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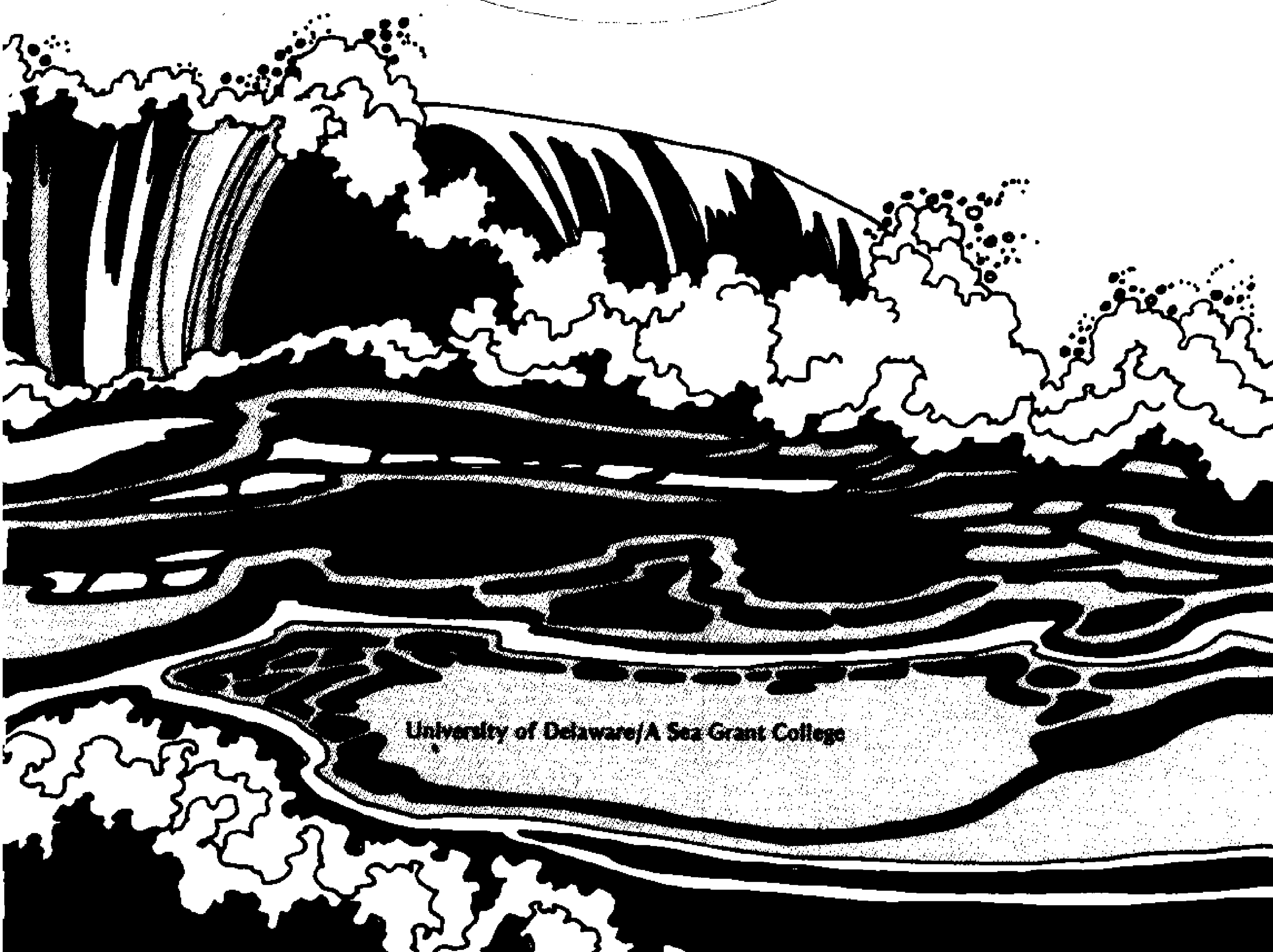
THE GEOLOGICAL STRUCTURE OF THE SHORELINES OF DELAWARE

by
John C. Kraft
and
Chacko J. John

DEL-SG-14-76



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This work is the result of research sponsored by NOAA Office of Sea Grant, Department of Commerce.

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ACKNOWLEDGMENTS

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INTRODUCTION

Coastal studies at the University of Delaware have proceeded in some detail since 1968. A series of publications including: Kraft, 1971a; Kraft, 1971b; Kraft and Margules, 1971; Kraft and Caulk, 1972; Strom, 1972; Elliott, 1972; Kraft and others, 1973; Richter, 1974; Kraft and others, 1974; Sheridan and others, 1974; are examples of this effort (Figure 1). In addition, a number of thesis and Ph.D. dissertation research projects have been completed (Oostdam, 1971; Moose, 1973; Maurmeyer, 1974; Allen, 1974; Belknap, 1975; Weil, 1976; Strom, 1976) or are in various stages of development. These studies detail the nature of the geology of coastal change. Some emphasize the nature of the actual erosion and depositional processes whereas others emphasize details of the physiographic structures, sedimentology, geochemistry, geophysics, and biology-paleobiology of the Delaware coastal zone.

A very large amount of work has been done on coastal erosion in the Delaware area by the U. S. Army Corps of Engineers. Some detailed statements as to rates of erosion, sediment sizes of beach sands, and recommendations for protection of the coastal zone against further erosion have been made. Much of the work of the U. S. Army Corps of Engineers has been analysis of the economics required of a system to protect the beach. In view of this, recommendations are sometimes made to build jetties or groins to interrupt the flow of sediment in the nearshore zone. Other recommendations have been to pump sand onto the beach to restore the beach to its former profile. As recognized by the U. S. Army Corps of Engineers, any such protection measures for the coastal zone, particularly the type of coastal zone that occurs in Delaware, are temporary in nature and must of necessity be considered procedures which need to be renewed. Over the short-term period (a decade or less), it is obvious to the geologist that change is the most pervasive element. This factor has long since been recognized by the U. S. Army Corps of Engineers and by other researchers. On the other hand, it is difficult for the public to recognize and accept this. Accordingly, there has existed considerable amounts of friction between

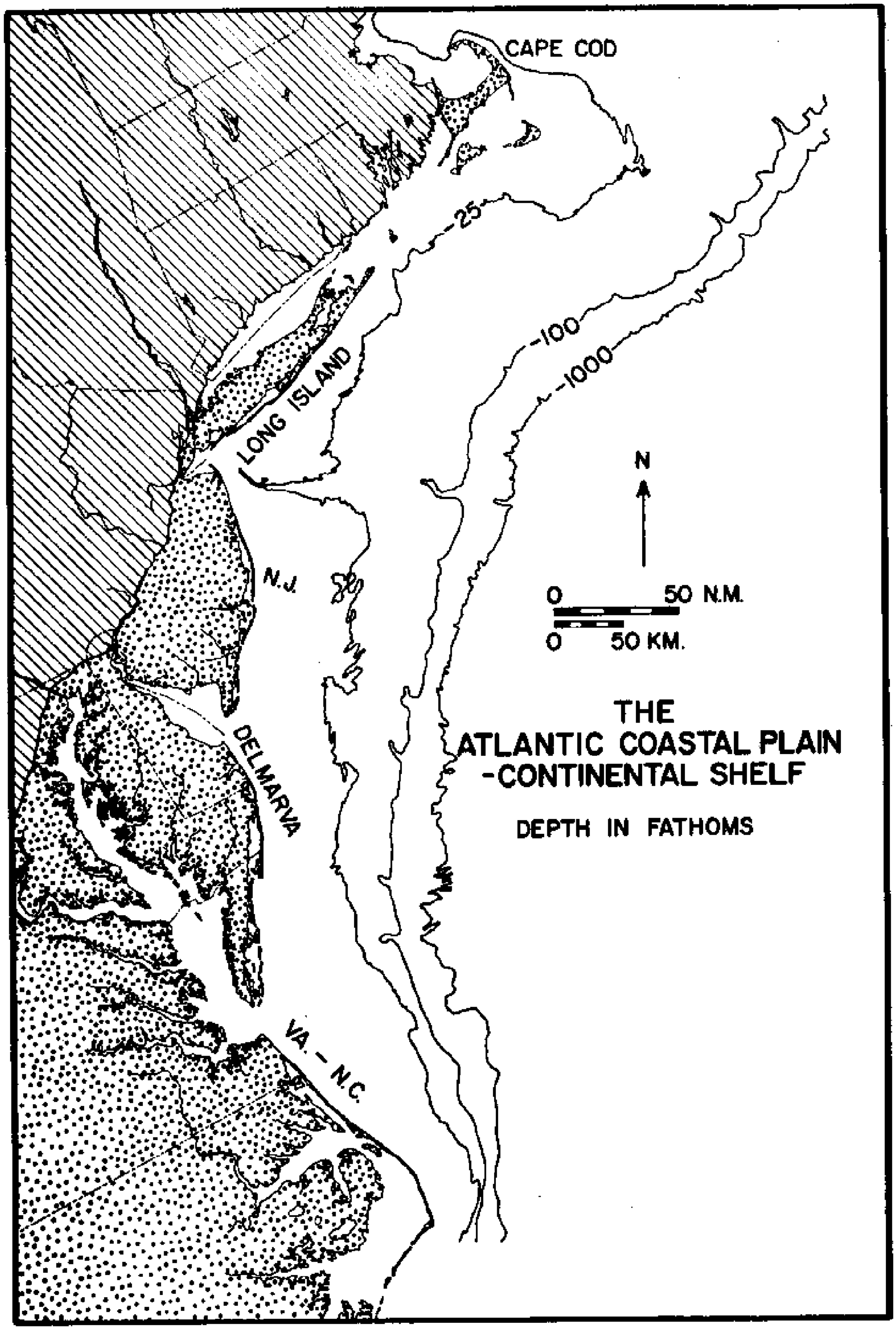


Figure 1. Index to the Atlantic coastal plain-continental shelf

agencies attempting to protect the shoreline position of the Delaware coastal zone and the public who "call for the protection." Concerned citizens often do not realize that the value of the land being protected may frequently be less than the cost of protection.

The Office of the State Planner, the Delaware State Highway Department, and the Division of Natural Resources and Environmental Control of the State of Delaware are also very much concerned with the subject of beach erosion control and protection of the coastal zone. These agencies are directly involved in the giving of contracts for local projects and in evaluating requests for permits to change the nature of the coastal environments. In the past, the Delaware State Highway Department has played a very important role in attempting to build higher dune lines along the open Atlantic Coast. In addition, it has devoted considerable effort to developing highways along the coastal zone, and to protecting them from short- and long-term erosion events. Perhaps most important of all, the Division of Natural Resources and Environmental Control and the Office of the State Planner are concerned with the overall aspects of coastal zoning and the translation of the desires of the citizens of the state into actions effecting the preservation, conservation, or alteration of the coastal zone.

PROCESSES OF COASTAL CHANGE

Obviously wave attack on the immediate beach face of the coastal zone is the most important process active in altering the shape of the coastal physiographic environment. On the other hand, it is too simple to say that waves erode. They also transport sediment in the "littoral drift stream" parallel to the beach, remove sediment from the beach face into the nearshore and adjacent deeper marine environment and sometimes toss sand further up onto the beach and wash it across the berm through the dune line. Thus, depending on the "state of the waves" they may be destructive or constructive in their effects on the shoreline zone. Obviously storm waves cause erosion, a common observation by everyone.

On the other hand, relatively minor waves that appear to be normal may also be causing coastal erosion. By simply standing on the beach and observing whether or not a small "cliff" is being cut or whether or not the beach face is full or convex upwards throughout, one can see whether or not erosion or deposition is occurring. An absolute test of this may be made by anyone who so desires by simply digging a trench across the beach face to determine whether the laminae of the sands are being truncated, or cut by the waves, or whether they are parallel to the beach face and developing or building upwards (Figure 2).

With the advent of the northeaster or hurricane, major coastal erosion occurs. Waves from nearly any direction that come with a frequency greater than ten per minute usually cause coastal erosion. When these waves are high, and are accompanied by high tides, they can cause massive destruction. Observers of the Delaware coastal zone have noted repeated cases of massive destruction of the beach face, berm, and dune line over the past several centuries. However, it appears that coastal erosion is occurring at a more frequent rate over the past decade or two. This in part could be "real" in the sense that the latter part of the decade of the 1960's was accompanied by a sharp rise in relative sea level of approximately 3.5 inches (Hicks and Crosby, 1974). On the other hand, it could be that this observation is due to the fact that more people occupy the coastal zone and are observing it more critically over the last quarter of a century.

Another aspect of coastal change that cannot be ignored is that people are intruding more and more into the coastal zone. Structures are being built across the dune and onto the beach face and berm (witness South Bethany). The building of structures in these positions guarantees their destruction. It becomes only a matter of time as to when this will occur. Simple observation of Delaware's open Atlantic coastal zone and some of the smaller villages or hamlets along Delaware Bay shows that the structures have been placed on washover features. Washover features mean just that: the sand has washed across the barrier toward the rear. This sand is washed across barriers in times of intensive storm activity.

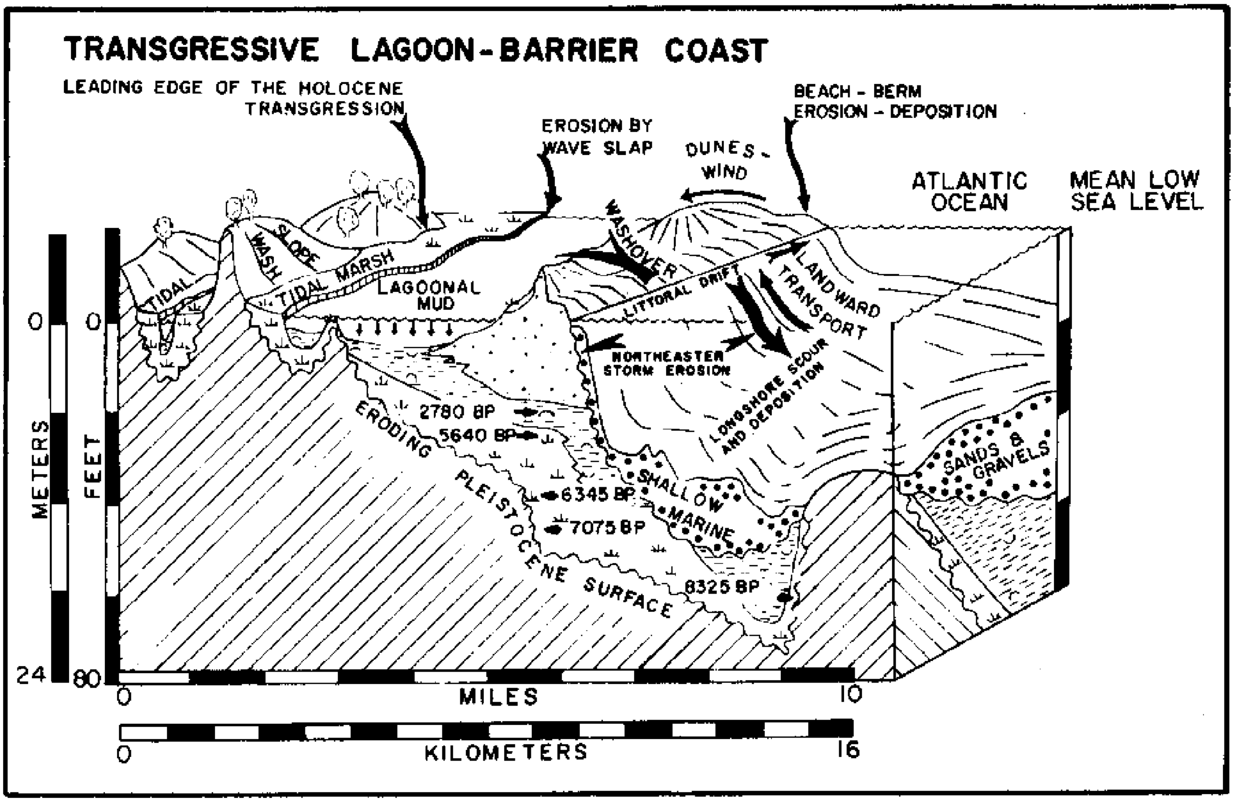


Figure 2. A schematic diagram of elements of coastal change, adapted to the Delaware coast

The mere existence of a washover barrier guarantees that the process occurs, and that it will occur again in the future. This is one reason why planning agencies concerned with controlling coastal erosion pay a great deal of attention to the dune line. By raising the elevation of the dune lines, there is a secondary protection against coastal washover of the barriers. Accordingly, it can be demonstrated easily that it is highly unwise and short-sighted to bulldoze down the dune lines along the open Atlantic coast in anticipation of a more pleasant place to put a structure on the beach facing the sea.

In general, the net littoral drift or flow of sand sediment in the surf zone is northward along the Delaware Atlantic shoreline. From time to time the average littoral drift shifts southward from the vicinity of Bethany Beach. This shift of the point or loci of change between northerly flow and southerly flow is not fully understood. However, the littoral drift flow is dominantly southward from Ocean City, Maryland, toward Cape Charles, Virginia, and dominantly northward from Bethany Beach, Delaware, to Cape Henlopen. On the other hand, littoral drift flows in the Delaware Bay are much more complex. For instance, tidal flow floods water into Delaware Bay in hugh arcs, sweeping around and then turning and ebbing back along the shoreline. For this reason, the dominant littoral drift in the area from Broadkill Beach south into Lewes Harbor is southeast. Littoral drift is not fully understood in terms of direction and magnitude on the other smaller beaches or shoreline regions of Delaware Bay.

It is interesting to note that historically we can show that the direction of littoral drift has changed along the Delaware Bay shorelines. For instance, the massive intrusion or growth of Cape Henlopen northwest around the inner breakwater in the Lewes Harbor area has set a condition which has changed the direction of littoral drift in the Lewes Beach area (Kraft and Caulk, 1972). Accordingly, Lewes Beach which formerly had been an area of building beach is now an area of eroding beach and its littoral drift direction, on the average, has altered. This is a direct effect of man's intrusion into the environment by the construction of the breakwaters in the early and later parts of the 19th century. It cannot, however, be said that this construction has been totally negative in effect; for instance, the shoreline from Lewes Beach eastward to Cape Henlopen is, in part, constructing northward and one of Delaware's massive building shorelines appears here. Some may argue that this is not a positive movement of the beach, in the sense that it is rather a filling-in of the inner harbor at Lewes. Indeed, if no dredging is done, it may be projected that the inner harbor at Lewes might be filled with sediments and become a coastal marsh within the next fifty years. Few people realize that events such as this have occurred in the past in coastal Delaware and will continue to occur. For instance, the area presently covered by the Great Marsh at Lewes, the northern part of Lewes, and the southwestern part of Broadkill Beach was a coastal lagoon in the near past (500 years ago and before). In addition, the Lewes Creek Marsh was a coastal lagoon or backwater only 300-400 years ago. There are also evidences that the marsh at Prime-hook was a coastal lagoon in the very recent past (see Elliott, 1972, and Kraft and others, 1973).

Tides and currents of other types may also have an effect on the formation of the shape of Delaware's coastal zone. This is true particularly in the areas of tidal inlets; for instance, at Indian River Inlet, in the southern part of Delaware's Atlantic shoreline, a very large tidal delta has been constructed by tidal currents flowing between the jetties into Indian River Bay and depositing sand and gravel eroded from the beach face to the south toward Bethany Beach. In addition, subsidiary smaller deltas are forming seaward from the Indian River Inlet, but are commonly planed off by higher wave activity in this area. In addition, before stabilization of the Indian River Inlet, a very large tidal delta intruded into the southeastern third of Rehoboth Bay. It is interesting to note that the flow of sediment northward from Bethany Beach to the Indian River Inlet jetties and then into the Indian River system robs the littoral drift stream of its sediment that normally would flow onward northward to Cape Henlopen. Thus, excessive erosion occurs north of the inlet.

