Jour. Sed. Petrology, v. 41, p. 651-670.

Clifton, H. E., R. E. Hunter, and R. L. Phillips, 1972, Depositional models from a high energy coast (abst.): Am. Assoc. Petroleum Geologists Bull., v. 56, p. 609.

Clifton, H. E., 1973, Marine-nonmarine facies change in Middle Miocene rocks, Southeastern Caliente Range, California; sedimentary facies changes in Tertiary rocks, California Transverse and Southern Coast Ranges: Ann. Mtg. Soc. Econ. Paleont. Mineral., Field Trip No. 2, p. 55-57.

Coastal Research Group, 1969, Coastal Environments of Northeastern Massachusetts and New Hampshire: Contribution No. 1-CRG, Geology Dept., Univ. of Massachusetts, Amherst, Mass., 462p.

Coates, D. R., ed., 1973, Coastal Geomorphology: Publications in Geomorphology, State Univ. of New York, Binghamton, New York, 404p.

Coleman, J. M., and S. M. Gagliano, 1965, Sedimentary structures, Mississippi River deltaic plain, p. 133-148, in G. V. Middleton, ed., Primary Sedimentary Structures and their Hydrodynamic Interpretation: Soc. Econ. Paleont. Mineral., Spec. Publ. No. 12, Tulsa, Oklahoma, 265p.

Colquhoun, D. J., 1965, Terrace sediment complexes in Central South Carolina: Atlantic Coastal Plain Geological Assoc. Field Conf., Columbia, Univ. of South Carolina Press, 62p.

Colquhoun, D. J., 1969a, Geomorphology of the Lower Coastal Plain of South Carolina: MS - 15, Division of Geology, State Development Board, Columbia, South Carolina, 36p., 1 map.

Colquhoun, D. J., 1969b, Coastal Plain Terraces in the Carolinas and Georgia, U. S. A., p. 150-162, in Quaternary Geology and Climate: Natl. Acad. Sci. Publ. 1701, Washington, D. C., 162p.

Colquhoun, D. J., J. W. Pierce, and M. L. Schwartz, 1968, Field and laboratory observations on the genesis of barrier islands (abst.): Geol. Soc. America Ann. Mtg., Mexico City, p. 59-60.

Conatser, W. E., 1971, Grand Isle, a barrier island in the Gulf of Mexico: Am. Assoc. Petroleum Geologists Bull., v. 82, p. 3049-3068.

Conybeare, C. E. B., 1976, Geomorphology of Oil and Gas Fields in Sandstone Bodies: Developments in Petroleum Science, v. 4, Elsevier Scientific Publishing Company, New York, 341p.

Cooke, C. W., 1968, Barrier island formation; discussion: Geol. Soc. America Bull., v. 79, p. 945-946.

Cooke, C. W., 1971, Holocene evolution of a portion of the North Carolina coast; discussion: Geol. Soc. America Bull., v. 82, p. 2369-2370.

Corbeille, R. L., 1962, New Orleans barrier island: Gulf Coast Assoc. Geol. Soc., Trans., v. 12, p. 223-229.

Cromwell, J. E., 1971, Barrier coast distribution, a world wide survey: Abst. vol., 2nd. Natl. Coastal and Shallow Water Res. Conf., 50(1971); also in M. L. Schwartz, ed., Barrier Islands (1973), p. 408: Dowden, Hutchinson, and Ross, Stroudsburgh, Pennsylvania, 451p.

Crooke, K. A., 1965, The classification of cross-stratified units; comment on a paper by J. R. L. Allen: Sedimentology, v. 5, p. 249-252.

Curray, J. R., 1960, Sediments and history of Holocene transgression, continental shelf, Northwest Gulf of Mexico, p. 221-266, in F. P. Shepard, F. B. Phlegar, and Tj. H. van Andel, eds., Recent Sediments, Northwest Gulf of Mexico: Am. Assoc. Petroleum Geologists, Tulsa, Oklahoma, 394p.

Curray, J. R., 1964, Transgressions and regressions, p. 175-203, in R. L. Miller, ed., Papers in Marine Geology, Shepard Commemorative volume: The Macmillan Company, New York, 531p.

Curray, J. R., 1969, Shore zone sand bodies; barriers, cheniers, and beach ridges, p. II.1-II.18, in D. J. Stanley, ed., New Concepts of Continental Margin Sedimentation: Am. Geol. Inst. Short Course Notes, Washington, D. C.

Curray, J. R., and D. G. Moore, 1964, Holocene regressive littoral sand, Costa de Nayarit, Mexico, p. 76-82, in L. M. J. U. van Straaten, ed., Deltaic and Shallow Marine Deposits: Developments in Sedimentology, v. 1: Elsevier Publishing Company, Amsterdam, 464p.

Davidson-Arnott, R. G. D., and B. Greenwood, 1974, Bed forms and structures associated with bar topography in the shallow water wave environment, Kouchibouguac Bay, New Brunswick, Canada: Jour. Sed. Petrology, v. 44, p. 698-704.

Davidson-Arnott, R. G. D., and B. Greenwood, 1976, Facies relationships on a barred coast, Kouchibouguac Bay, New Brunswick, Canada, p. 149-168, in R. A. Davis Jr., and R. L. Ethington, eds., Beach and Nearshore Sedimentation: Soc. Econ. Paleont. Mineral., Spec. Publ. No. 24, Tulsa, Oklahoma, 187p.

Davis, R. A. Jr., and R. L. Ethington, eds., 1976, Beach and Nearshore Sedimentation: Soc. Econ. Paleont. Mineral., Spec. Publ., No. 24, Tulsa, Oklahoma, 187p.

Davis, W. M., 1896, The outline of Cape Cod: Proc. Am. Acad. Arts and Science, v. 31, p. 303-332.

Davies, D. K., 1969, Shelf sediments, an example from the Jurassic of Britain: Jour. Sed. Petrology, v. 39, p. 1344-1370.

Davies, D. K., 1976, Models and concepts for exploration in barrier islands, p. 79-115, in R. S. Saxena, ed., Sedimentary Environments and Hydrocarbons: Short Course Notes, Ann. Mtg. AAPG/SEPM, New Orleans, Louisiana, 217p.

Davies, D. K., F. G. Ethridge, and R. R. Berg, 1971, Recognition of barrier environments: Am. Assoc. Petroleum Geologists Bull., v. 55, p. 550-565.

Davies, J. L., 1973, Geographical Variation in Coastal Development: Hafner Publishing Company, New York, 204p.

de Beaumont, E., 1845, Leçons de Géologie Pratique: Paris, p. 223-252.

de Ridder, N. A., 1960, Minor structures of some Holocene and Pleistocene sediments from the Southwestern part of the Netherlands: Geologie En Mijnbouw, v. 22, p. 679-685.

Dickinson, K. A., and R. E. Hunter, 1970, Grain size distributions and depositional history of Northern Padre Island, Texas (abst.): Geol. Soc. America Abst. with Programs, v. 2, No. 4, p. 280.

Dickinson, K. A., H. L. Berryhill Jr., and C. W. Holmes, 1972, Criteria for recognizing ancient barrier coastlines, p. 192-214, in J. K. Rigby and Wm. K. Hamblin, eds., Recognition of Ancient Sedimentary Environments: Soc. Econ. Paleont. Mineral., Spec. Publ. No. 16, 340p.

Dickinson, WM. R., 1975, Current Concepts of Depositional Systems with Applications for Petroleum Geology: Short Course Notes, San Joaquin Geological Society, Bakersfield, California, 12 chapters.

Dillon, W. P., 1970, Submergence effects on Rhode Island barrier and lagoon and inference on migration of barriers: Jour. Geology, v. 78, p. 94-106.

Doeglas, D. J., 1946, Interpretation of the results of mechanical analysis: Jour. Sed. Petrology, v. 16, p. 19-40.

Dolan, R., 1972, Barrier dune systems along the Outer Banks of North Carolina, a re-appraisal: Science, v. 176, p. 286-288.