It has been variously estimated that this littoral drift flow of sediment northward is in the order of a net 450,000 cubic yards per year

(Turner, 1968). This means that it is estimated that 450,000 cubic yards of sediment move along the beach past any single point en route from Bethany Beach northward to Cape Henlopen during any particular year. Obviously, for so massive a flow of sand to occur, coastal erosion must be taking place. Some of this sediment is deposited in the Indian River Inlet tidal deltas. The remaining sediment flows northward to Cape Henlopen and thence into the deep channel at the tip of Cape Henlopen, with some flowing in the tidal zone around the Cape into Lewes Harbor. It is hypothesized that some of this sediment also flows seaward on ebb tides onto Hen and Chickens Shoal which lies to the southeast of Cape Henlopen, extending almost southerly to Rehoboth Beach. In this particular case, tidal currents play an important role. They push sediment around Cape Henlopen and into Lewes Harbor and also selectively remove sediment of probable medium-to-fine sand size from the tip of Cape Henlopen onto Hen and Chickens Shoal.

Again, as stated above, the Indian River Inlet situation is one of tidal currents removing sediment from the littoral drift flow and depositing it in the large tidal deltas. The present large tidal delta in Indian River Bay is dissected by deep tidal currents with very strong tidal current flow rates. It is interesting to note that these tidal deltas also shift. A storm or hurricane of northeasterly magnitude is capable of breaking a new channel through a washover barrier and creating a new inlet. Study of the geomorphology of the coastal marsh and barrier area north and south of Indian River Inlet shows a very broad area of ancient tidal deltas. It can be said with fair certainty that the equivalent of Indian River Inlet has shifted from halfway up the barrier along Rehoboth Bay to the southernmost point of Indian River Bay. Charts made in the 17th century suggest direct inlets into Rehoboth Bay. Indeed, the historical inlet that is well known to some of the present residents of the coast used to lie to the north of the present location of Indian River Inlet, which is an artificially dredged location formed in the 1930's.

Study of some of the documents of the 1920's and 1930's regarding washover features in the Indian River Inlet area shows how barriers can change drastically, and how the occupants of the coastal zone might get false ideas as to how barriers work (see references U. S. Army Corps of Engineers). For a long time in the 1920's there existed no permanent inlet into Indian River Bay and into Rehoboth Bay. Rather, the storm tracks were such that major storms did not hit the coast during that time. Sand dunes were piled high and the barrier expanded and grew higher. As a result, salt water no longer flooded into Rehoboth and Indian River Bays. This caused a situation whereby the bays became highly evaporative and highly saline in part. This was known to occur back in Colonial times when Rehoboth Bay was an important source of salt. On the other hand, during times of heavy rainfall in these several decades, the Indian River and Rehoboth Bays became brackish and freshwater in turn. They were, for a time, known for their bass and sunfish population. At this time, farmers began to complain about the rising levels of the bay flooding their adjacent fields. As a result, they began to plow channels through the coastal barriers in an attempt to lower the water levels. Their work was frustrated by the fact that littoral drift systems tended to repair and close immediately the channels they had dug. This led, over the next decade, to legislative action and the eventual construction of the present Indian River Inlet jetty system.

Over the longer term, it is important that we also note that eustatic or absolute levels of the Atlantic Ocean have varied sharply. In addition, the relative level of the ocean-to-land (tectonic or subsidence effect) has varied. For instance, we know that since the end of the last great ice ages, approximately 14,000 years before present, sea level was at least 300 to 340 feet below present (Figure 3). Accordingly, the Delaware shoreline was in the outer third of the adjacent continental shelf 14 millenia ago. The salt water or tidal effects in the present area of Delaware were those of the heads of tidal creeks that penetrated deep into what might be called the ancestral Delmarva peninsula. With the melting of the polar ice caps and in particular the large ice caps across the Canadian Shield area and the Eurasian Shield area, sea level began to rise rapidly. Rates are estimated to have been up to 10 feet per century at first. Thus the shoreline of the ancestral Delmarva peninsula transgressed rapidly landward and upward in space and time. Detailed studies of the rates of sea level change in the Delaware coastal area have been made (Kraft, 1971a and Belknap, 1975). These rates show that over the long-term projection, sea level along coastal Delaware is still rising relative to land. Present long-term rates are approximately 0.25 feet per 100 years. This means that there is a pervasive ongoing effect that requires that the shoreline of Delaware move landward and upward over the longer term in space and time.

Many might argue that this effect is over such a long period that it does not affect us as individuals. Nevertheless, one must consider every storm or every high tide in terms of the fact that each decade it is a fraction of an inch higher and therefore more prone to wash landward greater distances. In addition to the above, Hicks and Crosby (1974) have recently published data on tidal gauges surrounding the North American continent. These show a peculiar pattern of an almost cyclic change of relative sea level to land, with a very persuasive trend upward over the longer-term 70-year period of observation. Specifically, data from the Atlantic City area show that during the late 1960's, over an 8-year period, relative sea level rose approximately 3.3 inches. Such a rate of change over less than a decade must be considered to be catastrophic. It might be pointed out from Hicks' curves that there are also downward directions shown. On the other hand, an averaging line drawn through all of the up-and-down segments of this curve clearly shows a major upward advance of relative sea level to land over the last 70 years. This advance is at a much higher rate than that projected from geologic data from the Delaware coastal area over the past 2,000 to 3,000 years. This is puzzling. We do not yet know whether or not we are simply on the upward cycle of a larger averaging effect over the past several thousand years. The geological data that we use to control our hypotheses are not accurate enough at present to enable us to solve this problem.

Another element of concern regarding Delaware's coastal environment and the relative level of sea is that of sediment compaction and tectonic subsidence; for instance, we know that the valleys of some of the major rivers such as Indian River, Mispillion, Murderkill, St. Jones, and

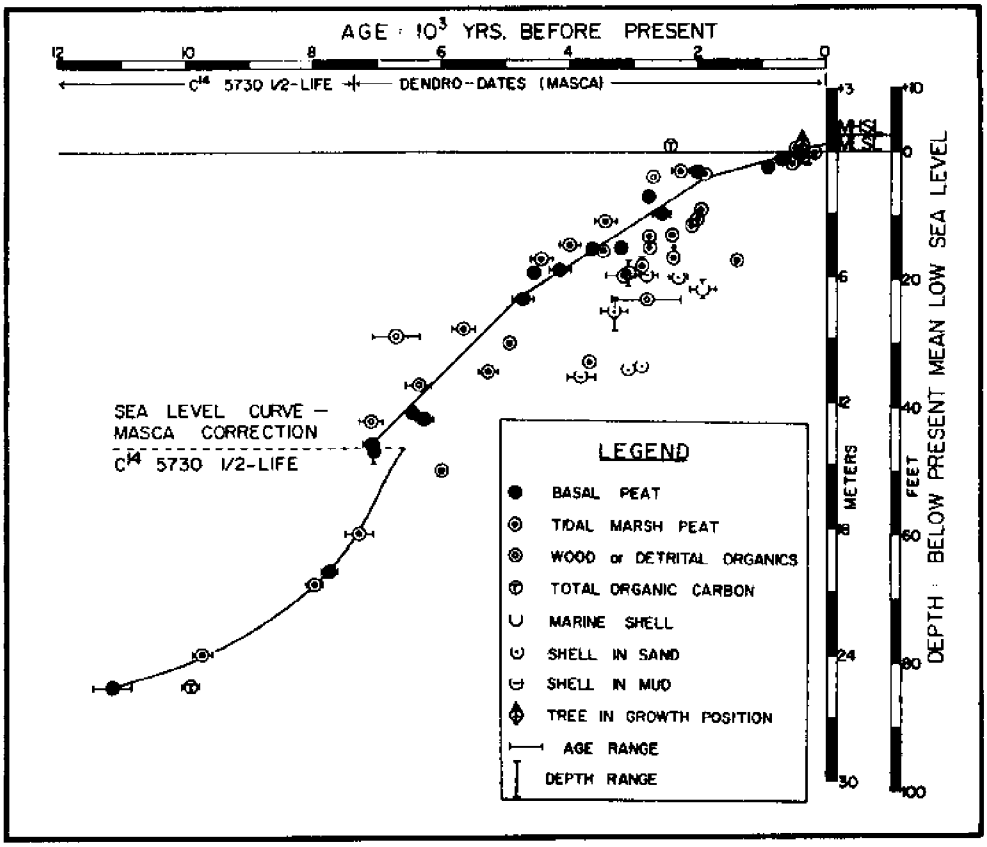


Figure 3. Relative sea level rise curve: the Delaware coast

Appoquinimink Rivers are filled in with sequences of sand and mud up to 100 feet thick. This mud compacts more readily than the sands and gravels of the adjacent highlands. As a result, sedimentary compaction under an area such as South Bowers is much greater than under an area such as North Bowers. This effect may be measured (Belknap, 1975). Another factor is that Delaware and the Delmarva peninsula lie on the westernmost flank of a huge geological feature known as the Baltimore Canyon Trough geosyncline (Figure 4). This sedimentary geosyncline or large basin of ancient sediments extends from Long Island southward to Cape Hatteras and from the Fall Zone along a line from Wilmington to Baltimore and outward to the edge of the continental shelf. It is rapidly subsiding in terms of geologic time.

The entire geosyncline has subsided 40,000 feet along its axis along the outer continental shelf over a 100,000,000-year period. This might be said to be at a rate too small to worry about. On the other hand, there are evidences that the water which has flowed across the outer Atlantic continental shelf as a result of the melting of the world's ice caps has pressed down on the shelf and increased the rate of subsidence of the Baltimore Canyon Trough geosyncline an extra 180 feet over the past 15,000 years. There presently appears to be a geologic hinge or structure near the present Delaware shoreline. Radiocarbon dates from shells and peat that were deposited in a coastal configuration approximately 75 miles offshore at depths greater than 300 feet are equal to those of similar materials that were deposited in the Delaware coastal area in the tidal creeks and lagoons at similar times and at depths of approximately 100 feet (Emery and Garrison, 1967). Accordingly, there appears to be a tilting of the shelf downward at least several hundred feet over the last 14,000 years. It is not yet certain whether or not this has partially affected the coastal zone and the Delmarva peninsula.

Another important process of coastal change in the Delaware coastal zone is that of wind and resultant dunes. A brief stroll along the Delaware coast will show that winds have been active in piling sand up along the parallel coastal dunes from Dewey Beach southward to Bethany Beach. In addition, observation of the area of Cape Henlopen from Whiskey

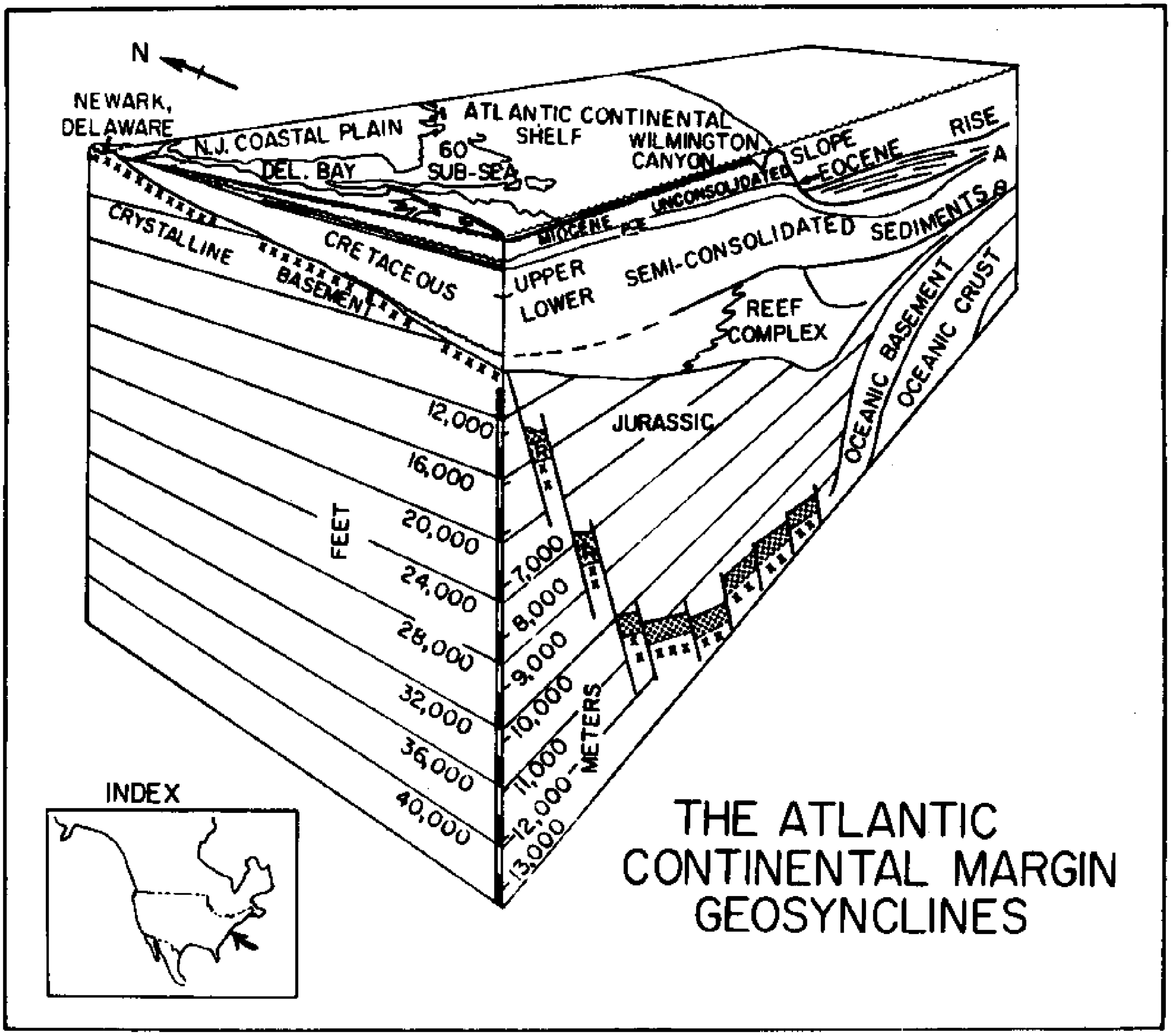


Figure 4. The Baltimore Canyon Trough geosyncline. Note that Delaware lies on this extreme northwest flank and is less subject to extremes of subsidence typical of the axis area.

Beach northward to the tip of the Cape and thence onward to the town of Lewes shows very high dune sequences. The strong winds that frequently sweep the Delaware shoreline pick up the dry sand washed ashore along the beach face and across the berm and remove it into the coastal dunes which are so common in Delaware. In some areas, the dunes cannot build to great heights. This is because coastal storm activity is so great and the washover process proceeds with such great frequency that storm washover waves destroy the incipiant dunes before they can form. The great exception to this has been the dunes that have been constructed around Cape Henlopen. In this area, winds from the northwesterly to southeasterly quadrants have all been active in blowing sand away from the beach and into the dunes. Accordingly, they are the highest along the coast. As previously stated, dunes can very easily be destroyed by washover processes caused by storms. On the other hand, should coastal dunes be built high enough, they form an effective barrier against flooding. The very existence of a high coastal dune means that storm waves must erode through it before they can get to houses and other man-made structures that should logically be positioned behind the dunes. It is for this reason that it is so important that the public be aware of the problems of building on the dunes and of removing the dunes in the immediate shoreline area. It is an absolute certainty that an area without coastal dunes on a washover barrier will in fact be washed over by storm waves. Accordingly, any structures located there should be capable of withstanding the force of waves of hurricanes. If not, then their destruction over a fifty- to a hundred-year period is assured.

THE DELAWARE COAST

This report utilizes data of cumulative works over the past decade by various people in the Department of Geology at the University of Delaware. Profiles or geologic cross sections of the highly varied elements of Delaware's coastal zone have been contrasted in a uniform manner related to air photos in a mosaic of the Delaware coast. It is

Figure 5. LANDSAT-1 (ERTS) photo of coastal Delaware and New Jersey

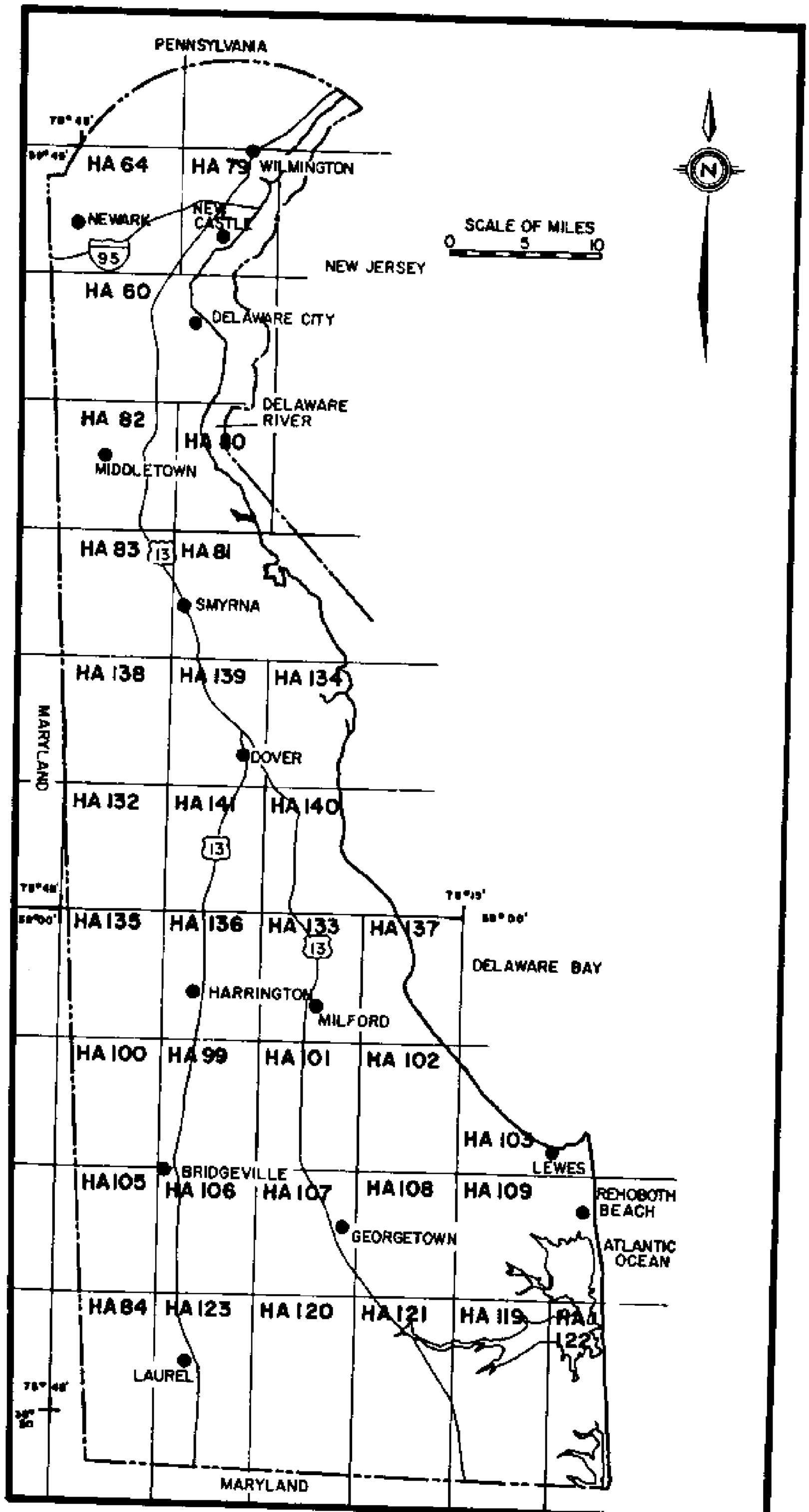


Figure 6. Index map to the Hydrologic Investigation Atlases (Soils Maps) prepared co-operatively by U.S. Geological Survey, Delaware Geological Survey, & Delaware State Highway Department (Published by U.S. Geological Survey, Reston, Virginia)

believed that the presentation of these fairly detailed geological cross sections will be of use to the public and to planners and developers of the coastal zone. As may be seen in Figure 1, the Delmarva peninsula lies on the western flank of the Atlantic coastal plain-continental shelf structure of the Middle Atlantic Bight or "Virginian Sea." Almost the entire continental shelf is submerged at the Long Island area. On the other hand, increasing amounts of coastal plain are exposed above sea level as one proceeds southward from Long Island across the New Jersey peninsula, the Delmarva peninsula, and onward to the Cape Hatteras area where a fairly large portion of the Atlantic coastal plain-continental shelf structure is emerged from the sea. The axis of the previously mentioned Baltimore Canyon Trough geosyncline extends slightly to the west of and parallel to the 100-fathom contour.

Figure 5 shows a LANDSAT-1 (ERTS) satellite photograph of the coastal Delaware area. The color shown is false color. One can quickly see the entire drainage system of the Delmarva and southern New Jersey area with its logical extensions into the "drowned valleys" of the tidal streams of Delaware. The present drainage system is one that is very ancient in aspect; it is gradually being flooded by relative sea level rise across the peninsula. Figure 6 is an index to the highly useful Hydrologic Investigation Atlases (soils maps) which show detail of surface geology and geomorphology of the entire Delaware coastal zone.

Figure 7 is an index map to Delaware Bay and to coastal morphology. In Figure 7, the coastal marshes have been emphasized in black to show that a great portion of the geomorphic elements of the coastal zone of Delaware is in fact tidal wetlands and lagoons, not stable highland. A much lesser portion of the coastal zone is the sandy barriers between the coastal lagoons and tidal wetlands and the waters of Delaware Bay and the Atlantic coast. Viewed from this point, the fragility of the Atlantic and Delaware Bay coastal sandy barriers is emphasized. They are, as we have said before, merely washover barriers formed by sand being eroded up and across the marsh or barrier during times of storm. These relatively thin and fragile barriers may also be considered as rapidly moving geomorphic features, in the sense that they are eroding in the surf zone and being washed across and developed upwards and landwards. This can be very distressing to occupants of the coastal zone. In the long run, over the centuries, it means that present coastal positions will cease to be coastal positions and beach front lots must be considered to be short-term or ephemeral. However, more important to us is the fact that the coastal zone is rapidly altering, over decades, or even very short periods of time during major coastal storm events.

It is interesting to hypothesize that, should sea level continue to rise in a relative fashion to land as it has over the past ten thousand years, then most certainly in another several thousand years our Delaware coastal zone will be many miles inland. In the longer-term geologic time, which probably does not matter to us, the entire Delmarva peninsula may be submerged. During the last major rise of sea level along the Atlantic coast, with the ending of the second last previous glaciation in time approximately 80,000 to 100,000 years before present, the shoreline in the Delmarva area extended across the Delmarva peninsula approximately in a line through the Smyrna-Dover region. Almost all the sediment observed to have been deposited by this previous high stand of sea in a time called the Sangamon Age is marine from Dover southwards. The very flat plains of Sussex County are plains of deposition of sand and silts in a shallow sea bottom and in coastal dunes, barriers, and marshes.

Another detail, seen in Figure 7, is the morphology of the bottom of the nearshore Atlantic Ocean and Delaware Bay. Most visible is the linear element that extends from the Delaware River to the south across Delaware Bay and thence southeastward to the southeast corner of the map. This is the depression or channel eroded by the ancestral Delaware River over the last 14,000 to 80,000 years. The ancestral Delaware River had eroded its base level downward to such a point that tidal waters occurred in the Delaware coastal area approximately 10,000 years ago, up the Delaware River and its tributaries (e.g., the Mispillion, St. Jones, Murderkill, and Indian Rivers) to beyond Philadelphia. Essentially then, the morphology of the bottom of Delaware Bay and of the nearshore Delaware

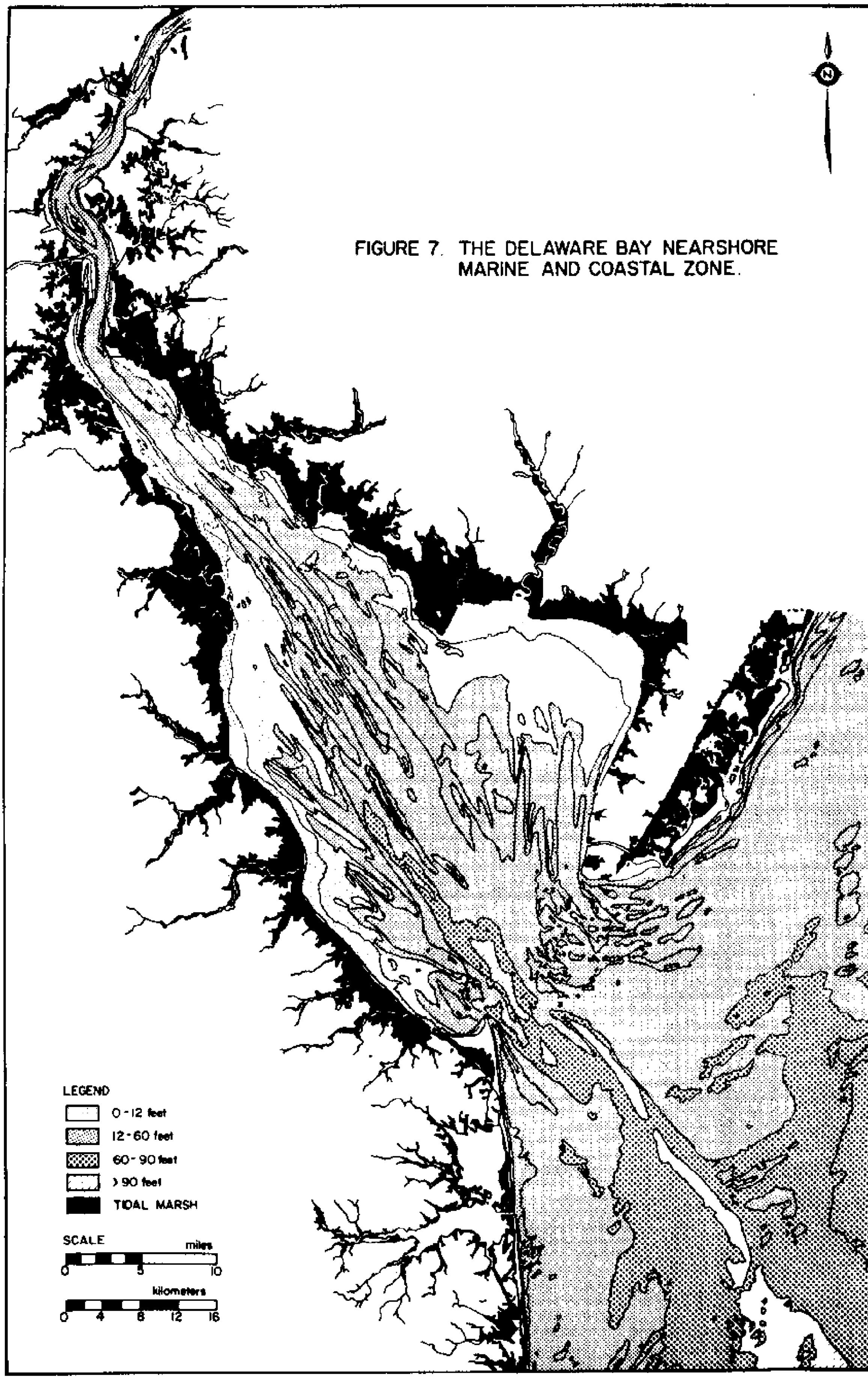


FIGURE 7. THE DELAWARE BAY NEARSHORE MARINE AND COASTAL ZONE.
LEGEND
0 - 12 feet
12 - 60 feet
60 - 90 feet
> 90 feet
TIDAL MARSH
SCALE
miles
0
5
10
kilometers
0
4
8
12
16

coastal area is a relict of the past 80,000 years. It has simply been partially eroded and covered by sediment and water as the sea level rose during the Holocene Epoch time (the past 10,000 years).

If we view Cape Henlopen and look to the southeast at the minus 60-foot contour line, we can see a line similar in shape to that of the present Cape Henlopen and Delaware coast. In addition, some broad indentations occur south from this area east of Rehoboth Bay and east of Indian River-Assawoman Bay. It is believed that these shapes or submarine features are probably the ancestral position of Cape Henlopen and the coastal lagoons and barriers perhaps 6,000-7,000 years ago. Similarly, one can trace the deep channels across the southern Delaware Bay northward into the Delaware River, northwesterly into the St. Jones-Murderkill system, and into the Broadkill and Mispillion River systems. Ancestral Cape May shows up as a broad shoaling area at approximately minus 60 feet below the present sea level southward and southeasterly from its present position.

Further examination of Figure 7 shows that we can subdivide the coastal zone of Delaware into various geomorphic classifications; for instance, in the northernmost part of the state, between the site of Wilmington and the Pennsylvania border, the coastal zone of Delaware includes a tidal river, the Delaware River, and the flat area leading to a sharp change in topography at the hills of the Delaware Piedmont or Crystalline province. The coastal zone here is very linear and narrow; nevertheless a coastal zone of marshes has existed here in the past. Presently this area is mainly developed with the Governor Printz Boulevard, I-495, the Penn-Central Railroad, several power transmission lines and a modest amount of fill. Accordingly, only very small elements of the original coastal environment remain.

The mouth of the Christina River is the northernmost area of major coastal tidal marshes developed in Delaware. These tidal marshes penetrate a great distance inland across the Delmarva peninsula to Churchman's Swamp and further. Essentially, from the edge of the Piedmont at Wilmington southward to the New Castle County-Kent County line, the area is one of a meandering tidal river with coastal tidal marshes against a heavily dissected highland coastal plain. This is the area in which the softly rounded hills of New Castle County drop off sharply to the narrow coastal plain of tidal marshes such as at Delaware City. Southward from the Chesapeake and Delaware Canal to the area at Woodland Beach, the smoothly rounded highlands are bordered by extensively developed broad tidal marshes. Here the Delaware River is much wider and shows stronger effects of drowning by relative sea level rise. In this area, large stretches of highlands merge with the edge of the lower Delaware River in very narrow points.

Still further south, starting with the Duck Creek-Bombay Hook area, broad tidal marshes are developed along the bay shore of Kent and Sussex County to the site of the town of Lewes. This major coast borders on the Delaware Bay itself, a broad tidal-water body with very strong tidal currents. Here again the tidal marshes are concentrated around major stream systems such as Duck Creek, the St. Jones River, the Murderkill River, the Mispillion River, and the Broadkill River. Again it is by the drowning of these river valleys by relative sea level rise that the marshes have formed and penetrated landward deeply into the Delmarva peninsula.

Many interesting elements are shown by examination of the cross sections of this area; for instance, in the Primehook and great marsh areas at the southernmost part of Delaware Bay, there is clear evidence that open bodies of water or lagoons, similar to Rehoboth Bay and Indian River Bay existed there in the past several thousand years. Indeed, the infill of these lagoons may have been as recent as only a few hundred years before present. The next major geomorphic province to the south is that of the Cape Henlopen complex, extending roughly from the Roosevelt Inlet area southward to the North Shores area north of Rehoboth Beach. Here a cuspate foreland and simple spit protrude into the deeper waters of Delaware Bay and the Atlantic Ocean. They are being sharply eroded on the Atlantic Ocean side and built northward from the tip of the Cape to the easterly edge of the town of Lewes. Historic records clearly show that formerly part of this spit-building process extended northward as far as Primehook. It has been the alteration by man of the Lewes Harbor area that caused a cut-off of this flow of sediment northward through Broadkill Beach and on to Primehook. Accordingly, currents have reversed and the littoral drift is now erosive and flowing southward along Broadkill Beach, Beach Plum Island, and the major portion of Lewes Beach.

The towns of Lewes and Rehoboth Beach are on a highland which was adjacent to the open edge of Delaware Bay up to about three or four thousand years before present. Accordingly, the ancient scarp or shoreline extends from Lewes in a sharp line or edge southward to Rehoboth Beach. This can still be observed by traveling along the Lewes-Rehoboth Canal. More important, however, the location of the highlands of older (Sangamon Age circa 80,000-100,000 years before present) marine and coastal sediments that formed the relative highland surface of Rehoboth Beach explained the emplacement of the city. The city is located on land up to 25 feet above sea level. Accordingly, it is much more protected against the effects of the short-term events of severe storms. Nevertheless, the point of intersection of the highlands with the beach face is one of major erosion. Indeed, it could be said that over the long-term period, the erosion of the beach at Rehoboth provides a major portion of sediment for the beaches of Delaware's Atlantic coast. A similar highland occurs southward at Bethany Beach and again is the reason for the development of a town site. These highlands are relatively safe locations for coastal construction because they are not affected by massive storms, other than by winds and extremely high tides and waves. Even so, the slowness of erosion of the beach face area protects much of the town landward from the immediate shore zone.

Southward from Rehoboth Beach lie Rehoboth Lagoon and Indian River Lagoon, interrupted by a highland at Bethany Beach, and thence Assawoman Lagoon. These are typical coastal lagoons with a barrier between them and the Atlantic Ocean. The barrier is relatively narrow, low-lying, formed in part by a lagoonal tidal marsh and in part by washover sand features brought across the barrier and into the coastal lagoons by storm wave action. In addition, small dunes are built up but are usually not maintained at high levels. A single storm -- the 1962 storm event -- removed most of the original dunes. A major contribution to this area has been the Highway Department's redevelopment of these dunes in an attempt to protect the low-lying coast. Much of this coast is fortunately not occupied by man. It is an area in which it can be guaranteed that major storm washovers will occur over the longer-term event. Certainly, as events indicated in 1962, washover of these low-lying barriers occurred. Deep holes were scoured out, structures were removed, and geomorphic features altered. Only very specially designed structures can survive such strong storm actions.

As indicated earlier, these coastal lagoons (Rehoboth Bay and Indian River Bay) are like coastal lagoons that once existed under Lewes Creek marsh, the Great Marsh at Lewes, and Primehook Marsh. Whether or not they will eventually infill and become broad tidal flats to be followed by coastal tidal marshes is uncertain. Certainly such an event would take hundreds of years to occur. In addition, so long as there is a strong current flow through the bays, it is unlikely that such a thing will occur. It is also interesting to note that it is the process of relative sea level rise or landward migration of the sea upward and landward that keeps the lagoons open and clear bodies of water. Were they allowed to stay in their present position for a long period of time (centuries), with only sediment washing into them, then eventually they would fill and be destroyed. An indication of their eventual fate may be seen by looking at the tip of Cape May on the easterly side. As can be seen here the coastal lagoons are relatively narrow and interconnected by meandering tidal channels. Much of the area that was once a broad coastal lagoon in the Cape May vicinity of New Jersey is now broad coastal marsh with relatively small isolated bodies of water and marshy islands. This is the ultimate fate of the Delaware coastal lagoons if the present marine transgression does not continue at its relatively high rate.

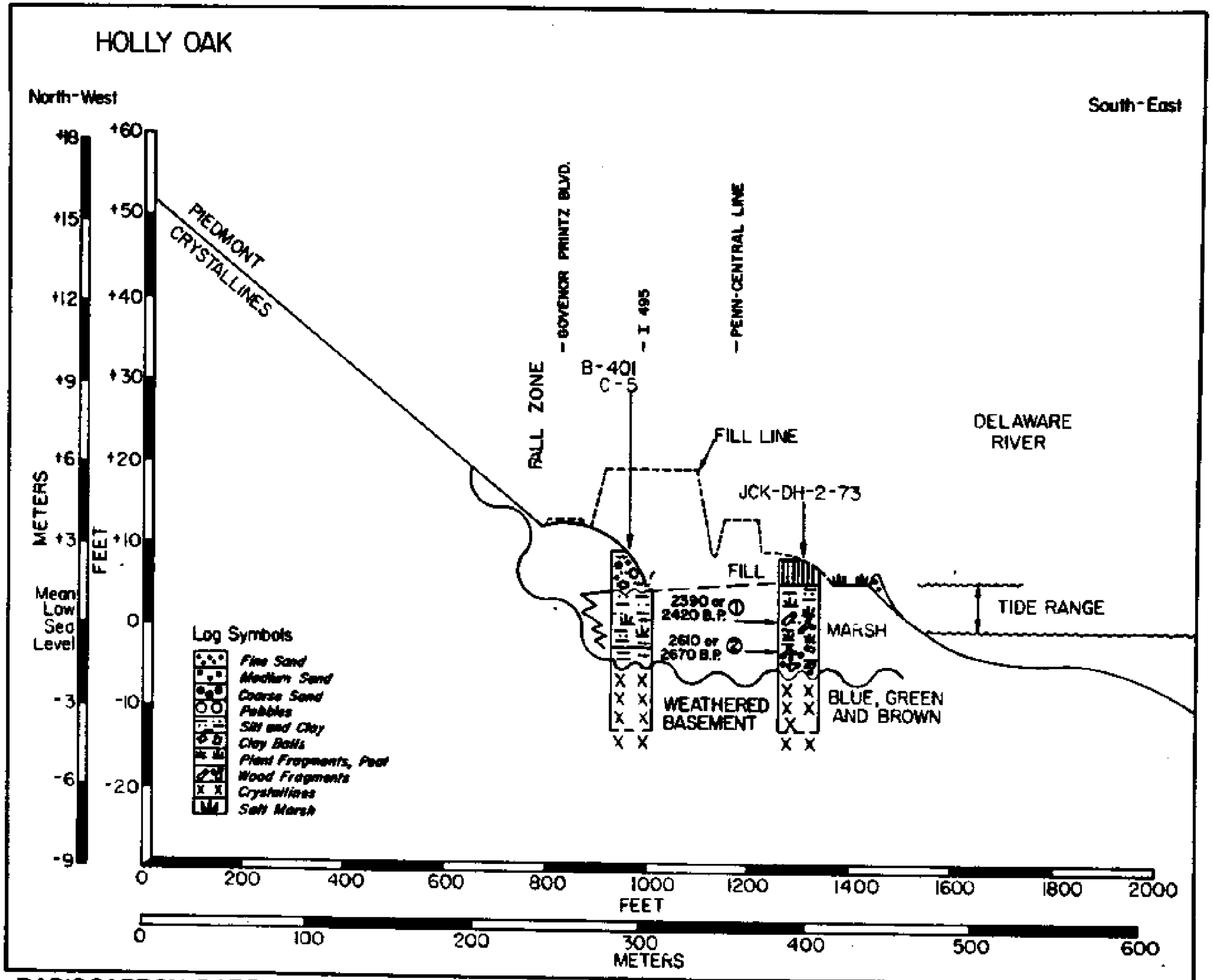
FIGURE 8. THE DELAWARE PIEDMONT, HIGH COASTAL PLAIN, AND CHRISTINA RIVER MARSHES

GEOLOGICAL CROSS-SECTIONS OF THE COASTAL ZONE

The Delaware Estuary -- The Bay and Lower River

This report will now discuss in considerable detail geologic cross sections constructed through the coastal zone of Delaware (Figure 1). Observations are made on the nature of the geomorphic setting, the interpretations of relatively recent geologic history and any indications of change in terms of the shorter-term event that might effect man. Figure 8 shows the upper tidal Delaware River along northern Delaware. This is the area of joining of the tidal Delaware River with the Delaware Piedmont or Crystalline province. The Delaware Piedmont comprises hills that rise to greater than 400 feet above sea level. As may be seen in the photograph mosaic, the bulk of the Piedmont area here is covered by a developed city because of its desirability for industrial and housing uses. The heavy housing and industrial development continues southward across the Brandywine River and in part across the Christina River southward to the area of the Delaware Memorial Bridge.

Figure 9, a geologic cross section across the Piedmont-Fall Zone and Delaware River near Holly Oak shows the nature of the very small coastal zone area in the extreme north of Delaware. It should be noted at the outset that the line of cross section chosen is meant to be one typical of the area under discussion. However, movement laterally for a very short distance and drill holes to confirm these structures show considerable variance. This point will be emphasized in discussions later on the North Bowers-South Bowers area, an area of extreme geologic difference. From the cross section (Figure 9), it can be seen that the area is one of considerable alteration by man. Governor Printz Boulevard, I-495, the Penn-Central system, and other industrial development has covered much of the natural coastal zone of this area. Nevertheless, by drilling test holes through this area, we can determine what the area was like before industrialization. As may be seen in Figure 9, the area is underlain by coastal marsh muds. These tidal marsh muds were deposited from approximately 2700 years before present to present time. Presently small coastal tidal marshes and extremely small sand barriers



RADIOCARBON DATES ARE SHOWN IN CALENDAR TIME MASCA CORRECTIONS: RADIOCARBON YEARS, 5568 - 1/2 LIFE = ① 2355 ± 85 B.P. ② 2450 ± 85 B.P.

Figure 9. Geologic cross section Piedmont-Fall Zone-Delaware River: Holly Oak, Delaware. The line of cross section is shown in Figure 8.

occur in a natural state in very rare locations such as those near Holly Oak. However, for this stretch of the Delaware River-Delaware coastal zone, nearly all of the remainder of the natural setting is gone.