Dolan, R., 1973, Barrier islands; natural and controlled, p. 263-278, in D. R. Coates, ed., Coastal Geomorphology: Publications in Geomorphology, State Univ. of New York, Binghamton, New York, 404p.

Dolan, R., and P. J. Godfrey, 1973, Effects of hurricane Ginger on the barrier islands of North Carolina: Geol. Soc. America Bull., v. 84, p. 1329-1334.

Dolan, R., P. J. Godfrey, and W. E. Odum, 1973, Man's impact on the barrier islands of North Carolina: American Scientist, v. 61, p. 152-162.

Donn, W. L., and D. M. Shaw, 1963, Sea level and climate of the past century: Science, v. 142, p. 1166-1167.

Duane, D. B., 1964, Significance of skewness in Recent sediments, Western Pamlico Sound, North Carolina: Jour. Sed. Petrology, v. 34, p. 864-874.

Dubois, R. N., 1975, Support and refinement of the Bruun rule on beach erosion: Jour. Geology, v. 83, p. 651-657.

El-Ashry, M. T., and H. R. Wanless, 1965, Birth and early growth of a tidal delta: Jour. Geology, v. 73, p. 404-406.

Embry, A. F., G. E. Reinson, and P. R. Schluger, 1974, Shallow marine sandstones - a brief review, p. 53-66, in M. S. Shawa, ed., Use of Sedimentary Structures for Recognition of Clastic Environments: Canadian Soc. Petroleum Geologists, 66p.

Emery, K. O., and R. E. Stevenson, 1950, Laminated beach sand: Jour. Sed. Petrology, v. 20, p. 220-223.

Evans, O. F., 1942, The origin of spits, bars, and related structures: Jour. Geology, v. 50, p. 846-865.

Exum, F. A., and J. C. Harms, 1968, Comparison of marine bar with valley fill stratigraphic traps, Western Nebraska: Am. Assoc. Petroleum Geologists Bull., v. 52, p. 1851-1868.

Fairbridge, R. W., 1961, Eustatic changes in sea level: Physics and Chemistry of the Earth, v. 4, Pergamon Press, p. 99-185.

Farrell, S. C., 1969, Growth cycle of a small recurved spit, Plum Island, Massachusetts, p. 316-336, in Coastal Research Group, Coastal Environments of Northeastern Massachusetts and New Hampshire: Contribution No. 1-CRG, Geology Dept., Univ. of Massachusetts, Amherst, Mass., 462p.

Field, M. E., and Duane, D. B., 1976, Post-Pleistocene history of the United States Inner Continental Shelf; significance to origin of barrier islands: Geol. Soc. America Bull., v. 87, p. 691-702.

Fischer, A. G., 1961, Stratigraphic record of transgressing seas in light of sedimentation on Atlantic coast of New Jersey: Am. Assoc. Petroleum Geologists Bull., v. 45, p. 1656-1666.

Fisher, J. J., 1967, Origin of barrier island chain shorelines, Middle Atlantic States (abst.): Geol. Soc. America, Spec. Paper 115, p. 66-67.

Fisher, J. J., 1968, Barrier island formation; discussion: Geol. Soc. America Bull., v. 79, p. 1421-1426.

Fisher, J. J., 1973, Bathymetric projected profiles and the origin of barrier islands - Johnson's shoreline of emergence, revisited, p. 161-178, in D. R. Coates, ed., Coastal Geomorphology, Publications in Geomorphology, State Univ. of New York, New York, 404p.

Fisher, J. J., and D. R. Regan, 1977, Relationship of shoreline erosion rates to eustatic sea level rise, Rhode Island coast (abst.): Geol. Soc. America Abst. with Programs, Northeastern section, v. 9, No. 3, p. 265.

Fisher, J. S., S. P. Leatherman, and F. C. Perry, 1974, Overwash processes on Assateague Island: 14th. Coastal Engineering Conf., Proc., Copenhagen, Denmark, p. 1194-1212.

Fisher, W. L., and J. H. McGowen, 1969, Depositional systems in Wilcox Group (Eocene) of Texas and their relationship to oil and gas: Am. Assoc. Petroleum Geologists Bull., v. 53, p. 30-54.

Fisk, H. N., 1959, Padre Island and the Laguna Madre flats Coastal South Texas, in R. J. Russell, ed., 2nd. Coastal Geography Conf., Louisiana State Univ., Baton Rouge, Louisiana, p. 103-151.

Folk, R. L., 1966, A review of grain size parameters: Sedimentology, v. 6, p. 73-93.

Folk, R. L., 1968, Petrology of Sedimentary Rocks: Hemphills, Drawer M. University Station, Austin Texas, 170p.

Folk, R. L., and W. C. Ward, 1957, Brazos River bar; a study in the significance of grain size parameters: Jour. Sed. Petrology, v. 27, p. 3-26.

Fons, L., 1969, Geological application of well logs: Tenth Ann. Logging Symp., Trans., Soc. Prof. Well Log Anal., Paper AA, 44p.

Frey, R. W., and J. D. Howard, 1969, A profile of biogenic sedimentary structures in a Holocene barrier island salt marsh complex, Georgia: Gulf Coast Assoc. Geol. Soc., Trans., v. 19, p. 427-444.

Frey. R. W., and T. V. Mayou, 1971, Decapod burrows in Holocene barrier island beaches and washover fans, Georgia: Senckenbergiana Maritima, v. 3, p. 53-77.

Friedman, G. M., 1961, Distinction between dune, beach, and river sands from their textural characteristics: Jour. Sed. Petrology, v. 31, p. 514-529.

Friedman, G. M., 1967, Dynamic processes and statistical parameters compared for size frequency distribution of beach and river sands: Jour. Sed. Petrology, v. 37, p. 327-354.

Friedman, G. M., 1973, Textural parameters of sands; useful or useless? (abst.): Geol. Soc. America Abst. with Programs, Ann. Mtg., Dallas, Texas, v. 5, No. 7, p. 626-627.

Gary, M., R. McAfee, and C. L. Wolf, ed.'s, 1972, Glossary of Geology: Am. Geol. Inst., Washington, D. C., 858p.

Gees, R. A., 1965, Moment measures in relation to the depositional environments of sands: Ecol. Geol. Helv., v. 58, p. 209-213.

Gibbons, G. S., 1967, Shell content in quartzose beach and dune sands, Dee Why, New South Wales: Jour. Sed. Petrology, v. 37, p. 869-878.

Gierloff-Emden, H. G., 1961, Nehrungen und Lagunen: Petermanns Geog. Mitt., v. 105(2) p. 81-92, and v. 105(3) p. 161-176.

Gilbert, G. K., 1885, The topographic features of lake shores: U. S. Geol. Survey 5th. Ann. Rept., p. 69-123.

Giles, R. T., and Pilkey, O. H., 1965, Atlantic beach and dune sediments of the Southern United States: Jour. Sed. Petrology, v. 35, p. 900-910.

Gill, E. D., 1967, Evolution of shoreline barriers: Victorian Naturalist, v. 84, p. 282-283.

Glaister, R. P., and H. W. Nelson, 1974, Grain size distributions, an aid in facies identification: Canadian Petroleum Geology Bull., v. 22, p. 203-240.

Godfrey, P. J., 1970, Oceanic overwash and its ecological implications on the Outer Banks of North Carolina: Natl. Park Service Rept., Office of Natl. Sci. Studies, Natl. Park Service, Washington D. C., 37p.

Godfrey, P. J., and M. M. Godfrey, 1973, Comparison of ecological and geomorphic interactions between altered and unaltered barrier island systems in North Carolina, p. 239-258 in D. R. Coates, ed., Coastal Geomorphology, Publications in Geomorphology, State Univ. of New York, Binghamton, New York, 404p.

Godfrey, P. J., and M. M. Godfrey, 1974, The role of overwash and inlet dynamics in the formation of salt marshes in the North Carolina barrier islands, p. 407-427, in R. J. Reimold and W.H.Queen, eds., Ecology of Halophytes: Academic Press, New York, 605p.

Grant, U. S., 1943, Waves as a sand transporting agent: Am. Jour. Science, v. 241, p.117-123.