Further south, a broad coastal marsh has developed. This coastal marsh encompasses the mouth of the Christina River and the area southward to Pigeon Point near the Delaware Memorial Bridge. These broad coastal marshes have now been heavily developed, e.g., the Edgemoor area to the north and the area at the mouth of the Christina River (Figure 8). Some of the natural marsh still exists along the river and extends backward to the Churchman's Swamp near Newport. Data was not available to us regarding the depth or thickness of marsh materials at the Christina River area; however, based on our studies for the south, it might be assumed that the marsh here is at least 50-60 feet thick, indicating tidal waters in this area at least back to 6,000 or 7,000 years before present. It is interesting to note that the Delaware Memorial Bridge spans the Delaware River at one of its narrow points in terms of highlands coming close to the edge of the Delaware River on both the Delaware and the New Jersey side.

On the right in Figure 10, the coastal plain of New Jersey is shown. This coastal plain is also penetrated in part by tidal rivers and coastal tidal wetlands. However, in the area immediately adjacent, a ridge of Cretaceous age (± 100,000,000 years ago) sediment forms a highland equivalent to that of the area south of the Delaware Memorial Bridge on the Delaware side. Photo-mosaic Figure 10 shows the area from Pigeon Point and Delaware Memorial Bridge southward to Pea Patch Island and Fort Delaware. This area of coastal plain merging with the tidal Delaware River is one of relative highlands deeply dissected but smoothly rounded and merging with coastal tidal marshes such as those at Red Lion Creek and just south of New Castle. In this part of Delaware and New Jersey, one can note that areas of development are usually along the highlands, whereas the coastal marshes are only rarely intruded upon by industrial development. Pea Patch Island itself is an area of a major early American fortification. Much of the island is formed by sediment accretion in historic times, and a great portion of the marsh is less than 150 years old.

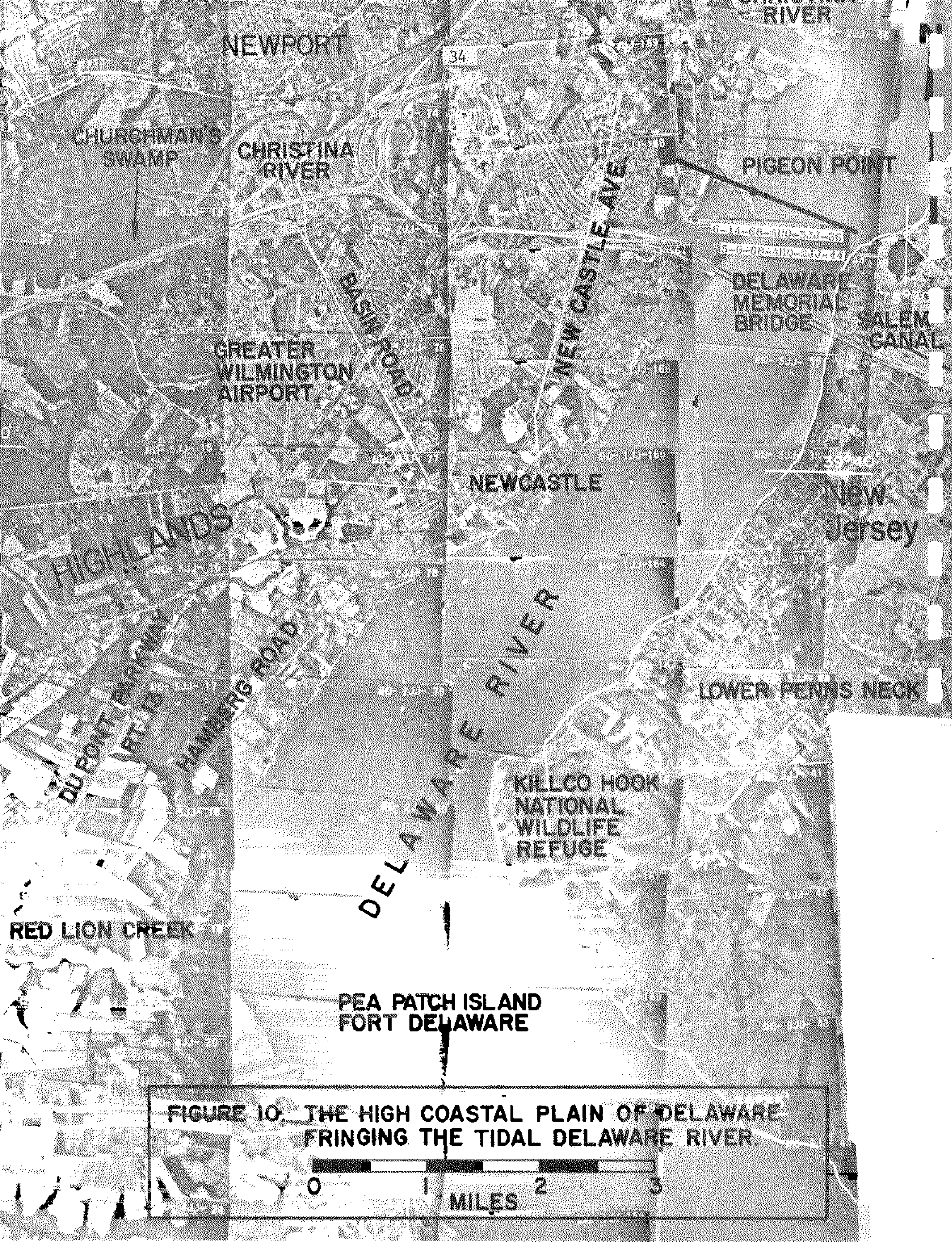


FIGURE 10. THE HIGH COASTAL PLAIN OF DELAWARE FRINGING THE TIDAL DELAWARE RIVER.

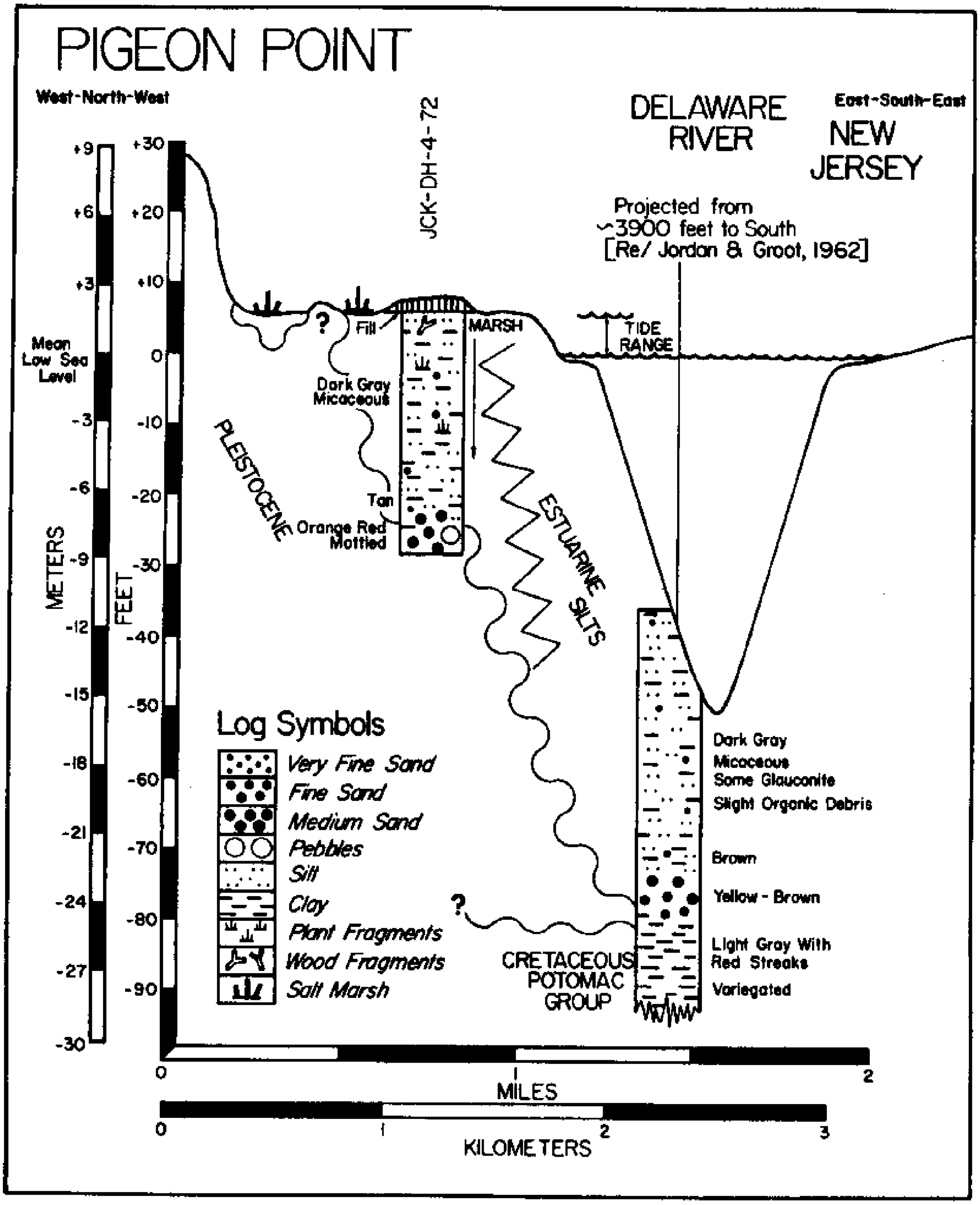


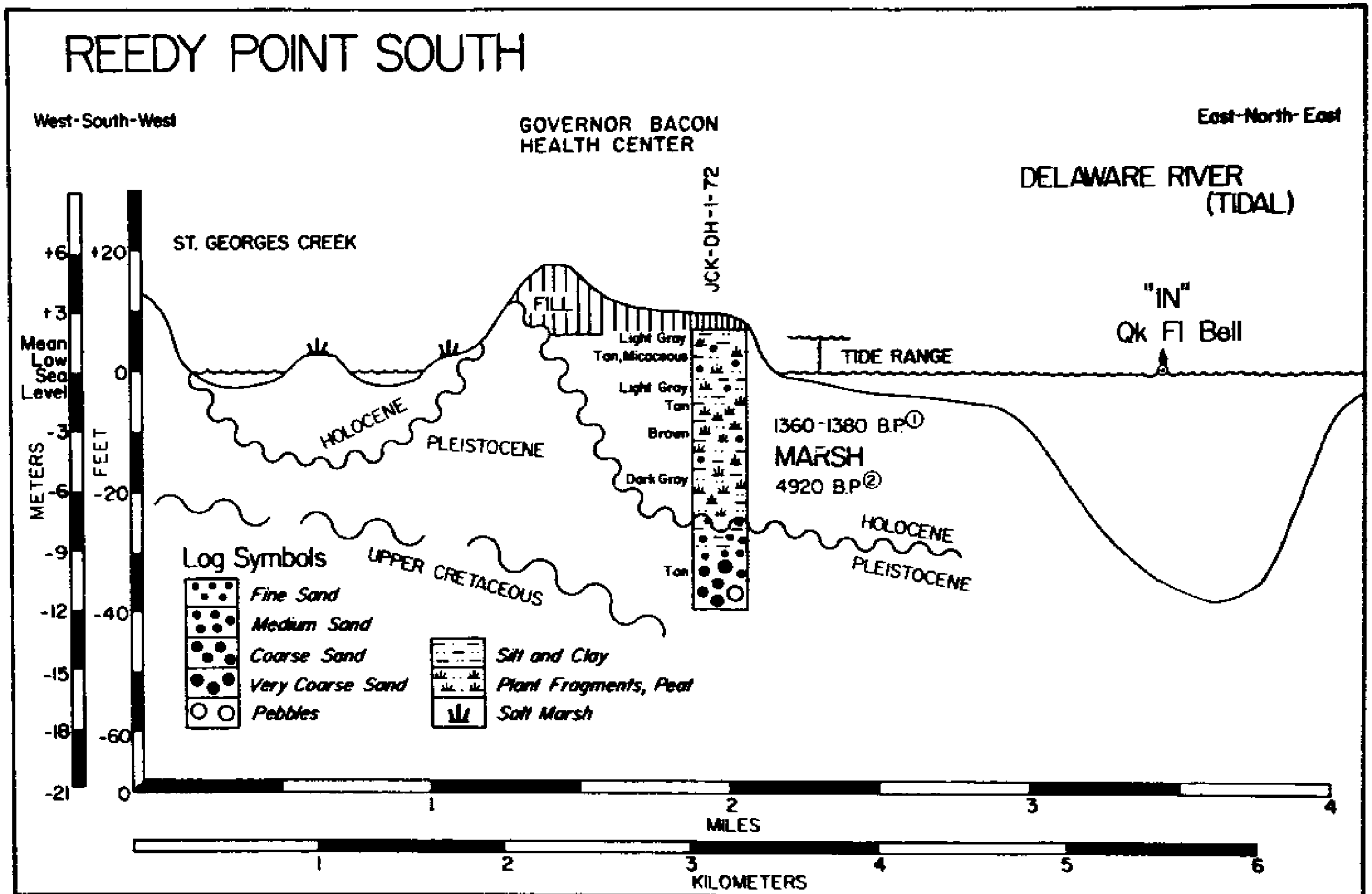
Figure 11. Geologic cross section Pigeon Point, Delaware. See Figure 10 for line of cross section.

Figure 11 shows a geologic cross section through the Pigeon Point area. This figure gives a better idea of the magnitude of the transgression of the marine from its low point 10,000 years ago to present. The channel of the Delaware River is approximately 50 feet below present sea level. However, the channel of the ancestral Delaware River, the river of 12,000 to 14,000 years ago, was incised to about 80 feet below present sea level. Accordingly, at least 30 feet of silt have filled in this tidal river since the time that sea level began to rise and tidal flow intruded into the ancestral Delaware River valley. A test boring in the Pigeon Point area (JCK-DH-4-72) penetrated a coastal marsh mud to about -20 feet. This indicates that the adjacent highland coastal plain drops off relatively sharply under the coastal marshes toward the base of the previously existing ancestral Delaware River. Probably very few of the marshes of this particular map area are very much thicker or deeper than shown in the test boring at Pigeon Point. However, as emphasized before, sharp or rapid variations exist. For instance, at the mouth of Red Lion Creek, the tidal marsh sediment may be considerably thicker than at Pigeon Point.

Figure 12 shows an air photo-mosaic of the area from Delaware City and the Chesapeake and Delaware Canal southward to the Appoquinimink River marshes. The area shown on this figure is one of deeply incised valleys cutting a dendritic pattern into the coastal plain highlands. Streams such as the Appoquinimink River, Augustine Creek, and St. Georges Creek formerly had eroded headward nearly halfway across the Delmarva peninsula. With the drowning of these valleys by relative sea level rise, tidal marshes extend up the valleys for great distances. On the other hand, the coastal plain highlands are relatively high above sea level here and extremely well drained.

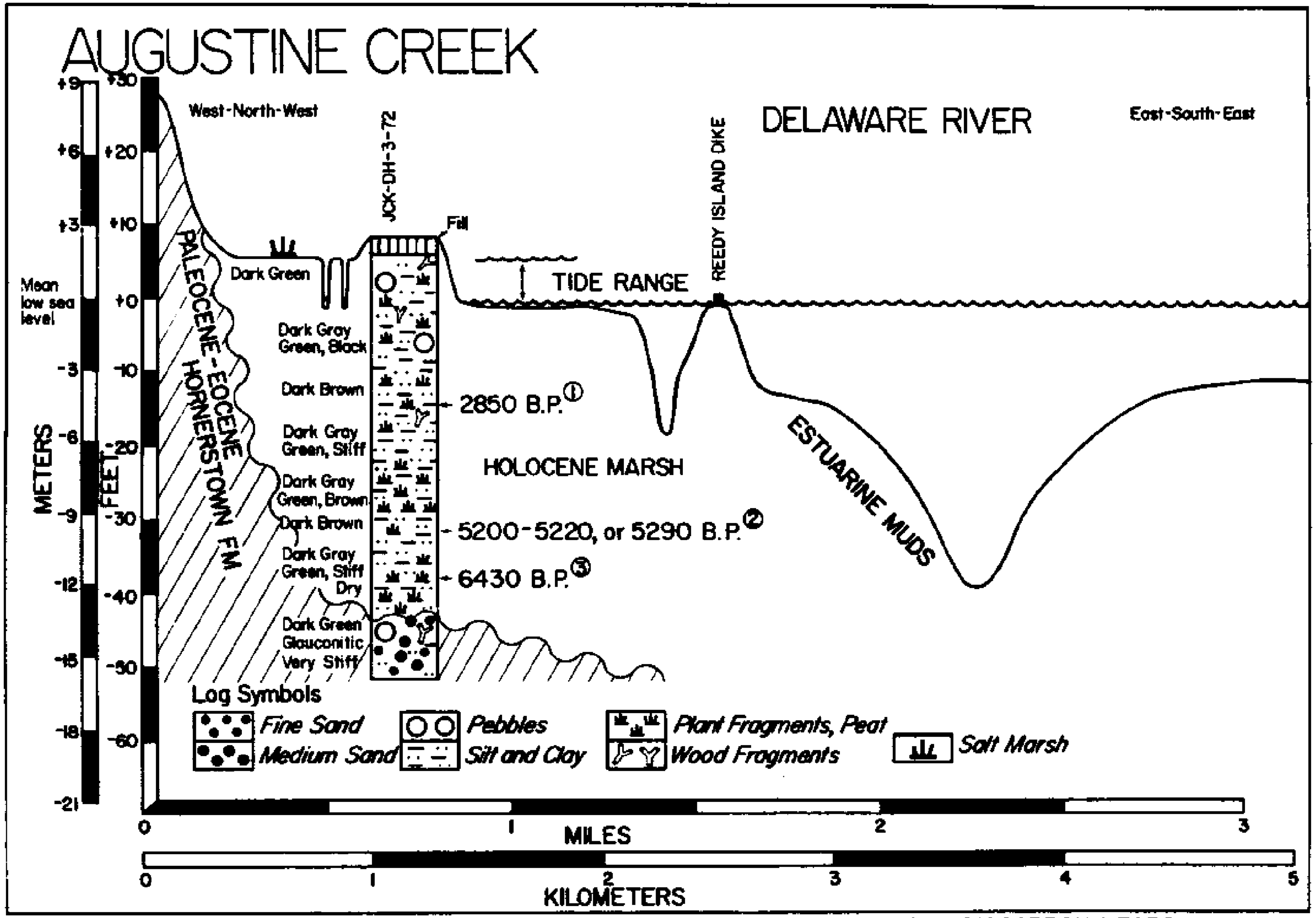
Figure 13 shows a geologic cross section in the area of Reedy Point. Here, as at Pigeon Point further north, the coastal marsh was found to be about 25 feet thick. Some radiocarbon dates obtained from marsh peats in this area show that the marsh was extant here 4920 years before present and has continued to present. Since a great deal of fill has been placed in recent years in the Reedy Point area, its

FIGURE 12. THE HIGH COASTAL PLAIN OF DELAWARE WITH BROAD COASTAL MARSHES FRINGING THE TIDAL DELAWARE RIVER AND ITS TRIBUTARIES.



RADIOCARBON DATES ARE SHOWN IN CALENDAR TIME MASCA CORRECTIONS: RADIOCARBON YEARS; 5568 - 1/2 LIFE =
① 1410 ± 90 B.P. ② 4265 ± 95 B.P.

Figure 13. Geologic cross section, Reedy Point, Delaware. The line of section is shown in Figure 12.



RADIOCARBON DATES ARE SHOWN IN CALENDAR TIME MASCA CORRECTIONS: RADIOCARBON YEARS, 5568 - 1/2 LIFE ① 2685± 90 B.P. ② 4515±100 B.P. ③ 5600±100 B.P.

Figure 14. Geologic cross section, Augustine Creek, Delaware. See Figure 12 for line of cross section.

natural features have been subdued by the fill and by foundations for the new bridge, by the Governor Bacon Health Center, and by the dredgings of the Chesapeake and Delaware Canal.

Further south, at Augustine Creek, the coastal tidal marsh proved to be 45 feet thick (Figure 14). Marsh conditions extend downward to 45 feet below present sea level. Radiocarbon dates on coastal peats in this area date back to 6430 years before present. A continuous sequence has been dated in this particular area. This tells us that coastal tidal marshes existed in the area with an advancing and rising relative level of sea from over 6500 years before present to present. Evidently the process continues. Accordingly, the marsh surface in a broad marsh area such as Augustine Creek should be considered to be rising in an amount equivalent to the presently ongoing relative change in sea level. Again one can observe a relatively sharp drop-off from the highlands of 30+ feet above sea level to the coastal tidal marsh. Tidal ranges in this area are up to 6 feet; accordingly, tidal currents flow along the edge of the coastal wetlands and have a considerable effect on transporting sediments.

Essentially, the St. Georges Creek area, Augustine Creek area, and Appoquinimink marsh are the beginning of the formation of the very broad and extensive tidal marshes of southern New Castle County and Kent and Sussex Counties. Over a great portion of this area, only very thin sandy beaches are developed. One of these may be seen at the southernmost part of the air photo-mosaic, Figure 12. These are not properly referred to as washover barriers as only a very little amount of sediment flows along the littoral drift stream of these shorelines. Rather, these shorelines are eroded ones, as sediment is winnowed and transported by high-tide flow landward across the marsh surfaces and up the tidal creeks to the tidal limit. The reason for there being no sandy beaches over most of this area is that the entire shoreline (the area of erosion) is comprised of mud and very little sand. There are no significant sources of sand developed from which erosion of sand into the beach system can be developed. The closest that one comes to highlands against the sea is the area north of Silver Run and at Augustine Beach. Here a muddy sandy beach system is partially developed.

Figure 15 is an air photo-mosaic of the area from the Silver Run and Appoquinimink River marshes southward to the border of Kent County and the Smyrna River. Broad marshes continue over this area. Many of the marshes are typical of those further south and north and continue along the axes of the stream valleys which extend deep into the Delmarva Peninsula. However, several of these marshes, such as tidal Cedar Swamp marsh, are slightly different. These are marshes that are strongly controlled by tidal flow. They bifurcate from the mouth or entrance into the marsh area instead of forming tree-like branches so typical of the other larger tidal creeks of Delaware. The highlands of this area are not so high as those further to the north. Typical highlands adjacent to the coastal swamps and marshes are only 20 feet above sea level. Accordingly, these highlands are much more subject to flooding in extreme storm events in which the storm tide plus winds push water landward and up the tidal valleys.

In addition, as may be observed from the westerly and southerly part of the air photo-mosaic, the land is poorly drained. The small round black or gray spots indicate poorly drained areas and, in some cases, small ponds. These are typical of an emerged sea bottom, and are a product of the sediments formed on the bottom of the sea in this area approximately 80,000 years before present in the Sangamon geologic age, when the Atlantic Ocean was much higher than its present level. More pervasive, however, is the fact that the drainage system of the tributary streams to the Delaware River form the axes along which the present sea level rise extends coastal wetlands or swamps. The Delaware River is now somewhat broader as it emerges into the broader northern part of Delaware Bay.

Again, very few sandy beaches exist and they are ephemeral. Little sand-size sediment is available for littoral transport. Here again the entire shoreline area is one in which almost no highland merges with the waters of the Delaware River. Collins Beach is an exception. A small amount of sand may be eroding from this area and it forms a very narrow beach.

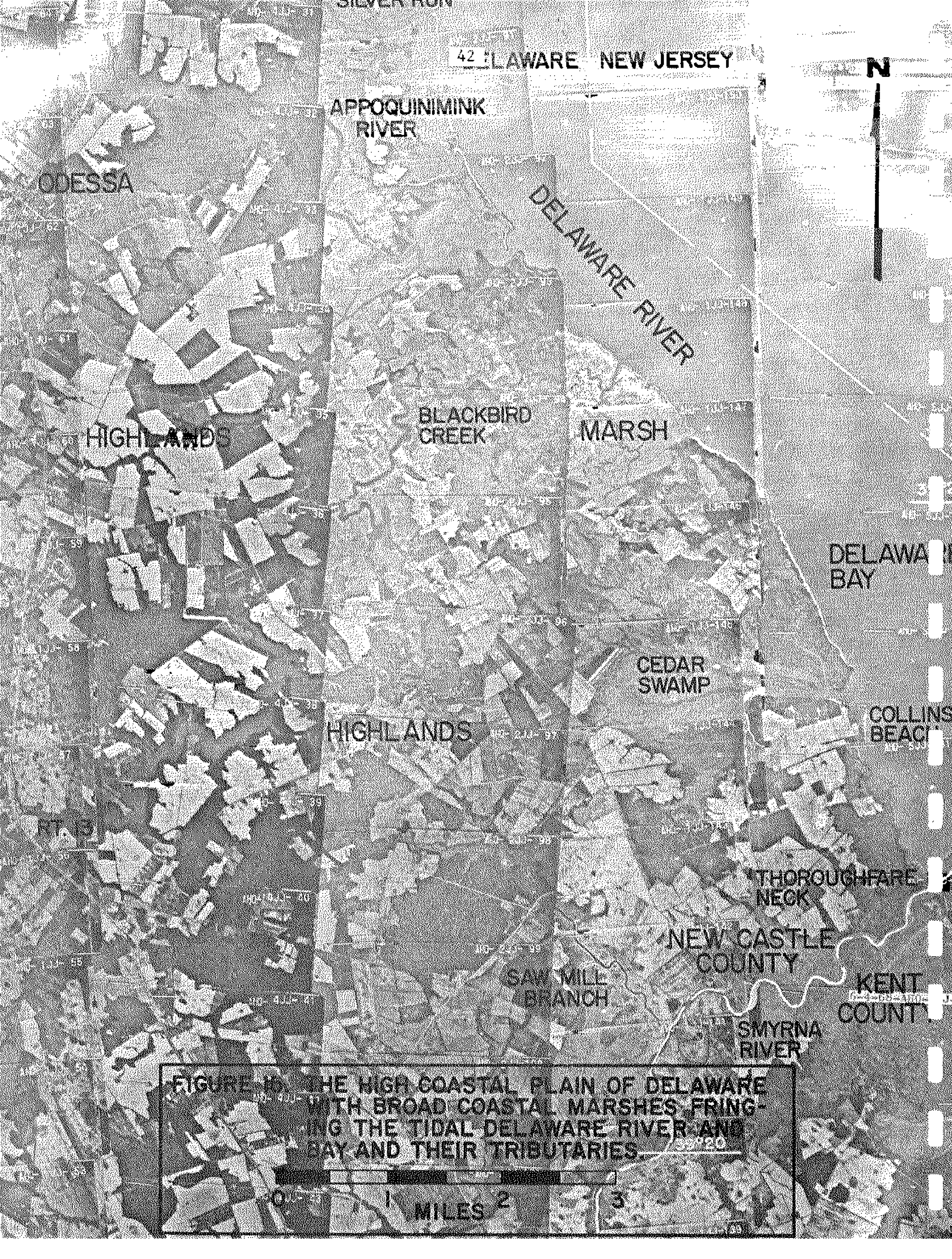


FIGURE 16. THE HIGH COASTAL PLAIN OF DELAWARE WITH BROAD COASTAL MARSHES FRINGING THE TIDAL DELAWARE RIVER AND BAY AND THEIR TRIBUTARIES.

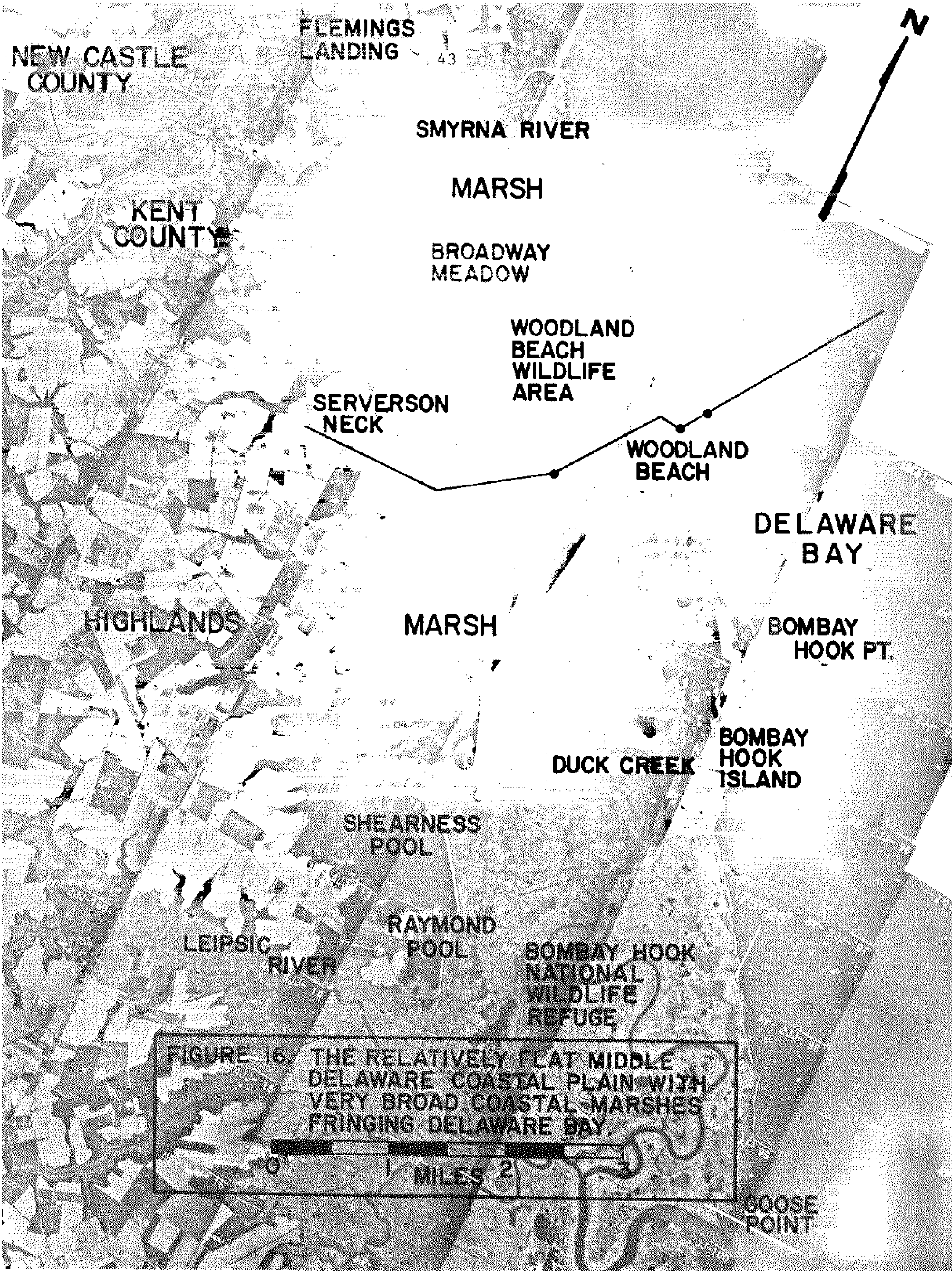
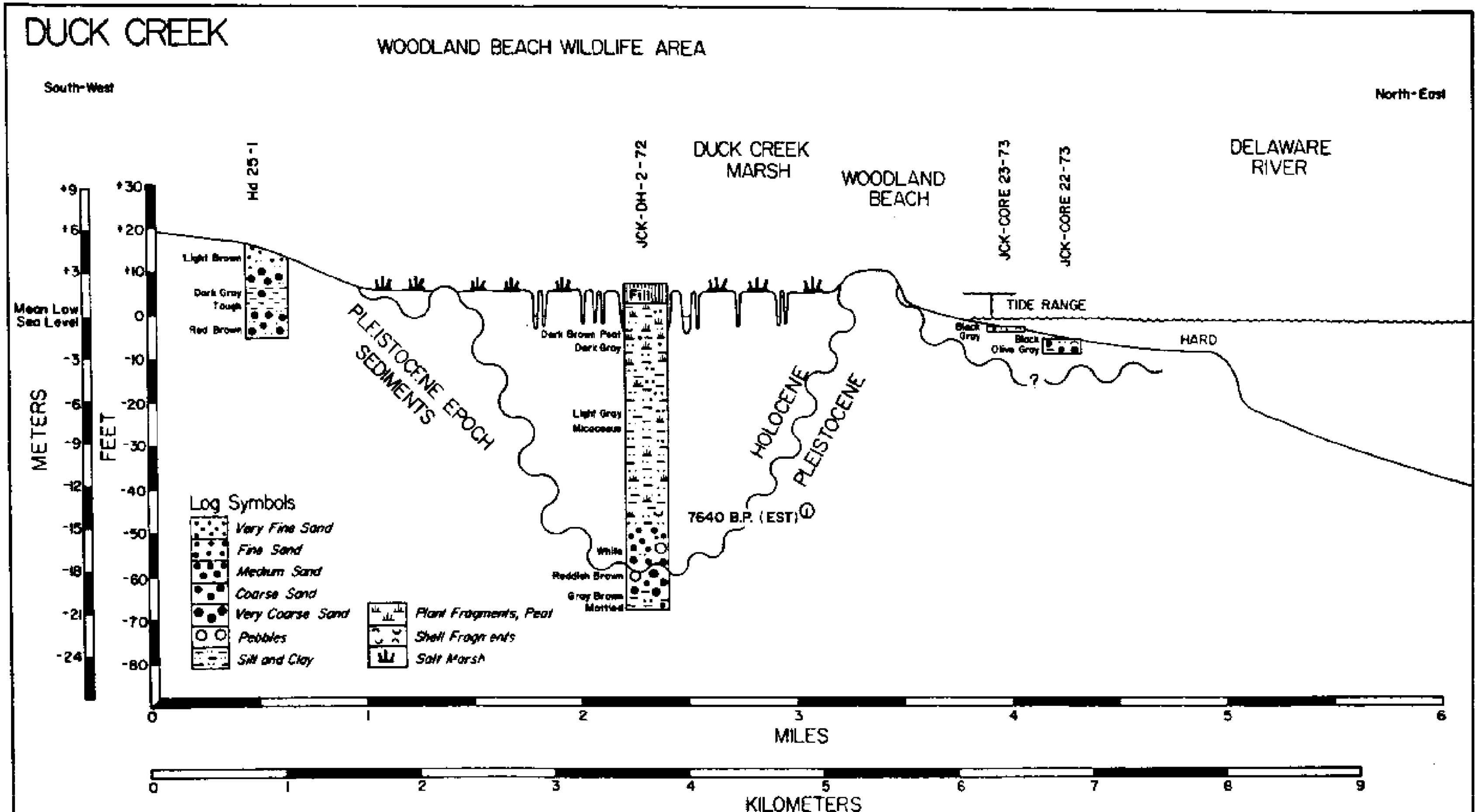


FIGURE 16. THE RELATIVELY FLAT MIDDLE DELAWARE COASTAL PLAIN WITH VERY BROAD COASTAL MARSHES FRINGING DELAWARE BAY.

Figure 16 is an air photo-mosaic from the Smyrna River southward to the Leipsic River. This is an area of one of Delaware's broadest and most extensively developed coastal marshes. The Bombay Hook National Wildlife Refuge is located here. In addition, a wildlife area has been developed at Woodland Beach. These broad marshes are an infill of the upper part of a fairly extensive earlier expansion of the Delaware Bay or alternate channel of the ancestral Delaware River. Again, the highlands are pointing toward the Delaware Bay but merging with the marsh along the midline north-south through Figure 16. The highlands are very similar to highlands further south that are in contact with the erosional forces at the shoreline of Delaware Bay. In this area, however, with the exception of Bombay Hook Island and Woodland Beach, almost no highlands are exposed to the erosion of waves of Delaware Bay and thus very little sand is supplied to the beach system.

Woodland Beach and Bombay Hook, being the exception, are potential areas of development. One is associated with the wildlife refuge and the other is presently a resort area. However, one must cross marsh muds of up to 60-feet thickness to get to Woodland Beach.

Figure 17 is a cross section across the northern part of Duck Creek marsh through Woodland Beach. This shows the geologic structure that has given rise to the possibility of putting a resort at Woodland Beach. An ancestral valley of Duck Creek or possibly an alternate ancestral Delaware River channel formed part of the streams flowing through the broadway meadow area extended through the line of section. This ancestral stream excavated a relatively narrow and deep (more than 60 feet below present sea level) ancestral valley. Indeed, this valley is deep enough for the ancestral Delaware River to have flowed through this marsh area and thence around Bombay Hook Island to the south and on out to Delaware Bay. However, there is no direct evidence of this. Woodland Beach is a hill to the east of this valley that still remains above sea level. However, by rise of relative sea level and growth of marsh landward and upward it has become isolated, as has Bombay Hook point, and has now become an island between upper Delaware Bay and the



RADIOCARBON DATE IS SHOWN IN CALENDAR TIME MASCA CORRECTION: RADIOCARBON YEARS, 5568 - 1/2 LIFE = 6835 ± 115 B.P.

Figure 17. Geologic cross section, Duck Creek-Woodland Beach, Delaware. The line of cross section is shown in Figure 16.