Gressly, A., 1838, Observations géologiques sur le Jura Soleurois: Neue Denkschr. allg. schweiz. Ges. ges. Naturw., v. 2, p. 1-112.

Gretener, P. E., 1967, Significance of the rare event in geology: Am. Assoc. Petroleum Geologists Bull., v. 51, p. 2197-2206.

Groen, P., and G. W. Groves, 1962, Surges, p. 611-646, in M. N. Hill, ed., The Sea, v. 1, Physical Oceanography: Interscience Publishers, New York, 864p.

Guy, H. P., 1969, Laboratory theory and methods for sediment analysis: Techniques of water resources investigations of the U. S. Geol. Survey, Chapter C_1, Book 5, Suptd. of Documents, U. S. Govt. Printing Office, Washington D. C., 58p.

Hails, J. R., 1967, Significance of statistical parameters for distinguishing sedimentary environments in New South Wales, Australia: Jour. Sed. Petrology, v. 37, p. 1059-1069.

Hails, J. R., 1971, Holocene evolution of a portion of the North Carolina coast; discussion: Geol. Soc. America Bull., v. 82, p. 3525-3526.

Hails, J. R., and J. H. Hoyt, 1969, The significance and limitations of statistical parameters for distinguishing ancient and modern sedimentary environments of the Lower Georgia Coastal Plain: Jour. Sed. Petrology, v. 39, p. 559-580.

Halsey, S. D., and J. C. Kraft, 1971, Anatomy of a spit, Cape Henlopen, Delaware (abst.): Geol. Soc. America Abst. with Programs, Southeastern section, v. 3, No. 5, p. 314-315.

Hand, B. M., 1967, Differentiation of beach and dune sands using settling velocities of light and heavy minerals: Jour. Sed. Petrology, v. 37, p. 514-520.

Harms, J. C., D. B. Mackenzie, and D. G. McCubbin, 1965, Depositional environment of the Fox Hills sandstones near Rock Springs, Wyoming: Wyoming Geol. Assoc. Guidebook, 19th. Ann. Field Conf., p. 113-130.

Harms, J. C., and R. K. Fahnestock, 1965, Stratification, bed forms, and flow phenomena (with an example from the Rio Grande), p. 84-115, in G. V. Middleton, ed., Primary Sedimentary Structures and their Hydrodynamic Interpretation: Soc. Econ. Paleont. Mineral., Spec. Publ. No. 12, 265p.

Harms, J. C., J. B. Southard, D. R. Spearing, and R. G. Walker, 1975, Stratification and sequence in prograding shoreline deposits, p. 81-102, in Depositional Environments as interpreted from Primary Sedimentary Structures and Stratification Sequences: Lecture notes for short course No. 2, Soc. Econ. Paleont. Mineral., 161p.

Harris, S. A., 1959, The mechanical composition of some inter-tidal sands: Jour. Sed. Petrology, v. 29, p. 412-424.

Hayes, M. O., and A. J. Scott, 1964, Environmental complexes, South Texas Coast: Gulf Coast Assoc. Geol. Soc., Trans., v. 14, p. 237-240.

Hayes, M. O., 1965, Sedimentation in a semi-arid wave dominated coast (South Texas) with an emphasis on hurricane effects: Ph. D. dissertation, Univ. of Texas, 350p.

Hayes, M. O., 1967a, Hurricanes as geological agents, South Texas Coast: Am. Assoc. Petroleum Geologists Bull., v. 51, p. 937-942.

Hayes, M. O., 1967b, Hurricanes as geological agents; case studies of hurricanes Carla 1961, and Cindy, 1963: Bureau Econ. Geology, Rept. of Investigation No. 61, The Univ. of Texas, Austin, Texas, 56p.

Hayes, M. O., F. S. Anan, and R. N. Bozeman, 1969, Sediment dispersal trends in the littoral zone; a problem of paleogeographic reconstruction, p. 290-315, in Coastal Research Group, Coastal Environments of Northeastern Massachusetts and New Hampshire: Contribution No. 1 - CRG, Geology Dept., Univ. of Massachusetts, Amherst, Mass., 462p.

Hayes, M. O., and J. C. Boothroyd, 1969, Storms as modifying agents in the coastal environment, p. 245-265, in Coastal Research Group, Coastal Environments of Northeastern Massachusetts and New Hampshire: Contribution No. 1 -CRG, Geology Dept., Univ. of Massachusetts, Amherst, Mass., 462p.

Hayes, M. O., and T. W. Kana, ed.'s, 1976, Terrigenous Clastic Depositional Environments; some modern examples: Tech. Rept. No. 11 - CRD, Coastal Research Division, Dept. of Geology, Univ. of South Carolina, Columbia, South Carolina, 302p.

Henry, V. J. Jr., and J. H. Hoyt, 1968, Quaternary paralic and shelf sediments of Georgia: Southeastern Geology, v. 9, p. 195-214.

Hobday, D. K., 1974, Beach and barrier island facies in the Upper Carboniferous of Northern Alabama, p. 209-224, in G. Briggs, ed., Carboniferous of the South-eastern United States: Geol. Soc. America Spec. Paper 148, 361p.

Hollenshead, C. T., and R. L. Pritchard, 1961, Geometry of producing Mesaverde sandstones, San Juan basin, p. 98-118, in J. A. Peterson and J. C. Osmond, eds., Geometry of Sandstone Bodies: Am. Assoc. Petroleum Geologists, Tulsa, Oklahoma, 240p.

Horn, Dietrich, 1965, Zur geologischen Entwicklung der südlichen Schleimündung im Holozän: Meyniana, v. 15, p. 42-58.

Hosier, P. J., 1973, The effects of oceanic overwash on the vegetation of Core and Shackleford Banks, North Carolina: Ph.D dissertation, Duke University, 230p.

Howard, J. D., 1969, Radiographic examination of variations in barrier island facies, Sapelo Island, Georgia: Gulf Coast Assoc. Geol. Soc., Trans., v. 19, p. 217-232.

Howard, J. D., 1972, Trace fossils as criteria for recognizing shorelines in the stratigraphic record, p. 215-225, in J. K. Rigby and Wm. K. Hamblin, eds., Recognition of Ancient Sedimentary Environments: Soc. Econ. Paleont. and Mineral., Spec. Publ. No. 16, 340p.

Howard, J. D., and H. E. Reineck, 1972a, Georgia coastal region, Sapelo Island, U. S. A.: Sedimentology and Biology, IV. Physical and biogenic sedimentary structures of the nearshore shelf: Senckenbergiana Maritima, v. 4, p. 81-123.

Howard, J. D., and H. E. Reineck, 1972b, Georgia coastal region, Sapelo Island, U. S. A.: Sedimentology and Biology, VIII. Conclusions: Senckenbergiana Maritima, v. 4, p. 217-222.

Howard, J. D., J. Dorjes, R. W. Frey, S. Gadow, G. Hertwick, H. E. Reineck, and F. Wunderlich, 1972, Usable beach to offshore model for tide dominated shoreline, Sapelo Island, Georgia (abst.): Am. Assoc. Petroleum Geologists Bull., v. 56, p. 629.

Hoyt, J. H., 1962, High-angle beach stratification, Sapelo Island, Georgia: Jour. Sed. Petrology, v. 32, p. 309-311.

Hoyt, J. H., 1967a, Barrier island formation: Geol. Soc. America Bull., v. 78, p. 1125-1136.

Hoyt, J. H., 1967b, Occurrence of high-angle stratification in littoral and shallow neritic environments, Central Georgia coast, U. S. A.: Sedimentology, v. 8, p. 229-238.

Hoyt, J. H., 1968a, Barrier island formation; reply: Geol. Soc. America Bull., v. 79, p. 947.

Hoyt, J. H., 1968b, Genesis of sedimentary deposits along coasts of submergence: 23rd. Int. Geol. Congress, v. 8, p. 311-321.

Hoyt, J. H., 1968c, Barrier island formation; reply: Geol. Soc. America Bull., v. 79, p. 1427-1432.

Hoyt, J. H., 1970, Development and migration of barrier islands, Northern Gulf of Mexico; discussion: Geol. Soc. America Bull., v. 81, p. 3779-3782.

Hoyt, J. H., 1972, Shoreline processes: Jour. Geol. Education, v. 20, p. 16-22.

Hoyt, J. H., V. J. Henry Jr., and R. J. Weimer, 1962, Geologic history and development of the barrier islands in the vicinity of Sapelo Island, Georgia (abst.): Geol. Soc. America Spec. Paper 73, p. 11.

Hoyt, J. H., R. J. Weimer, and V. J. Henry Jr., 1964, Late Pleistocene and Recent sedimentation, Central Georgia coast, U. S. A., p. 170-176, in L. M. J. U. van Straaten, ed., Deltaic and Shallow Marine Deposits: Developments in Sedimentology, v. 1, Elsevier Publishing Co., New York, 464p.

Hoyt, J. H., and V. J. Henry Jr., 1965, Significance of inlet sedimentation in the recognition of ancient barrier islands: Wyoming Geological Soc., 19th. Field Conf., p. 190-194.

Hoyt, J. H., and J. R. Hails, 1967, Pleistocene shoreline sediments in coastal Georgia; deposition and modification: Science, v. 155, p. 1541-1543.

Hoyt, J. H., and V. J. Henry Jr., 1967, Influence of island migration on barrier island sedimentation: Geol. Soc. America Bull., v. 78, p. 77-86.

Hubbard, D. K., and J. H. Barwis, 1976, Discussion of tidal inlet sand deposits; examples from the South Carolina coast, p. II.128-II.142, in M. O. Hayes and T. W. Kana, eds., Terrigenous Clastic Depositional Environments: Tech. Rept. No. 11-CRD, Coastal Research Division, Dept. of Geology, Univ. of South Carolina, Columbia, South Carolina, 302p.

Ingle, J. C. Jr., 1975, Nearshore processes and beach deposits, p. 2.1-2.11, in WM. R. Dickinson, ed., Current Concepts of Depositional Systems with Applications for Petroleum Geology: Short course notes, San Joaquin Geol. Soc., Bakersfield, California, 12 chapters.

Ingram, R. L., 1954, Terminology for the thickness of stratification and parting units in sedimentary rocks: Geol. Soc. America Bull., v. 65, p. 937-938.

Inman, D. L., 1952, Measures for describing the size distribution of sediments: Jour. Sed. Petrology, v. 22, p. 125-145.

Inman, D. L., and T. K. Chamberlain, 1955, Particle size distribution in nearshore marine sediments, p. 106-129, in J. L. Hough and H. W. Menard, eds., Finding Ancient Shorelines: Soc. Econ. Paleont. Mineral., Spec. Publ. No. 3, 129p.

Jelgersma, S., 1961, Holocene sea level changes in the Netherlands: Meded. Geol. Sticht., Series C-VI, 101p.

Jennings, J. N., and R. J. Coventry, 1973, Structure and texture of a gravelly barrier island in the Fitzroy estuary, Western Australia, and the role of mangroves in shore dynamics: Marine Geology, v. 15, p. 145-167.

Johnson, D. W., 1919, Shore Processes and Shoreline Development: John Wiley, New York, 584p.

Johnson, J. W., 1956, Dynamics of nearshore sediment movement: Am. Assoc. Petroleum Geologists Bull., v. 40, p. 2211-2232.

Jopling, A. V., 1965, Hydraulic factors and the shape of laminae: Jour. Sed. Petrology, v. 35, p. 777-791.

Keller, W. D., 1945, Size distribution of sand in some dunes, beaches, and sandstones: Am. Assoc. Petroleum Geologists Bull., v. 29, p. 215-221.

King, C. A. M., 1951, Depth of disturbance of sand on sea beaches by waves: Jour. Sed. Petrology, v. 21, p. 131-140.

King, C. A. M., 1970, Changes in the spit at Gibralter Point, Lincolnshire, 1951 to 1969, p. 371-382, in M. L. Schwartz, ed., Spits and Bars (1972): Dowden, Hutchinson, and Ross Inc., Stroudsburg, Pennsylvania, 452p.

King, C. A. M., 1972, Beaches and Coasts: St. Martins Press, New York, 570p.

King, C. A. M., 1974, Introduction to Marine Geology and Geomorphology: Edward Arnold (Publishers) Ltd., London, 309p.

King, C. A. M., and M. J. McCullagh, 1971, A simulation model of a complex recurved spit: Jour. Geology, v. 79, p. 22-37.

Klein, G. deV., 1971, A sedimentary model for determining paleotidal range: Geol. Soc. America Bull., v. 82, p. 2585-2592.

Klein, G. deV., 1972, Determination of paleotidal range in clastic sedimentary rocks: 24th. Int. Geol. Congr., Montreal, Section 6, Stratigraphy and Sedimentology, p. 397-405.

Klein, G. deV., 1974, Estimating water depths from analysis of barrier island and deltaic sedimentary sequences: Geology, v. 2, p. 409-412.

Klein, G. deV., 1975, Sandstone Depositional Models for Exploration for Fossil Fuels: Continuing Education Publishing Co., P. O. Box 2590, Station A, Champaign, Illinois, 109p.

Kraft, J. C., 1971a, Sedimentary facies patterns and geologic history of a Holocene marine transgression: Geol. Soc. America Bull., v. 82, p. 2131-2158.

Kraft, J. C., 1971b, A Guide to the Geology of Delaware's Coastal Environments: Publication No. 2GL039, College of Marine Studies, Univ. of Delaware, Newark, Delaware, 220p.

Kraft, J. C., 1971c, The migration of Holocene sedimentary environments in coastal Delaware, North American continental shelf: Quaternaria, v. 14, p. 23-28.

Kraft, J. C., 1972a, A reconnaissance of the geology of the sandy coastal areas of Eastern Greece and the Peloponnese: Tech. Rept. No. 9, College of Marine Studies, Univ. of Delaware, Newark, Delaware, 158p.

Kraft, J. C., 1972b, Facies relations in Holocene-Pleistocene coastal sediments; models for interpretation of ancient transgressive-regressive sequences (abst.): Am. Assoc. Petroleum Geologists Bull., v. 56, p. 634.

Kraft, J. C., and G. Margules, 1971, Sediment patterns, physical characters of the water mass and foraminiferida distribution in Indian River Bay, coastal Delaware: Southeastern Geology, v. 12, p. 223-252.

Kraft, J. C., R. E. Sheridan, and M. Maisano, 1971, Time stratigraphic units and petroleum entrapment models in Baltimore Canyon Basin of Atlantic continental margin geosyncline: Am. Assoc. Petroleum Geologists Bull., v. 55, p. 658-679.

Kraft, J. C., and R. L. Caulk, 1972, The evolution of Lewes Harbor: Tech. Rept. No. 10, College of Marine Studies, Univ. of Delaware, Newark, Delaware, 58p.

Kraft, J. C., R. B. Biggs, and S. D. Halsey, 1973, Morphology and vertical sedimentary sequence models in Holocene transgressive barrier systems, p. 321-354, in D. R. Coates, ed., Coastal Geomorphology: Publications in Geomorphology, State Univ. of New York, Binghamton, New York, 404p.

Kraft, J. C., and E. A. Allen, 1975, A transgressive sequence of Late Holocene epoch tidal environmental lithosomes along the Delaware coast, p. 39-46, in R. N. Ginsburg, ed., Tidal Deposits, Springer-Verlag, New York, 428p.

Kraft, J. C., and D. F. Belknap, 1975, Transgressive and regressive sedimentary lithosomes at the edge of a late Holocene marine transgression: Extraits des Publications du Congrès, IX Congrès International De Sedimentologie, Nice, p. 87-95.