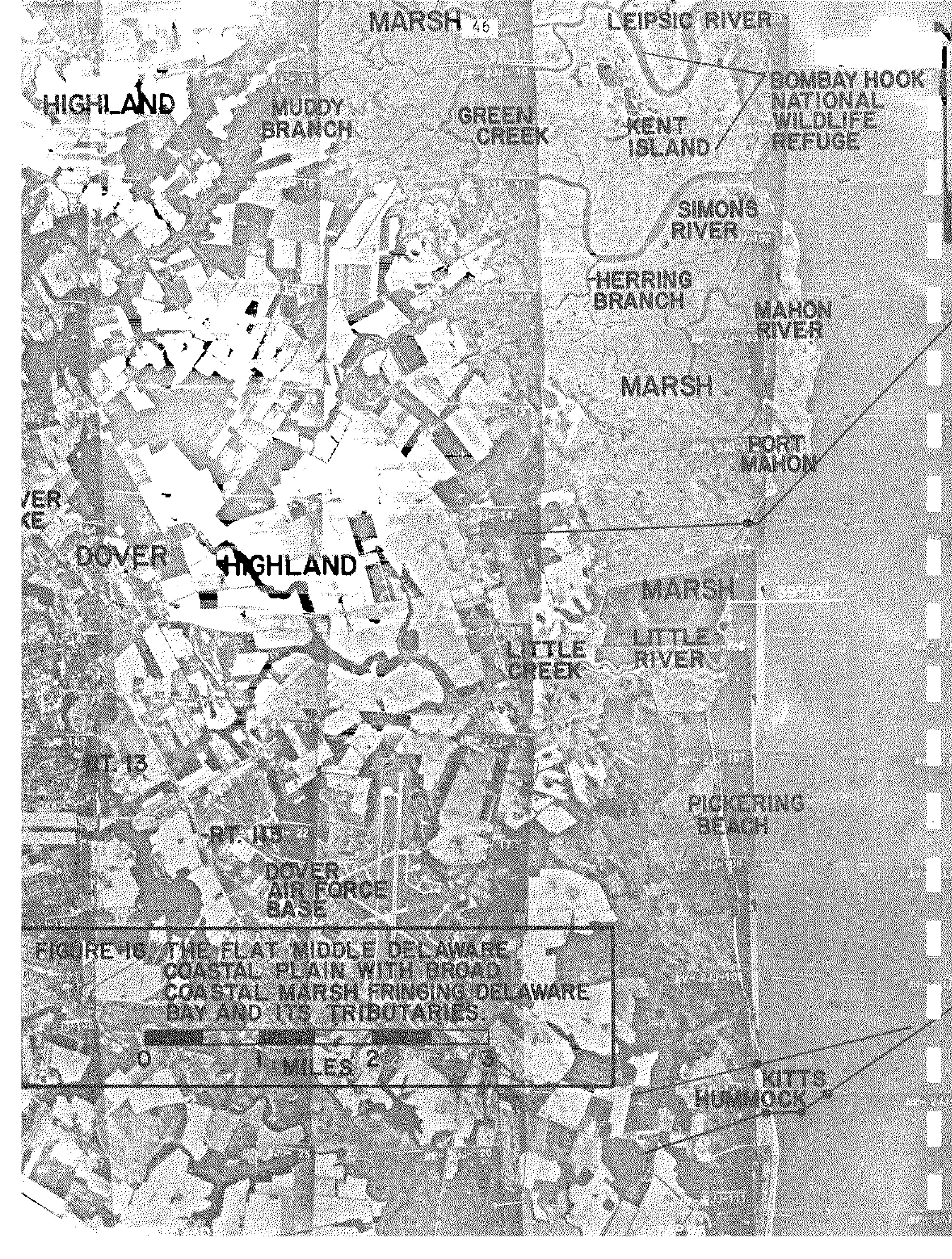
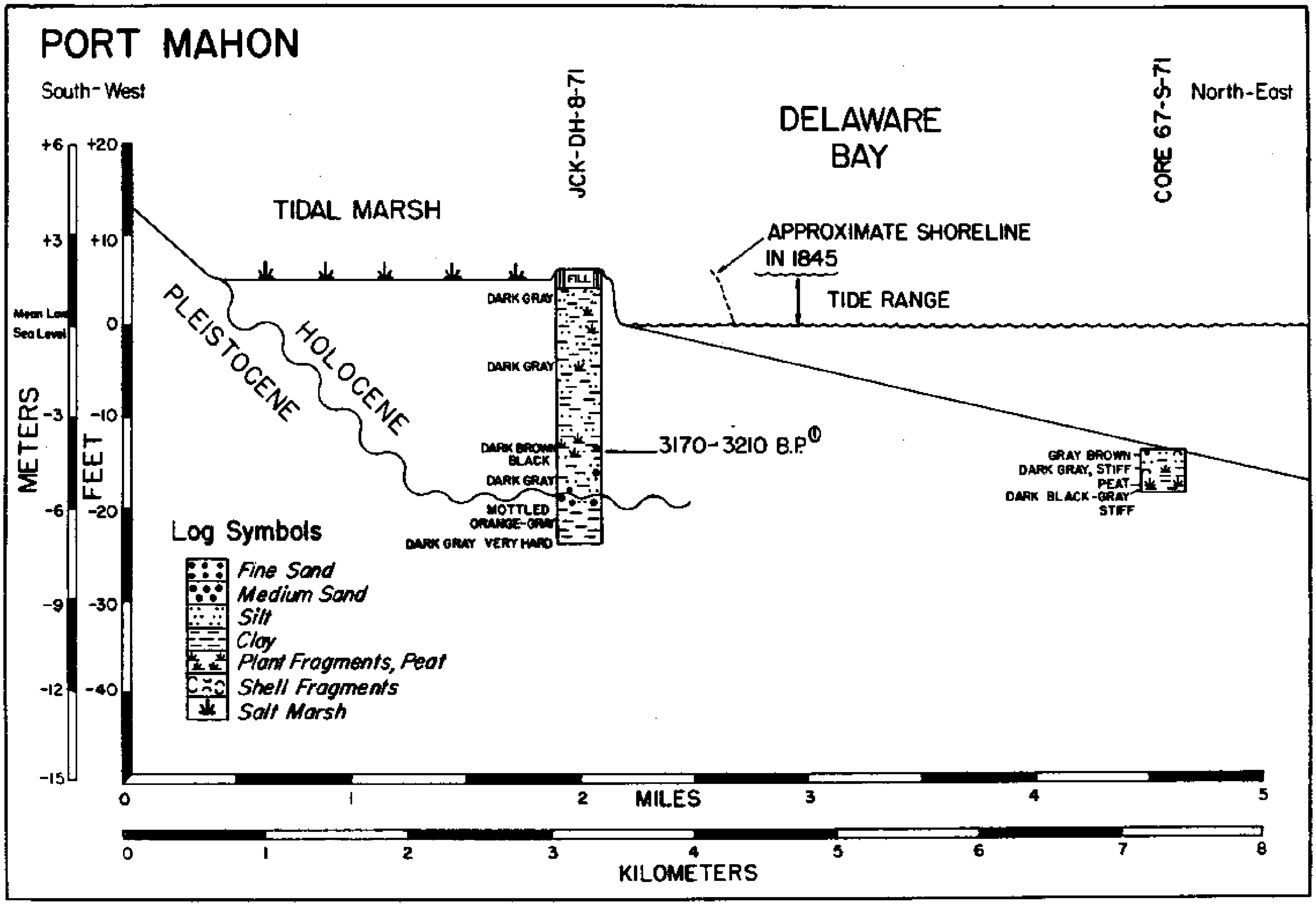


FIGURE 16. THE FLAT MIDDLE DELAWARE COASTAL PLAIN WITH BROAD COASTAL MARSH FRINGING DELAWARE BAY AND ITS TRIBUTARIES.

broad tidal marsh areas. One radiocarbon date taken from the base of the marsh section in the Duck Creek marsh indicates that the marsh has been infilling this ancestral stream valley since at least 7640 years before present. Thus the ancestral valley, whether Duck Creek or an ancestral Delaware River Valley, has been extant for a very long time.

Similar depths of marsh infill may be predicted along the axis of Duck Creek valley, the Leipsic River, and other major streams tributary to the Delaware River in this area. Here again, the highlands adjacent are moderately low-lying and rounded and merge very smoothly with the marsh but with a fairly dendritic pattern indicating drowning by relative sea level rise.

Figure 18 is an air photo-mosaic of the area from the Leipsic River southward to the small hamlet of Kitts Hummock. This area includes the end of the broad upper Delaware Bay marshes at Port Mahon and an area in which highlands once again reach toward Delaware Bay. Accordingly, a very major geologic change occurs. As may be seen in Figure 19 through Port Mahon, a very broad tidal marsh has developed, much like that at Duck Creek to the north. But a test boring at Port Mahon indicates the marsh to be only 20 feet thick. Here tidal marshes have existed, based on radiocarbon dating, from 3170 to 3210 years before present. Port Mahon is an area of major coastal erosion. Engineered maps clearly indicate erosion of more than 10 feet per year averaged over the past century and a quarter. Figure 19 shows the approximate shoreline position in 1845. As those familiar with the area will know, the State of Delaware has begun an extensive program to bulkhead a highway out to a small old port facility called Port Mahon in order to stop erosion of the coastal highway. By bulkheading this coastal highway, the erosion will stop until such time as relative sea level rises to swamp the bulkhead and moves on landward, or the bulkhead decays and is destroyed. Careful examination of the area from Port Mahon north to Woodland Beach shows very positive evidences of massive coastal erosion. Weil (1976) has documented, by the use of modern air photographs and older maps, erosion through the marsh and the meandering



Radiocarbon Date is shown in Calendar Time Masca Correction:
Radiocarbon Years, 5568½ Life = 02945± 95 B.P.

Figure 19. Geologic cross section, Port Mahon, Delaware. See Figure 18 for line of cross section.

rivers. Because of the stability of the shapes of the meandering rivers, careful maps of this area as made since 1845 may be used to show clearly the precise rates of coastal erosion.

Further to the south (Figure 18), lie Pickering Beach and Kitts Hummock. The highlands of Kent County closely approach the Delaware shoreline at the Kitts Hummock area. Indeed, Kitts Hummock itself lies at the very tip of a highland. Because of these highlands which project bayward from the Little Creek area and Dover Air Force Base area, longer-term erosion of the beach area in this vicinity has provided some sand to the littoral drift stream. Accordingly, a narrow sand beach exists at Pickering Beach and Kitts Hummock. However, here coastal erosion is also pervasive. As the actual highlands do not encounter the ocean, the amount of sand supplied to the littoral drift stream is very small; in fact, it is erosion in the lower tidal zone and below the tide that actually supplies the sand. Here wave action in extreme storm events sometimes can encounter varied highland sand and gravel materials.

Figures 20 and 21 are cross sections based on shallow test holes made at Kitts Hummock. Here a very thin marsh is overlain by a relatively thin sand-gravel beach. Essentailly, then, this is a situation in which highlands are in contact with the sea even though the immediate surroundings would indicate otherwise. Some shallow test holes made offshore from Kitts Hummock are shown in Figure 21: the offshore area is a mixture of mud and very small amounts of sand; further offshore, erosion of the advancing shoreline of Delaware Bay exposes muddy peats which are indicative of coastal marshes having been in that place some time in the past. Radiocarbon dates of the easternmost peats encountered on the bottom of Delaware Bay east of Kitts Hummock indicate that a marsh was alive and in position as shown from 4650 years ago to 4780 years before present. We have no way of determining what the width of that marsh was and where the shoreline would have been. However, the shoreline of 4500 years before present must have been somewhere to the east of core 29-W-71, Figure 21. As may also be seen in Figure 21, part of the Kitts Hummock barrier has

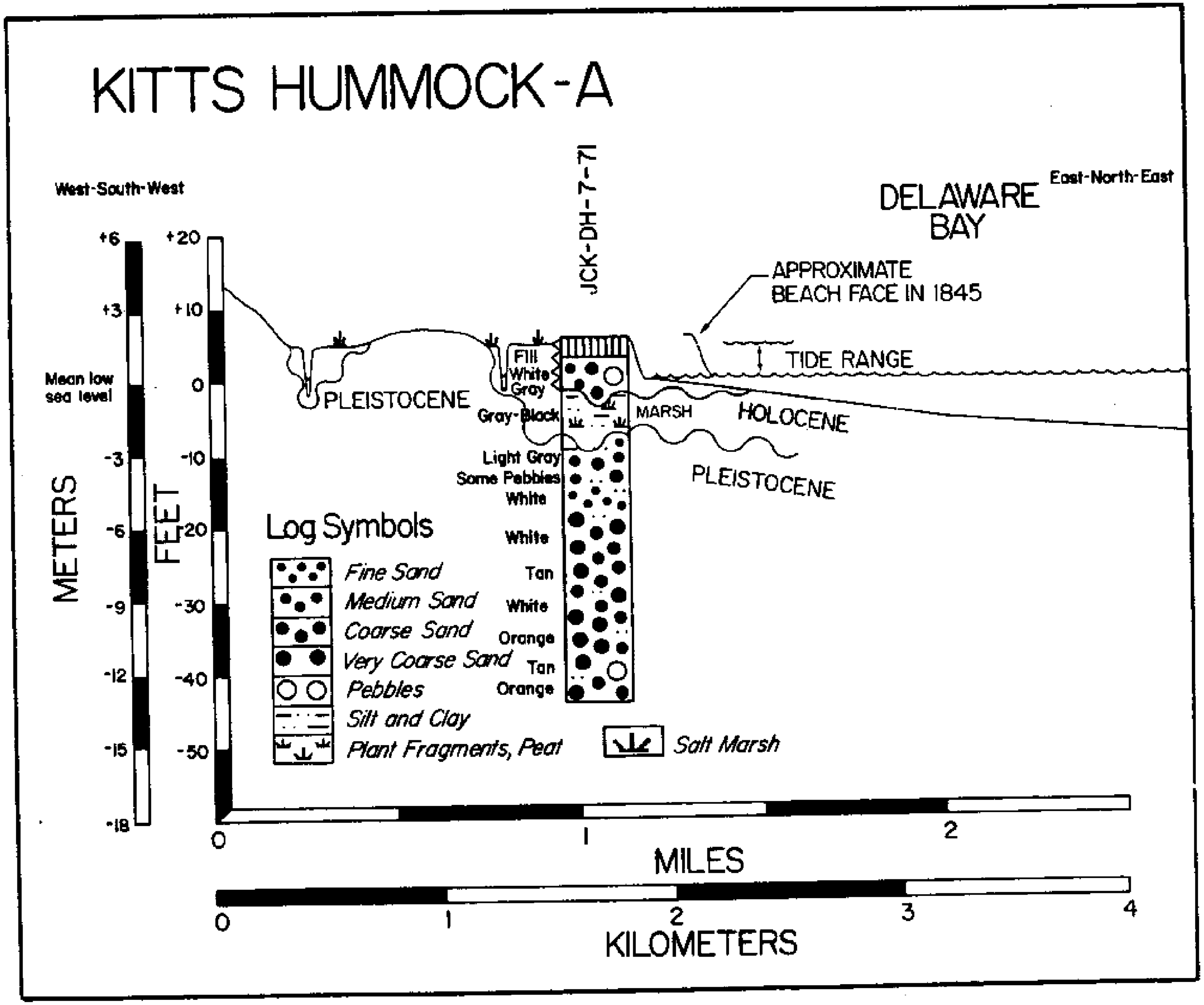
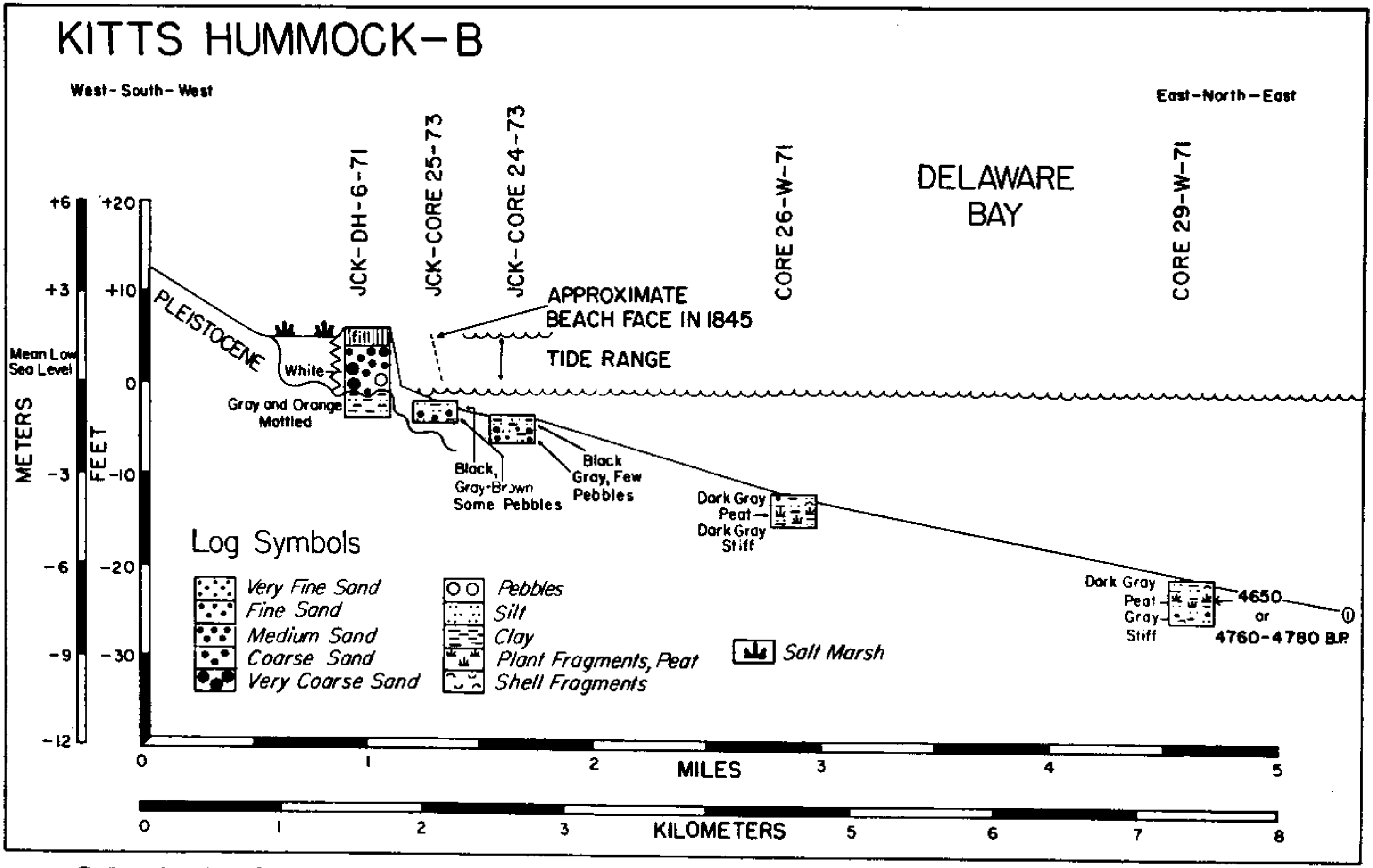


Figure 20. Geologic cross section, Kitts Hummock, Delaware, Part A. The line of cross section is shown in Figure 18.



Radiocarbon Date is shown in Calendar Time Masca Correction:
Radiocarbon Years, 5568 ½ Life = ⓪4090 ± 100 B.P.

Figure 21. Geologic cross section, Kitts Hummock, Delaware, Part B. See Figure 18 for line of cross section.

had a fill or dike constructed on the beach for the purpose of protecting the small hamlet from coastal erosion. From the tidal ranges indicated, we can see that simple tidal water levels reach almost the height of the washover barriers of Kitts Hummock. For this reason, the towns of Kitts Hummock and Pickering Beach will forever be subject to storm wave attack. There appears to be no economically reasonable way to protect them from the extreme storm event because they are simply too close to the high tide limit for their area.

The St. Jones and Murderkill Rivers flow into Rehoboth Bay along the north and south edges of an eroding upland surface. The town of Bowers is located on this low-lying upland surface. In view of the fact that Bowers is constructed on an upland surface rather than on a low-lying sandy barrier on a coastal marsh, coastal erosion in the town itself is proceeding at a slightly lower rate than to the north and to the south (Figure 22). This is not to say that the town of Bowers is not undergoing erosion. Quite the contrary; highlands such as the one upon which Bowers lies are the major source of sediment supply by erosion and transportation in the littoral drift stream along the low-lying sandy coastal barriers of the central Delaware Bay shoreline area. The St. Jones River and the Murderkill River, as the other rivers previously described, are infilled with tidal marsh sediments that are the product of a slowly rising sea level. Accordingly, the overall impression one gets from Figure 22 is that of a drowned river valley system with an almost dendritic pattern of the lesser streams or tributaries to the Murderkill and St. Jones Rivers. These two rivers in particular are known to flow through low-lying tidal marsh valleys that have infilled previously deeply incised rivers to depths at least of -90 to -100 feet below present sea level. As illustrated in Kraft (1976), the valley of the Murderkill River has been infilled with marsh and lagoonal muds over the past 9700 years. In addition, the shoreline of this area has been eroding gradually landward across the marsh surface, which is slowly building upward, keeping pace with the present ongoing rise in relative sea level of approximately 0.2 feet per century.

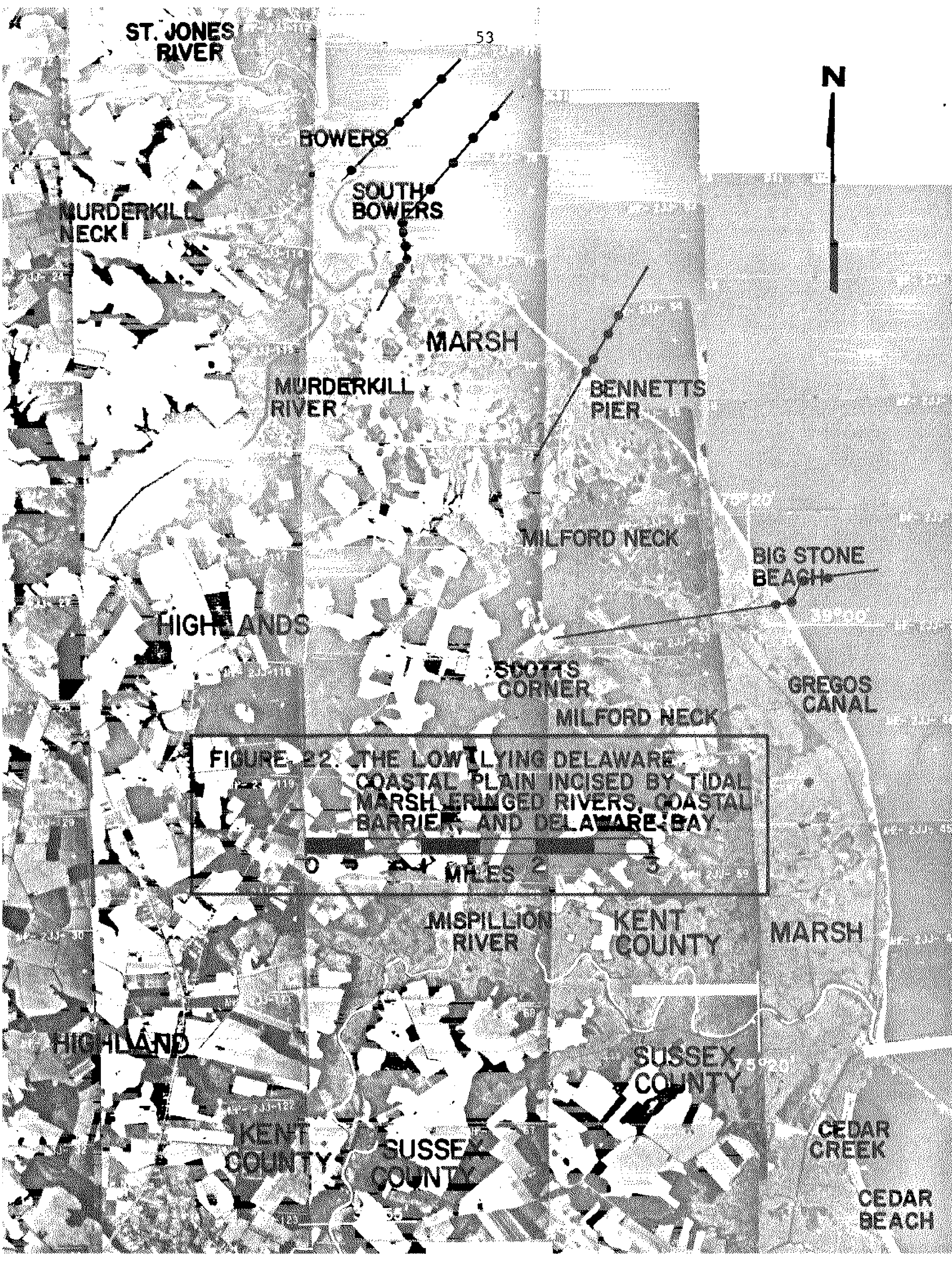


FIGURE 22. THE LOWLYING DELAWARE COASTAL PLAIN INCISED BY TIDAL MARSH FRINGED RIVERS, COASTAL BARRIER, AND DELAWARE BAY.