Kraft, J. C., E. A. Allen, D. F. Belknap, C. J. John, and E. M. Maurmeyer, 1976, Geologic processes and the geology of Delaware's coastal zone; a report to the Executive Dept., Delaware State Planning Office, Dover, Delaware, 394p. Published as "Delaware's Changing Shoreline", Tech. Rept. No. 1, Delaware's Coastal Management Program, Delaware State Planning Office, Executive Dept., Dover, Delaware, 319p.

Kraft, J. C., and C. J. John, 1976, The Geological Structure of the Shorelines of Delaware: DEL-SG-14-76, College of Marine Studies, Univ. of Delaware, Newark, Delaware, 106p.

Krumbein, W. C., and L. L. Sloss, 1963, Stratigraphy and Sedimentation, 2nd. edition: W. H. Freeman and Co., San Francisco, 660p.

Kukal, Z., 1971, Geology of Recent Sediments: Academic Press, New York, 490p.

Kumar, N., 1973, Modern and Ancient barrier sediments; new interpretation based on stratal sequence in inlet filling sands and on recognition of nearshore storm deposits: Ann. New York Acad. Sci., v. 220, p. 245-340.

Kumar, N., and J. E. Sanders, 1970, Are basal transgressive sands chiefly inlet filling sands?: Maritime Sediments, v. 6, p. 12-14.

Kumar, N., and J. E. Sanders, 1972, Sand body created by migration of Fire Island Inlet, Long Island, New York (abst.): Am. Assoc. Petroleum Geologists Bull., v. 56, p. 634.

Kumar, N., and J. E. Sanders, 1974, Inlet sequence; a vertical succession of sedimentary structures and textures created by the lateral migration of tidal inlets: Sedimentology, v. 21, p. 491-532.

Kumar, N., and J. E. Sanders, 1975, Inlet sequence formed by the migration of Fire Island Inlet, Long Island, New York, p. 75-83, in R. N. Ginsburg, ed., Tidal Deposits: Springer Verlag, New York, 428p.

Kwon, H. J., 1969, Barrier islands of the Northern Gulf of Mexico coast; sediment source and development: Coastal Studies Series No. 25, Louisiana State Univ. Press, Baton Rouge, Louisiana, 51p.

Land, C. B. Jr., 1972, Stratigraphy of Fox Hills sandstone and associated formations, Rock Springs Uplift and Wamsutter Arch area, Sweetwater County, Wyoming; a shoreline-estuary sandstone model for the late Cretaceous: Colorado School of Mines Quart., v. 67, No. 2, 69p.

Langford-Smith, T., 1969, Coastal sand barrier: The Australian Geographer, v. 11, p. 176-178.

Lankford, R. R., and J. J. W. Rogers, eds., 1969, Holocene Geology of the Galveston Bay area: Houston Geol. Society, 141p.

Leatherman, S. P., 1976, Quantification of overwash processes: Ph.D dissertation, Dept. of Environmental Sciences, Univ. of Virginia, 244p.

Leatherman, S. P., 1977, Interpretation of overwash sedimentary sequences (abst.): Geol. Soc. America Abst. with Programs, Northeastern section, v. 9, No. 3, p. 292-293.

LeBlanc, R. J., and W. D. Hodgson, 1959, Origin and development of the Texas shoreline: Gulf Coast Assoc. Geol. Soc., Trans., v. 9, p. 197-220.

LeBlanc, R. J., 1972, Geometry of sandstone reservoir bodies: Am. Assoc. Petroleum Geologists Mem. 18, Underground Waste Management and Environmental Implications, p. 133-190.

Leontyev, O. K., 1965, On the cause of the present day erosion of barrier bars: Coastal Research Notes, No. 12, p. 5-7.

Leontyev, O. K., 1969, Flandrean transgression and genesis of barrier bars, in H. E. Wright, ed.; Quaternary Geology and Climate, v. 16, Natl. Acad. Sci. Publ. 1701, p. 146-149.

Leontyev, O. K., and L. G. Nikiforov, 1966, An approach to the problem of the origin of barrier bars: 2nd. Int. Oceangr. Congr., Abst. of Papers, p. 221-222.

Lobeck, A. K., 1939, Geomorphology: McGraw Hill Book Co., New York, 349p.

Logvinenko, N. V., and I. N. Remizov, 1967, Structure of beaches of the sea of Azov and cross-bedding of beach type: Lithology and Mineral Resources, No. 4, July-August, p. 489-494.

Longwell, C. R., ed., 1949, Sedimentary Facies in Geologic History: Geol. Soc. America Mem. 39, 171p.

Markevich, V. P., 1960, The concept of facies: Intern. Geol. Rev., v. 2, No. 5, p. 376-379, No. 6, p. 498-507, No. 7, p. 582-604.

Martins, L. R., 1965, Significance of skewness and kurtosis in environmental interpretation: Jour. Sed. Petrology, v. 35, p. 768-770.

Mason, C. C., and R. L. Folk, 1958, Differentiation of beach, dune, and eolian flat environments by size analysis, Mustang island, Texas: Jour. Sed. Petrology, v. 27, p. 211- 226.

Maurmeyer, E. M., 1974, Analysis of short and long term elements of coastal change in a simple spit system; Cape Henlopen, Delaware: Master of Science thesis, Dept. of Geology, Univ. of Delaware, Newark, Delaware, 149p.

McGee, W. J., 1890, Encroachments of the sea: the Forum, v. 9, p. 437-449.

McKee, E. D., 1948, Classification and interpretation of cross-lamination (abst.): Geol. Soc. America Bull., v. 59, p. 1378.

McKee, E. D., 1957, Primary structures in some Recent sediments: Am. Assoc. Petroleum Geologists Bull., v. 41, p. 1704-1747.

McKee, E. D., and G. W. Weir, 1953, Terminology for stratification and cross-stratification in sedimentary rocks: Geol. Soc. America Bull., v. 64, p. 381-390.

McKee, E. D., and T. S. Sterrett, 1961, Laboratory experiments on form and structure of longshore bars and beaches, p. 13-28, in J. A. Peterson and J. C. Osmond, eds., Geometry of Sandstone Bodies: Am. Assoc. Petroleum Geologists, Tulsa, Oklahoma, 240p.

McMaster, R. L., 1954, Petrography and genesis of the New Jersey beach sands: New Jersey State Dept. Conserv. Geol. Ser. Bull. 63, 239p.

Merrill, F. G. H., 1890, Barrier beaches of the Atlantic coast: The Popular Science Monthly, v. 37, p. 736-745.

Middleton, G. V., ed., 1965, Primary Sedimentary Structures and their Hydrodynamic Interpretation: Soc. Econ. Paleont. Mineral. Spec. Publ. No. 12, 265p.

Middleton, G. W., 1973, Johannes Walther's law of correlation of facies: Geol. Soc. America Bull., v. 84, p. 979-988.

Moiola, R. J., and D. Weiser, 1968, Textural parameters, an evaluation: Jour. Sed. Petrology, v. 38, p. 45-53.

Moiola, R. J., and A. B. Spencer, 1973, Sedimentary structures and grain size distribution, Mustang Island, Texas: Gulf Coast Assoc. Geol. Soc., Trans., v. 23, p. 324-332.

Moody, D. W., and E. B. Van Reenan, 1967, High resolution sub-bottom seismic profiles of the Delaware estuary and baymouth: U. S. Geol. Survey Prof. Paper 575D, p. D347-D352.

Moore, C. A., 1963, Handbook of Subsurface Geology: Harper and Row, Publishers, New York, 235p.

Moore, D. G., and P. C. Scruton, 1957, Minor internal structures of some Recent unconsolidated sediments: Am. Assoc. Petroleum Geologists Bull., v. 41, p. 2723-2751.

Moore, R. C., 1949, Meaning of facies, p. 1-35, in C. R. Longwell, ed., Sedimentary Facies in Geologic History: Geol. Soc. America Mem. 39, 171p.

Morgan, J. P., 1958, Coastal morphologic changes resulting from hurricane Audrey: Proc. Salt Marsh Conf. March 1958, Sapelo Island, Georgia.

Nordquist, R. W., 1972, Origin, development, and facies of a young hurricane washover fan on southern St. Joseph Island, Central Texas coast: Master of Science thesis, Univ. of Texas, Austin, Texas.

Orme, A. R., 1973, Barrier and lagoon systems along the Zululand coast, South Africa, p. 181-217, in D. R. Coates, ed., Coastal Geomorphology, Publications in Geomorphology, State Univ. of New York, Binghamton, New York, 404p.

Otto, G. H., 1939, A modified logarithmic probability graph for the interpretation of mechanical analysis of sediments: Jour. Sed. Petrology, v. 9, p. 62-76.

Otvos, E. G., 1970a, Development and migration of barrier islands, Northern Gulf of Mexico: Geol. Soc. America Bull., v. 81, p. 241-246.

Otvos, E. G., 1970b, Development and migration of barrier islands, Northern Gulf of Mexico; reply: Geol. Soc. America Bull., v. 81, p. 3783-3788.

Owens, E. H., 1974, Barrier beaches and sediment transport in the Southern Gulf of St. Lawrence: Proc. 14th. Coastal Engineering Conf., v. 2, Am. Soc. Civil Engineers, New York, p. 1177-1193.

Perkins, R. D., and P. Enos, 1968, Hurricane Betsy in the Florida-Bahama area; geological effects and comparison with hurricane Donna: Jour. Geology, v. 76, p. 710-717.

Pettijohn, F. J., 1957, Sedimentary Rocks: Harper and Row, Publishers, New York, 718p.

Pettijohn, F. J., P. E. Potter, and R. Siever, 1972, Sand and Sandstone: Springer Verlag, New York, 618p.

Pevear, D. R., and O. H. Pilkey, 1966, Phosphorite in Georgia continental shelf sediments: Geol. Soc. America Bull., v. 77, p. 849-858.

Pierce, J. W., 1969, Sediment budget along a barrier island chain: Sedimentary Geology, v. 3, p. 5-16.

Pierce, J. W., 1970, Tidal inlets and washover fans: Jour. Geology, v. 78, p. 230-234.

Pierce, J. W., and D. J. Colquhoun, 1970, Holocene evolution of a portion of the North Carolina coast: Geol. Soc. America Bull., v. 81, p. 3697-3714.

Pierce, J. W., and D. J. Colquhoun, 1971a, Holocene evolution of a portion of the North Carolina coast; reply: Geol. Soc. America Bull., v. 82, p. 2371.

Pierce, J. W., and D. J. Colquhoun, 1971b, Holocene evolution of a portion of the North Carolina coast; reply: Geol. Soc. America Bull., v. 82, p. 3529.

Pilkey, O. H., and D. M. Richter, 1965, Beach profiles of a Georgia barrier island: Southeastern Geology, v. 6, p. 11-19.

Pirson, S. J., 1970, Geologic Well Log Analysis: Gulf Publishing Company, Houston, Texas, 370p.

Potter, P. E., 1967, Sand bodies and sedimentary environments; a review: Am. Assoc. Petroleum Geologists Bull., v. 51, p. 337-365.

Price, W. A., 1936, Hurricanes, deltas, and resacas (abst.): Texas Acad. Sci. Proc. and Trans., v. 19 (Trans. 1934-1935), p. 30-31.

Price, W. A., 1947, Equilibrium of form and forces in tidal basins of coast of Texas and Louisiana: Am. Assoc. Petroleum Geologists Bull., v. 31, p. 1619-1663.

Price, W. A., 1951, Barrier island, not "offshore bar": Science, v. 113, p. 487-488.

Price, W. A., 1953, Shorelines and coasts of the Gulf of Mexico: Texas A and M University, Contr. in Oceanography and Meteorology, v. 1, p. 191-217.

Price, W. A., 1958, Sedimentology and Quaternary Geomorphology of South Texas: Gulf Coast Assoc. Geol. Soc., Trans., v. 8, p. 41-75.

Price, W. A., 1959, Hurricanes affecting the coast of Texas from Galveston to Rio Grande: U. S. Beach Erosion Board, Tech. Mem. No. 78.

Price, W. A., 1963a, Patterns of flow and channeling in tidal inlets: Jour. Sed. Petrology, v. 33, p. 279-290.

Price, W. A., 1963b, Origin of barrier chain and beach ridge, p. 219, in Geol. Soc. America Abst. for 1962: Geol. Soc. America Spec. Paper 73, 355p.

Psuty, N. P., 1965, Beach ridge development in Tabasco, Mexico: Ann. Assoc. American Geographers, v. 55, p. 112-124.

Psuty, N. P., 1966, The Geomorphology of beach ridges in Tabasco, Mexico: Coastal Studies Institute, Louisiana State Univ., Tech. Rept. No. 30, 51p.

Putnam, J. A., W. H. Munk, and M. A. Traylor, 1949, The prediction of longshore currents: Am. Geophys. Union, Trans., v. 30, p. 337-345.

Ralph, E. K., H. N. Michael, and M. C. Han, 1973, Radiocarbon dates and reality: MASCA Newsletter, Museum Applied Science Center for Archaeology, Univ. of Pennsylvania, v. 9, p. 1-20.

Reineck, H. E., and I. B. Singh, 1973, Depositional Sedimentary Environments: Springer Verlag, New York, 439p.

Resio, D., L. Vincent, J. Fisher, B. Hayden, and R. Dolan, 1973, Classification of coastal environments; analysis across the coast barrier island interfaces: Tech. Rept. No. 5, Dept. of Environmental Sciences, Univ. of Virginia and Office of Naval Research, Geography Programs, Non r-N00014-69-A-0060-0006, 31p.

Rich, J. L., 1923, Shoestring sands of Eastern Kansas: Am. Assoc. Petroleum Geologists Bull., v. 7, p. 103-113.

Rich, J. L., 1926, Further observations on shoestring oil pools of Eastern Kansas: Am. Assoc. Petroleum Geologists Bull., v. 10, p. 568-580.

Rigby, J. K., and Wm. K. Hamblin, eds., 1972, Recognition of Ancient Sedimentary Environments: Soc. Econ. Paleont. Mineral., Spec. Publ. No. 16, 340p.

Rittenhouse, G., 1961, Problems and principles of sandstone body classification, p. 3-12, in J. A. Peterson and J. C. Osmond, eds., Geometry of Sandstone Bodies: Am. Assoc. Petroleum Geologists, Tulsa, Oklahoma, 240p.

Royse, C. F. Jr., 1970, An Introduction to Sediment Analysis: Sediment Analysis, Tempe, Arizona, 180p.

Rudowski, S., and J. Tobolewski, 1974, Barrier island on Gull's Reef, Polish Baltic coast: Coastal Research Notes, v. 4, No. 1, p. 9-12.

Rusnak, G. A., 1960, Sediments of Laguna Madre, Texas, p. 153-196, in F. P. Shepard, F. B. Phleger, and Tj. H. van Andel, eds., Recent Sediments, Northwest Gulf of Mexico: Am. Assoc. Petroleum Geologists, Tulsa, Oklahoma, 394p.

Sabins, F. F. Jr., 1962, How do Bisti and Dead Horse Creek strat traps compare: Oil and Gas Jour., August 13, p. 192-198.

Sabins, F. F. Jr., 1963, Anatomy of stratigraphic traps, Bisti oil field, New Mexico: Am. Assoc. Petroleum Geologists Bull., v. 47, p. 193-228.

Saville, T. Jr., 1950, Model study of sand transport along an infinitely long straight beach: Am. Geophys. Union, Trans., v. 31, p. 555-565.

Schlee, J., E. Uchupi, and J. V. A. Trumbull, 1964, Statistical parameters of Cape Cod beach and eolian sands: U. S. Geol. Survey Prof. Paper 501D, p. D118-D122.

Schuberth, C. J., 1970, Barrier beaches of Eastern America: Natural History, v. 79, No. 6, p. 46-55.

Schwartz, M. L., 1965, Laboratory study of sea level rise as a cause of shore erosion: Jour. Geology, v. 73, p. 528-534.

Schwartz, M. L., 1967, The Bruun theory of sea level rise as a cause of shore erosion: Jour. Geology, v. 75, p. 76-92.