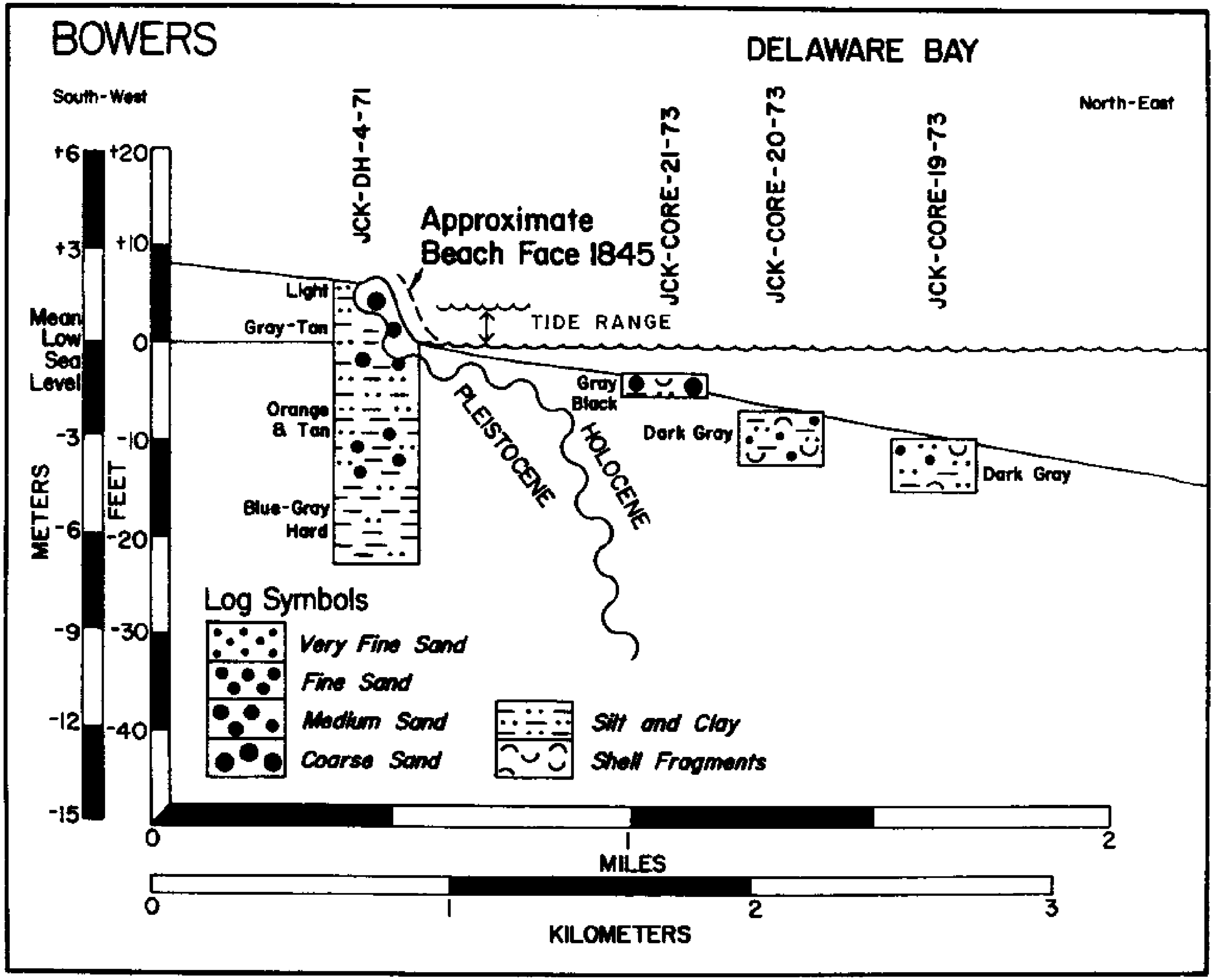


Figure 23. Geologic cross section, Bowers, Delaware. See Figure 22 for line of cross section.

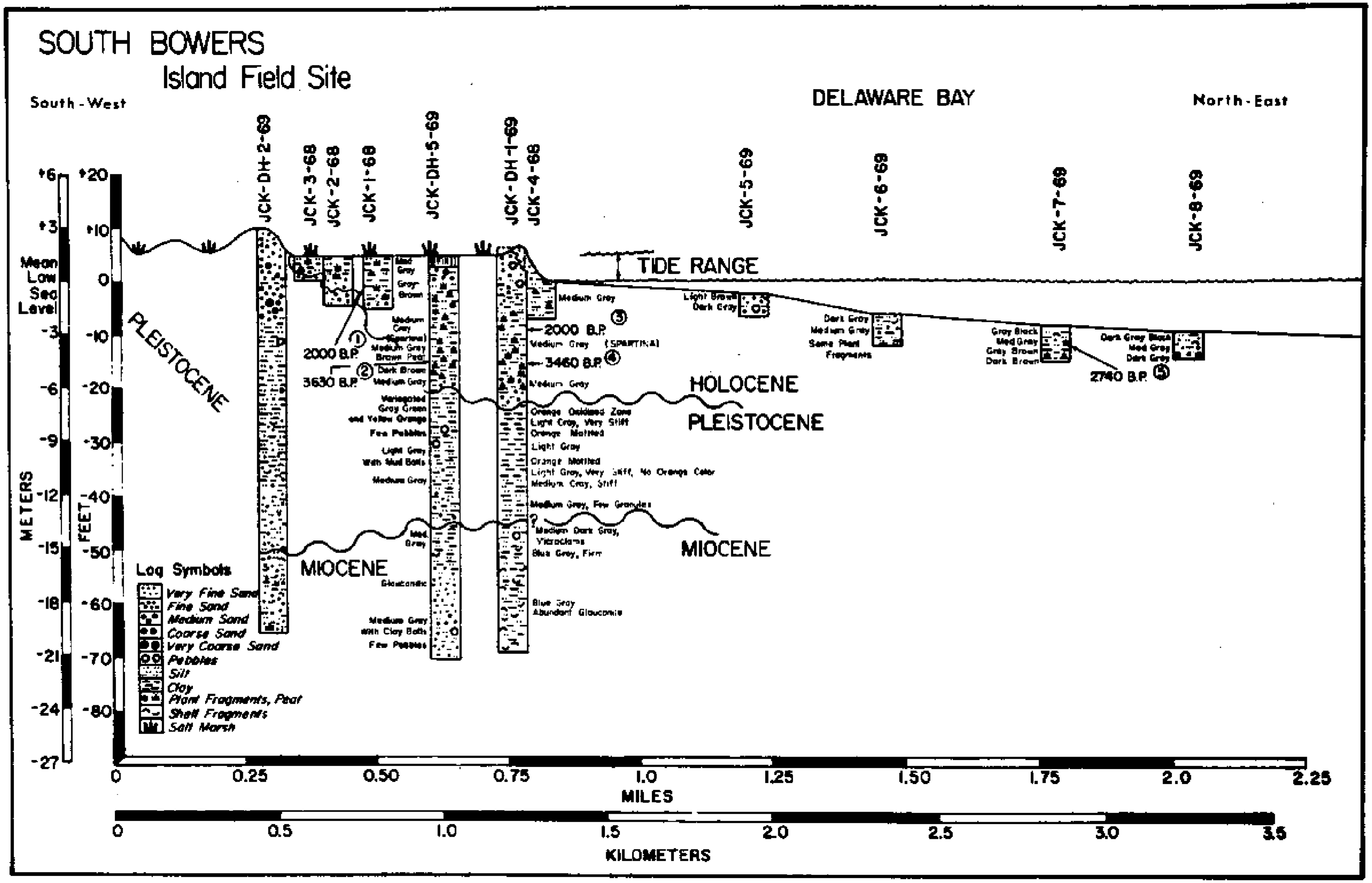
Figure 23 is a cross section through the upland surface at Bowers into the nearby shallow Delaware Bay. A boring made through the site at Bowers encountered only sandy and silty muds, relatively strongly compacted and oxidized, a product of deposition of a higher sea stand in the Sangamon Interglacial Age approximately 80,000-100,000 years before present. Offshore lies a lag surface of sand, gravel, shells, and mud. Some of the offshore shoals bury potential sources of sand and gravel that might be used for beach nourishment. However they have not been studied in detail. Much of the offshore sediment is strongly mixed with muds presently depositing in Delaware Bay.

Figure 24 is a geologic cross section from the Island Field site south of South Bowers Beach, across the low-lying marsh and sand-gravel washover barrier and into the shallow marine area of Delaware Bay. This cross section contrasts greatly with the previous cross section through the town site of Bowers Beach. The coast in this area is one of a low-lying tidal salt marsh rapidly eroding at the present shoreline. As shown in Figure 24, a great deal is known of this marsh from the numerous borings that have been made in this area. A number of radio-carbon dates of materials in the marsh have been determined. They show us that the area has been covered by low-lying coastal marsh since at least 3630 years before present. Furthermore, at an earlier time, previous to a lagoon which existed in the area five millenia ago, tidal marshes existed in the area back to at least 9700 years before present (Kraft, 1976) approximately 85 feet below present sea level, as noted in the axis of the ancestral Murderkill River Valley.

Approximately one mile offshore from the sandy washover beach area lie the remnant marsh peats of a tidal marsh at 12 feet below the present sea level. This marsh peat is dated at 2740 years before present. This means that 2740 years ago a coastal tidal marsh was growing one mile offshore, 12 feet below the present surface of the sea. Therefore, the shoreline at that time must have been still further seaward at a position presently unknown. Detailed cross sections of this type are extremely useful in determining rates of coastal erosion over the longer term. The site of Island Field itself is underlain by 70 feet of relatively hardened oxidized sands and silts deposited in a marine environment about 100,000 years before present. The surface, that is to say the present land surface, is strongly oxidized in view of the fact that it is in the present soil zone. At approximately -50 feet, Miocene (10,000,000 $\pm$ years before present) marine sediments were encountered. The layer of strata or Miocene sediments extends through wells drilled in the South Bowers Beach area. Thus, the entire peninsular area in the vicinity of Bowers-South Bowers is comprised of relatively young (geologically speaking) shallow marine and coastal sediments.

The Murderkill-St. Jones combined river systems were deeply incised with the lowering of sea level during the last great glaciation approximately 14,000 to 16,000 years before present. Proceeding further southward in air photo Figure 22, one can observe the Mispillion River, which was also deeply incised, similar to the Murderkill-St. Jones river system. In the in-between area from the mouth of the Mispillion River to the mouth of the Murderkill River lies the present Milford Neck. Milford Neck is comprised of low-lying coastal plain sediments also approximately 100,000 years old. Being in the interfluve area, the coastal marshes that are presently transgressing across the neck are relatively thin. Coastal erosion is ongoing along the continuous sand-gravel barrier from South Bowers to the mouth of the Mispillion River. However, this coastal erosion is migrating landward and upward across a broad but very thin coastal tidal marsh. Figure 25 is a geologic cross section of the coastal zone at Bennett's Pier to the south of the Murderkill River area. Here the coastal tidal marshes are less than 10 feet thick. The sand and gravel barrier has been migrating as elsewhere along Delaware Bay landward and upward at a relatively rapid rate as shown in Figure 22.

Figure 26 is a geologic cross section at Big Stone Beach. Here the coastal tidal marshes are even thinner at the extreme interfluve area between the Murderkill and the Mispillion River Valleys. Again, however, the sand-gravel barrier migrates landward and upward across low-lying tidal marshes that are thinly spread and developing across the relatively low-lying central Delaware coastal plain.



RADIOCARBON DATES ARE SHOWN IN CALENDAR TIME MASCA CORRECTIONS: RADIOCARBON YEARS, 5568 - 1/2 LIFE =
① 1952 ± 45 ② 3314 ± 63 ③ 1950 ± 55 ④ 2999 ± 59 ⑤ 2550 ± 100

Figure 24. Geologic cross section, Island Field archaeologic site to Delaware Bay. The line of cross section is shown in Figure 22.

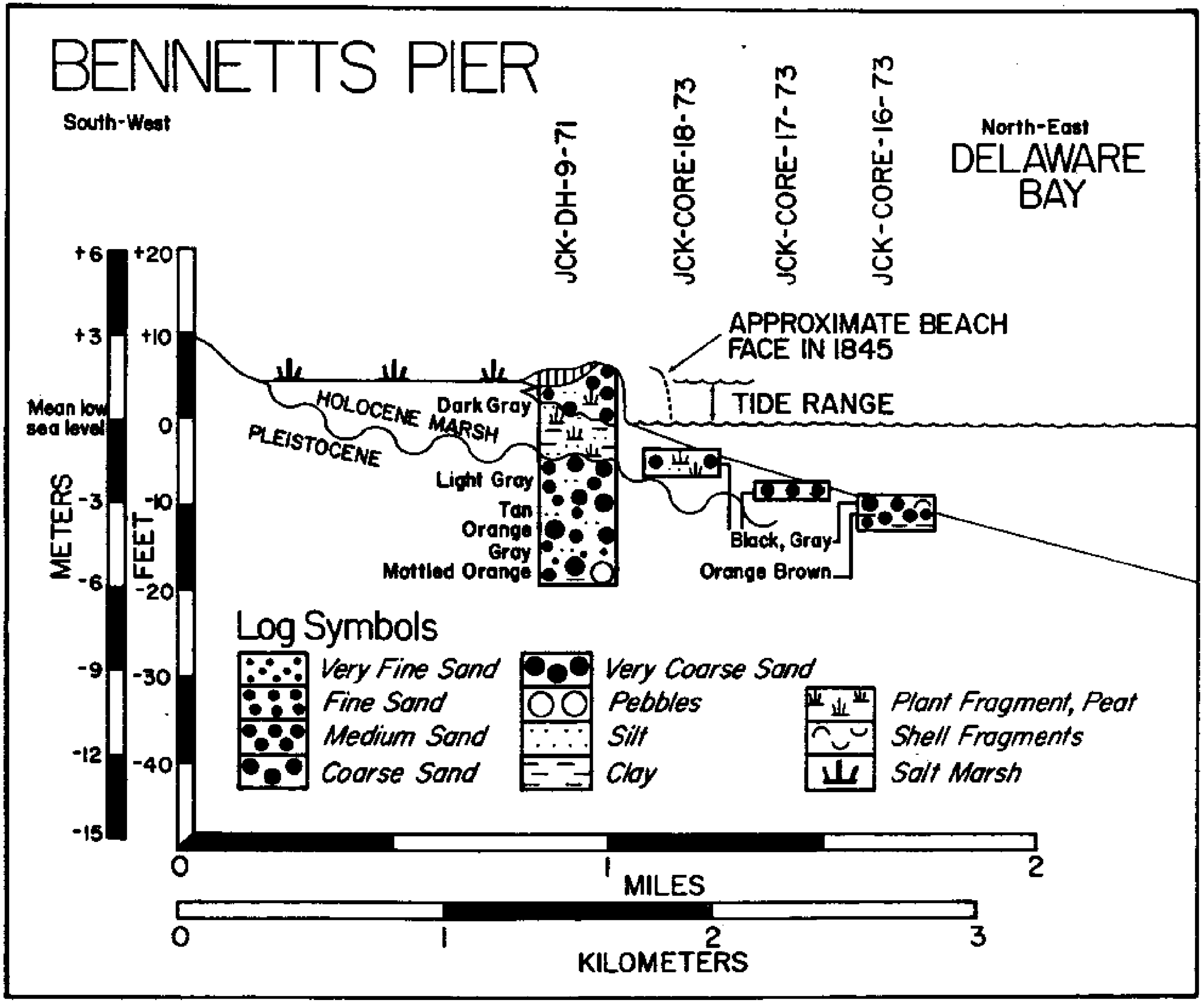


Figure 25. Geologic cross section, Bennett's Pier, Delaware. See Figure 22 for line of cross section.

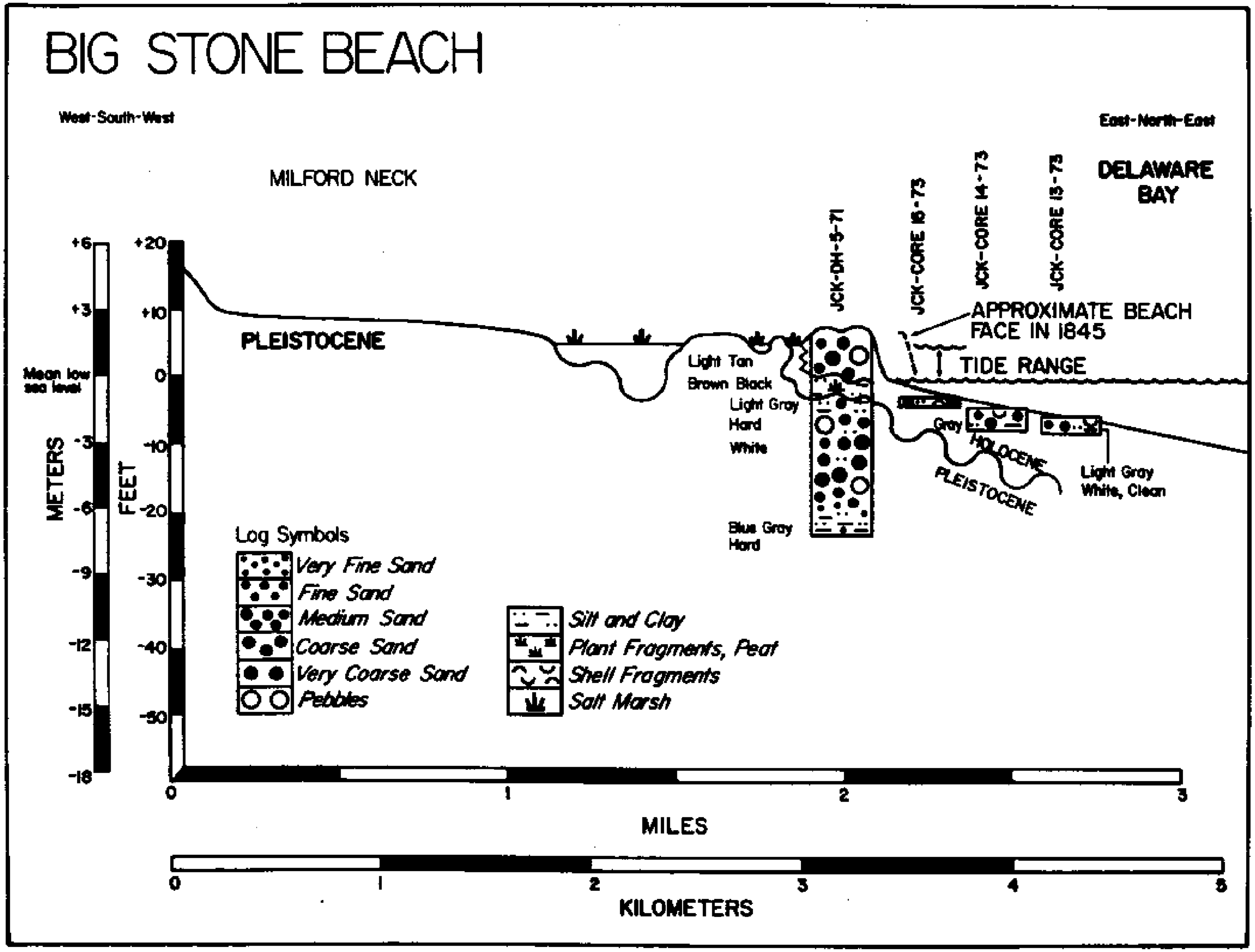


Figure 26. Geologic cross section, Big Stone Beach, Delaware. The line of cross section is shown in Figure 22.