Schwartz, M. L., 1971, The multiple causality of barrier islands: Jour. Geology, v. 79, p. 91-94.

Schwartz, M. L., ed., 1972, Spits and Bars: Dowden, Hutchinson, and Ross Inc., Stroudsburg, Pennsylvania, 452p.

Schwartz, M. L., ed., 1973, Barrier Islands: Dowden, Hutchinson, and Ross Inc., Stroudsburg, Pennsylvania, 451p.

Schwartz, R. K., 1975, Nature and Genesis of Some Storm Washover Deposits: U. S. Army Coastal Engineering Research Center, Tech. Mem. No. 61, Fort Belvoir, Virginia, 69p.

Scott, A. J., R. A. Hoover, and J. H. McGowen, 1969, Effects of hurricane "Beulah", 1967, on Texas coastal lagoons and barriers, p. 221-236, in A. A. Castanares and F. B. Phlegar, eds., Lagunas Costeras Un Simposio: Mem. Simp. Intern. Laguna Costeras, UNAM-UNESCO, Mexico, 686p.

Sears, J. D., C. B. Hunt, and T. A. Hendricks, 1941, Transgressive and regressive Cretaceous deposits in Southern San Juan Basin, New Mexico: U. S. Geol. Survey Prof. Paper 193F, p. 101-121.

Selley, R. C., 1970, Ancient Sedimentary Environments: Cornell Univ. Press, Ithaca, New York, 237p.

Selley, R. C., 1976, An Introduction to Sedimentology: Academic Press, New York, 408p.

Sevon, W. D., 1966, Distinction of New Zealand beach, dune, and river sands by their grain size distribution curves: New Zealand Jour. Geol. Geophys., v. 9, p. 212-223.

Shawa, M. S., ed., 1974, Use of Sedimentary Structures for Recognition of Clastic Environments: Canadian Soc. of Petroleum Geologists, 66p.

Shelton, J. W., 1965, Trend and genesis of lowermost sandstone unit of Eagle sandstone at Billings, Montana: Am. Assoc. Petroleum Geologists Bull., v. 49, p. 1385-1397.

Shelton, J. W., 1967, Stratigraphic models and general criteria for recognition of alluvial, barrier bar, and turbidity current sand deposits: Am. Assoc. Petroleum Geologists Bull., v. 51, p. 2441-2461.

Shelton, J. W., 1973, Models of Sand and Sandstone Deposits; a Methodology for determining Sand Genesis and Trend: Oklahoma Geol. Survey Bull. 118, 122p.

Shepard, F. P., 1952, Revised nomenclature for depositional coastal features: Am. Assoc. Petroleum Geologists Bull., v. 36, p. 1902-1912.

Shepard, F. P., 1960, Gulf Coast barriers, p. 197-220, in F. P. Shepard, F. B. Phlegar, and Tj. H. van Andel, eds., Recent Sediments, Northwest Gulf of Mexico: Am. Assoc. Petroleum Geologists, Tulsa, Oklahoma, 394p.

Shepard, F. P., 1963, Submarine Geology: Harper and Row, Publishers, New York, 557p.

Shepard, F. P., 1964, Criteria in modern sediments useful in recognizing ancient sedimentary environments, p. 1-25, in L. M. J. U. van Straaten, ed., Deltaic and Shallow Marine Deposits: Developments in Sedimentology, v. 1, Elsevier Publishing Company, New York, 464p.

Shepard, F. P., 1973, Submarine Geology: Harper and Row, Publishers, New York, 517p.

Shepard, F. P., and D. G. Moore, 1954, Sedimentary environments differentiated by coarse fraction studies: Am. Assoc. Petroleum Geologists Bull., v. 38, p. 1792-1802.

Shepard, F. P., and D. G. Moore, 1955a, Central Texas coast sedimentation; characteristics of sedimentary environment, recent history, and diagenesis: Am. Assoc. Petroleum Geologists Bull., v. 39, p. 1463-1593.

Shepard, F. P., and D. G. Moore, 1955b, Sediment zones bordering the barrier islands of Central Texas coast, p. 78-98, in J. L. Hough and H. W. Menard, ed.'s, Finding Ancient Shorelines: Soc. Econ. Paleont. Mineral., Spec. Publ. No. 3, Tulsa, Oklahoma, 129p.

Shepard, F. P., and R. Young, 1961, Distinguishing between beach and dune sands: Jour. Sed. Petrology, v. 31, p. 196-214.

Shepard, F. P., and H. R. Wanless, 1971, Our Changing Coastlines: McGraw Hill Book Co., New York, 579p.

Sheridan, R. E., C. E. Dill Jr., and J. C. Kraft, 1974, Holocene sedimentary environment of the Atlantic inner shelf off Delaware: Geol. Soc. America Bull., v. 85, p. 1319-1328.

Shideler, G. L., 1973a, Textural trend analysis of coastal barrier sediments along the Middle Atlantic Bight, North Carolina: Sedimentary Geology, v. 9, p. 195-220.

Shideler, G. L., 1973b, Evaluation of a conceptual model for the transverse sediment transport system of a coastal barrier chain, Middle Atlantic Bight: Jour. Sed. Petrology, v. 43, p. 748-764.

Shideler, G. L., 1974, Evaluation of textural parameters as beach-dune environmental discriminators along the Outer Banks barrier, North Carolina: Southeastern Geology, v. 15, p. 201-222.

Siebold, E., 1963, Geological investigations of nearshore sand transport; examples of methods and problems from Baltic and North Seas; Progress in Oceanography, v. 1, M. Sears, ed., Pergamon Press, New York, p. 1-70.

Sloss, L. L., 1962, Stratigraphic models in exploration: Am. Assoc. Petroleum Geologists Bull., v. 46, p. 1050-1057.

Stamp, L. D., 1922, An outline of the Tertiary geology of Burma: Geol. Mag., v. 59, p. 481-501.

Stapor, F., 1973, History and sand budgets of the barrier island system in the Panama City, Florida region: Marine Geology, v. 14, p. 277-286.

Steno, N., 1669, De Solido intra Solidum naturaliter contento dissertationis prodromus: Florence, 78p.

Summerson, C. H., ed., 1976, Sorby on Sedimentology; a collection of papers from 1851-1908 by Henry Clifton Sorby: Geological Milestones, v. 1, The Comparative Sedimentology Laboratory, Division of Marine Geology and Geophysics, Univ. of Miami, Miami, Florida, 226p.

Swift, D. J. P., 1968, Coastal erosion and transgressive stratigraphy: Jour. Geology, v. 76, p. 444-456.

Swift, D. J. P., 1969, Inner shelf sedimentation; processes and products, p. DS.4.1-DS.4.46, in D. J. Stanley, ed., New Concepts of Continental Margin Sedimentation: Am. Geol. Inst. Short Course Notes, Washington, D. C.

Swift, D. J. P., 1975, Barrier island genesis; evidence from the Central Atlantic Shelf, Eastern U. S. A.: Sedimentary Geology, v. 14, p. 1-43.

Teichert, C., 1958, Concept of facies: Am. Assoc. Petroleum Geologists Bull., v. 42, p. 2718-2744.

Thomas, W. A., and C. J. Mann, 1966, Late Jurassic depositional environments, Louisiana and Arkansas: Am. Assoc. Petroleum Geologists Bull., v. 50, p. 178-182.

Thompson, W. O., 1937, Original structures of beaches, bars, and dunes: Geol. Soc. America Bull., v. 48, p. 723-752.

Thompson, W. W., and R. A. Dalrymple, 1976, A history of Indian River Inlet, Delaware: Shore and Beach, v. 44, No. 2, p. 24-30.

Trask, P. D., 1932, Origin and environment of source sediments of petroleum: Gulf Publishing Company, Houston, Texas, 323p.

Udden, J. A., 1914, Mechanical composition of clastic sediments: Geol. Soc. America Bull., v. 25, p. 655-744.

U. S. Army Coastal Engineering Research Center, 1964, Land against the Sea: Misc. Paper No. 4-64, 43p.

U. S. Army Coastal Engineering Research Center, 1973, Shore Protection Manual, 3 volumes: Suptd. of Documents, U. S. Govt. Printing Office, Washington D.C.

van Andel, Tj. H., and H. Postma, 1954, Recent Sediments of the Gulf of Paria, North Holland: North Holland Publishing Co., Amsterdam, 245p.

van Andel, Tj. H., and D. M. Poole, 1960, Sources of Recent sediments in the Northern Gulf of Mexico: Jour. Sed. Petrology, v. 30, p. 91-122.

van Straaten, L. M. J. U., 1954, Composition and Structure of Recent marine sediments in the Netherlands: Leidse Geologische Mededelingen, v. 19, p. 1-110.

van Straaten, L. M. J. U., 1959, Minor Structures of some Recent littoral and neritic sediments: Geologie En Mijnbouw, v. 21, p. 197-216.

van Straaten, L. M. J. U., 1965, Coastal barrier deposits in South and North Holland, in particular in the area around Scheveningen and Ijmuiden: Mededelingen Van De Geologische Stichting, Nieuwe Serie No. 17, p. 41-75.

van Straaten, L. M. J. U., and Ph. H. Kuenen, 1957, Accumulation of fine grained sediment in the Dutch Wadden Sea: Geologie En Mijnbouw, v. 19, p. 329-354.

Visher, G. S., 1965, Use of vertical profile in environmental reconstruction: Am. Assoc. Petroleum Geologists Bull., v. 49, p. 41-61.

Visher, G. S., 1967, Relation of grain size to sedimentary processes (abst.): Am. Assoc. Petroleum Geologists Bull., v. 51, p. 484.

Visher, G. S., 1969a, How to distinguish barrier bar and channel sands: World Oil, v. 168, No. 6, p. 106-113.

Visher, G. S., 1969b, Grain size distributions and depositional processes: Jour. Sed. Petrology, v. 39, p. 1074-1106.

Walther, J., 1893-1894, Einleitung in die Geologie als historische Wissenschaft: Jena, Verlag Von Gustav Fischer, 3 volumes, 1055p. (The statement of Walther's Law is in v. 3, Chapter 27).

Wanless, H. R., 1976, Intracoastal sedimentation, p. 221-239, in D. J. Stanley and D. J. P. Swift, eds., Marine Sediment Transport and Environmental Management: John Wiley, New York, 602p.

Weber, K. J., 1971, Sedimentological aspects of oil fields in the Niger delta: Geologie En Mijnbouw, v. 50, p. 559-576.

Weidie, A. E., 1968, Bar and barrier island sands: Gulf Coast Assoc. Geol. Soc., Trans., v. 18, p. 405-415.

Weimer, R. J., 1961, Spatial dimensions of Upper Cretaceous sandstones, Rocky Mountain area, p. 82-97, in J. A. Peterson and J. C. Osmond, eds., Geometry of Sandstone Bodies: Am. Assoc. Petroleum Geologists, Tulsa, Oklahoma, 240p.

Weimer, R. J., ed., 1973a, Sandstone Reservoirs and Stratigraphic Concepts I: Am. Assoc. Petroleum Geologists, Reprint series No. 7, Tulsa, Oklahoma, 212p.

Weimer, R. J., ed., 1973b, Sandstone Reservoirs and Stratigraphic Concepts II: Am.Assoc. Petroleum Geologists, Reprint series No. 8, Tulsa, Oklahoma, 216p.

Wells, A. J., 1960, Cyclic sedimentation; a review: Geol. Mag., v. 97, p. 389-403.

Wentworth, C. K., 1929, Method of computing mechanical composition types in sediments: Geol. Soc. America Bull., v. 40, p. 771-790.

Williams, A. T., 1973, Some statistical parameters obtained from beach sediments: Proc. Geol. Assoc., London, v. 84, Part I, p. 9-26.

Woodford, A. O., 1973, Johannes Walther's law of the correlation of facies; discussion: Geol. Soc. America Bull., v. 84, p. 3737-3740.

Yasso, W. E., and E. M. Hartman, 1975, Beach Forms and Coastal Processes: Mesa New York Bight Atlas Monograph No. 11, New York Sea Grant Inst., Albany, New York, 51p.

Ziegler, J. M., 1959, Origin of sea islands of the southeastern United States: Geographical Rev., v. 49, p. 222-237.

Zenkovich, V. P., 1957, The origin of barrier and lagoon coasts: Trudy Inst. Okeanol. Akad. Nauk. SSR (works of the Oceanological Inst.), No. 21.

Zenkovich, V. P., 1959, On the genesis of cuspate spits along lagoon shores: Jour. Geology, v. 67, p. 269-277.

Zenkovich, V. P., 1962, Some new exploration results about sand shores development during sea transgression: De Ingenieur, v. 9, p. 113-121.

Zenkovich, V. P., 1964, Formation and burial of accumulative forms in littoral and nearshore marine environments: Marine Geology, v. 1, p. 175-180.

Zenkovich, V. P., 1967, Processes of Coastal Development, J. A. Steers, ed., Translated by D. G. Fry: Oliver and Boyd, London, 738p.

Zenkovich, V. P., 1969, Origin of barrier beaches and lagoon coast, p. 27-37, in A. A. Castanares and F. B. Phlegar, eds., Lagunas Costeras Un Simposio, Mem. of the Intern. Symp. on Coastal Lagoons, Mexico, UNAM-UNESCO: Universidad Nacional Autónoma De Mexico, 686p.

Zenkovich, V. P., 1971, A theory of the development of accumulation forms in the coastal zone, p. 94-116, in J. A. Steers, ed., Introduction to Coastline Development: M.I.T. Press, Cambridge, Massachusetts, 229p.

Zimmerle, W., 1964, Sedimentology of a Tertiary beach sand in the sub-alpine molasse trough, p. 447-457, in L. M. J. U. van Straaten, ed., Deltaic and Shallow Marine Deposits: Developments in Sedimentology, v. 1, Elsevier Publishing Company, Amsterdam, 464p.

****

APPENDIX - I

GRAIN-SIZE SCALES FOR SEDIMENTS

U. S. Standard Sieve Mesh #		Millimeters	Microns	Phi (Ø)	Wentworth Size Class	
		4096		-12		
		1024		-10	Boulder (-8 to -12Ø)	
Use		256		-8		
wire		64		-6	Cobble (-6 to -8Ø)	
squares		16		-4	Pebble (-2 to -6Ø)	GRAVEL
5		4		-2		
6		3.36		-1.75		
7		2.83		-1.5	Granule	
8		2.38		-1.25		
10		2.00		-1.0		
12		1.68		-0.75		
14		1.41		-0.5	Very coarse sand	
16		1.19		-0.25		
18		1.00		0.00		
20		0.84		0.25		
25		0.71		0.5	Coarse sand	
30		0.59		0.75		
35	1/2	0.50	500	1.0		
40		0.42	420	1.25		
45		0.35	350	1.5	Medium sand	SAND
50		0.30	300	1.75		
60	1/4	0.25	250	2.0		
70		0.210	210	2.25		
80		0.177	177	2.5	Fine sand	
100		0.149	149	2.75		
120	1/8	0.125	125	3.0		
140		0.105	105	3.25		
170		0.088	88	3.5	Very fine sand	
200		0.074	74	3.75		
230	1/16	0.0625	62.5	4.0		
270		0.053	53	4.25		
325		0.044	44	4.5	Coarse silt	
		0.037	37	4.75		
	1/32	0.031	31	5.0		
	1/64	0.0156	15.6	6.0	Medium silt	
Analyzed	1/128	0.0078	7.8	7.0	Fine silt	MUD
	1/256	0.0039	3.9	8.0	Very fine silt	
by		0.0020	2.0	9.0		
Pipette		0.00098	0.98	10.0		
or		0.00049	0.49	11.0		
		0.00024	0.24	12.0	Clay	
Hydrometer		0.00012	0.12	13.0		
		0.00006	0.06	14.0		

(Folk, 1968)