Figure 27 is an air photo of the region from the mouth of the Mispillion southward to the area of the Broadkill River-old Broadkill Inlet. The Mispillion River and Cedar Creek Valleys were relatively deeply incised during the last great glaciation. Accordingly, the marsh muds infilling these areas are relatively thick. As seen in Figure 28, a geologic cross section across the Slaughter Beach area, more than 50 feet of Holocene Epoch sediments have been deposited. These tidal marsh and lagoonal muds were deposited approximately 6300 years before present. In this region, the drill again encountered a section of lagoonal muds as evidenced by the presence of a microfossil typical of lagoonal muds, Elphidium clavatum. First the marsh overrode the land surface, after which a lagoon formed in the area, and then the lagoon became infilled with marsh as it continued to grow landward and upward. Finally, the shoreline of Delaware Bay eroded through the area into its present position, where it is slowly eroding westward or landward.

The presence of lagoonal muds in the geologic sections along the coast usually occurs in the axes or near the axes of deeply incised river valleys. Lagoonal muds such as those in the geologic cross section (Figure 28) were also seen in drill holes in the axis of the Murderkill River Valley to the north. Similar sections are encountered further south in the vicinity of the Broadkill River and Lewes Creek Marsh. It is theorized that the lagoons were very similar to those of present-day Rehoboth and Indian River coastal lagoons although perhaps not accompanied by so large a coastal barrier between them and the waters of the earlier Delaware Bay.

Further to the south, the next deeply incised river valley was that of the ancestral Broadkill River. The area in between was again an interfluve area of lesser erosion. Cross sections shown in Figures 29 and 30 at Fowler Beach and Primehook Beach indicate again the relatively thin (less than 20 feet thick) section of marsh and barrier sediments. These low-lying marshes are similar to those north of the Mispillion River area and are slowly building landward and upward across the narrow necks of land such as Primehook Neck and Slaughter

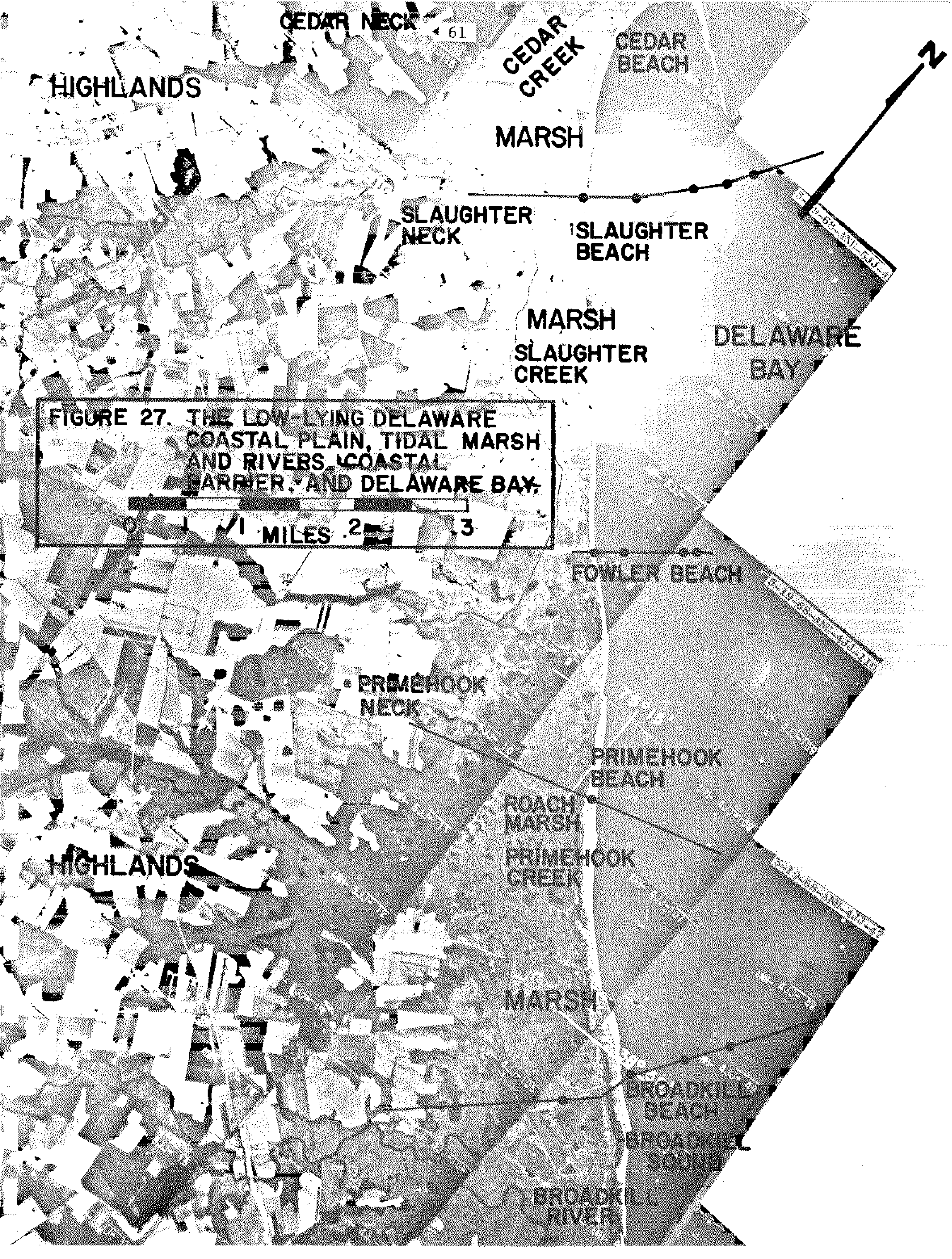
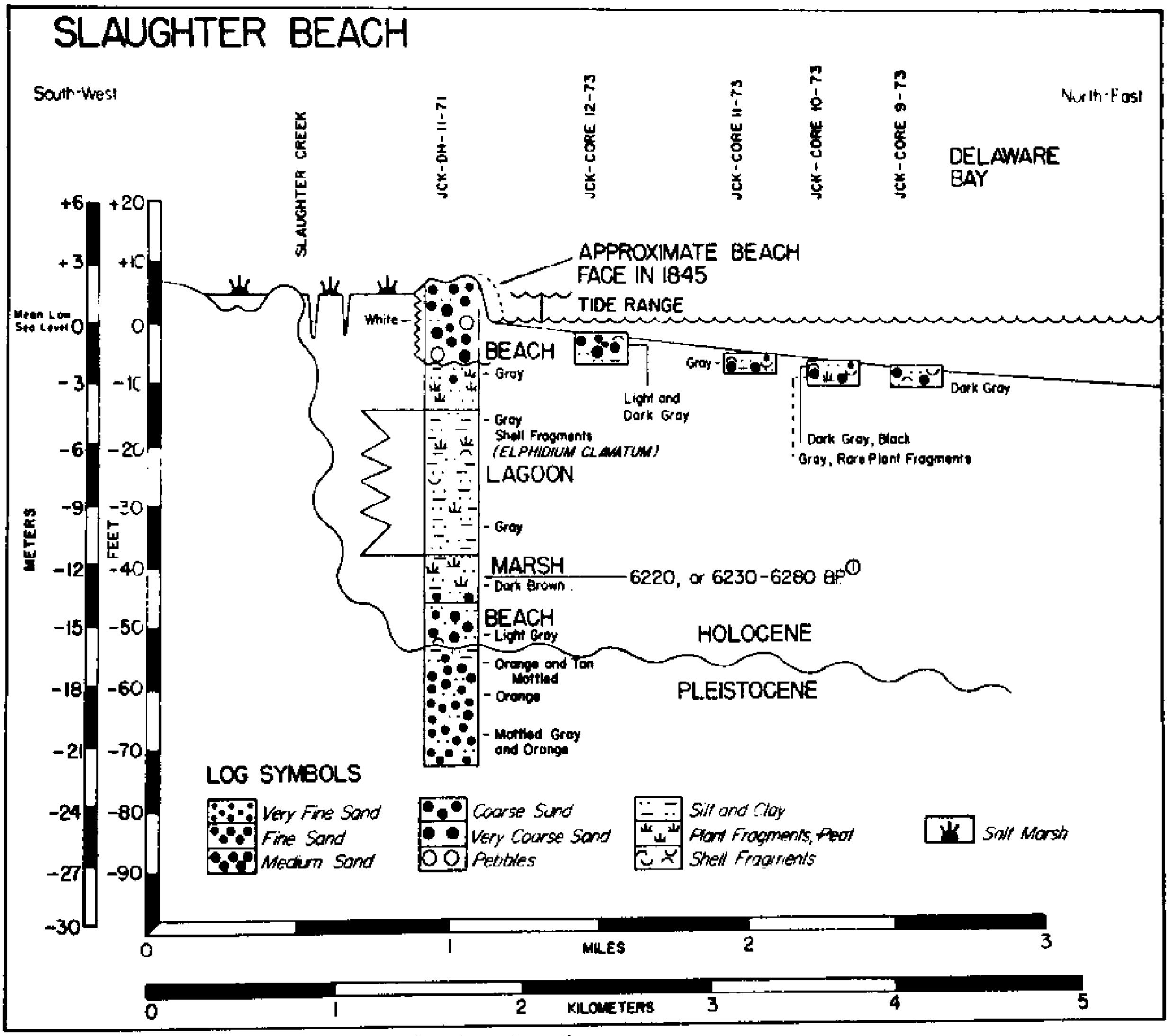
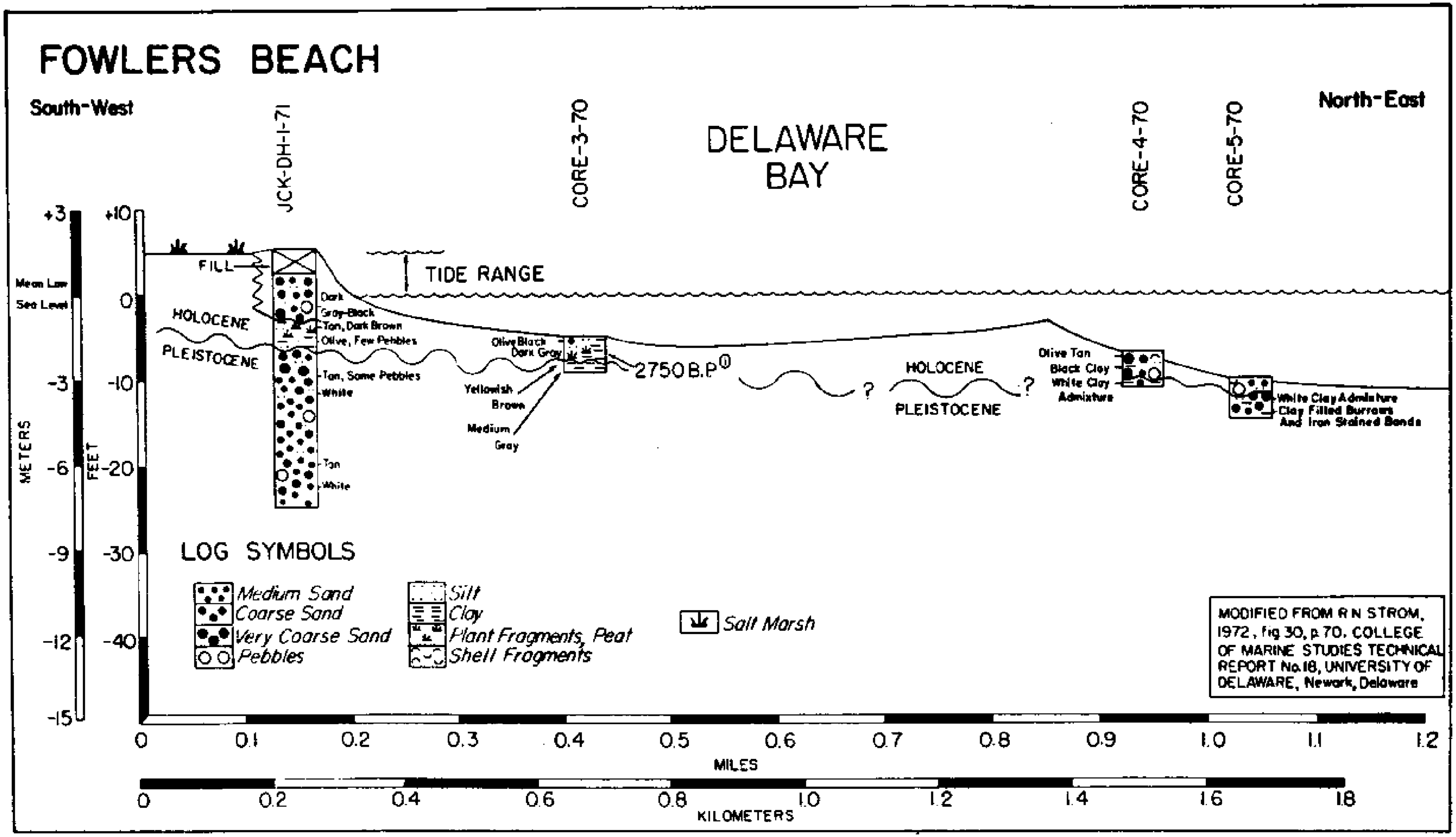


FIGURE 27. THE LOW-LYING DELAWARE COASTAL PLAIN, TIDAL MARSH AND RIVERS, COASTAL BARRIER, AND DELAWARE BAY.



Radiocarbon Date is shown in Calendar Time Masca Correction:
Radiocarbon Years, 5568 1/2 Life=①5345 ± 110 BP

Figure 28. Geologic cross section, Slaughter Beach, Delaware. The line of cross section is shown in Figure 27.



Radiocarbon Date is shown in Calendar Time Masca Correction:
Radiocarbon Years, 5568½ Life = ①2560± 95 Years B.P.

Figure 29. Geologic cross section, Fowlers Beach, Delaware. See Figure 27 for line of cross section.

Neck, keeping pace with relative rise in sea level. Again, a thin sandy coastal washover barrier migrates landward across the marsh, accompanying the present ongoing coastal erosion. Sand and gravels are supplied to the section whenever a portion of a relict highland is subjected to coastal erosion, such as at Slaughter Beach and in part in the subsurface at Big Stone Beach further to the north. The geologic cross section at Primehook Beach (Figure 30) indicates a large amount of sand in the cross section. Thus we might assume a relatively nearby highland surface undergoing erosion.

Fowlers Beach is particularly interesting in that here again coastal tidal marsh muds were encountered in an offshore position in boring core # 3-70 (Figure 29). A radiocarbon dating of these tidal marsh materials gave an age of 2750 years before present, approximately 8 feet below present mean low sea level. Here again we can assume accordingly that 2750 years before present the low-lying tidal marsh lay much lower and further to the east, and the sandy coastal barrier must have been positioned somewhere to the east of that, possibly in the eastern part of Figure 27.

The town site of Broadkill Beach is unique. Figure 31 is a geologic cross section across the broad marsh, west of the town of Broadkill Beach, through the town of Broadkill Beach and into the nearby adjacent shallow marine area of Delaware Bay. As may be seen from the profile (Figure 31), the broad marsh is interrupted by low-lying islands or portions of highland sediments similar to those of the entire Delaware coastal plain further to the west. In addition, the town of Broadkill lies just bayward of a relatively small abandoned stream valley. This abandoned stream valley known as Broadkill Sound, was the site of flow of the Broadkill River in the mid-to-late 19th century. During the 19th century, sands were flowing around Cape Henlopen further to the south and east along the shoreline of Lewes Beach, then northward along Beach Plum Island to the area of Broadkill Beach and on to the north. They were flowing in a littoral drift stream supplied by sediment eroding from the Atlantic shoreline of Delaware. This constant or relatively steady flow or stream of sand built a

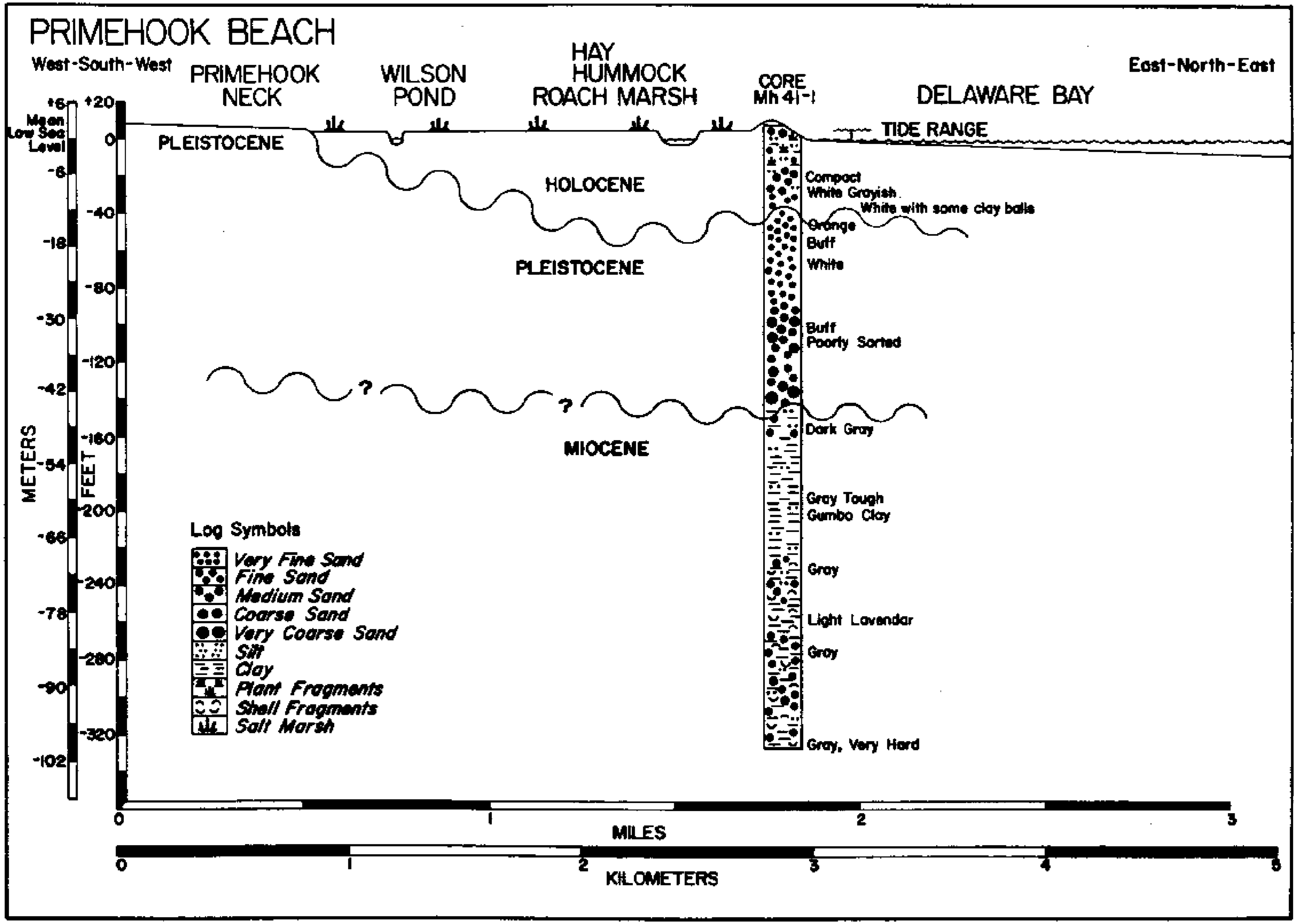


Figure 30. Geologic cross section, Primehook Beach, Delaware. The line of cross section is shown in Figure 27.

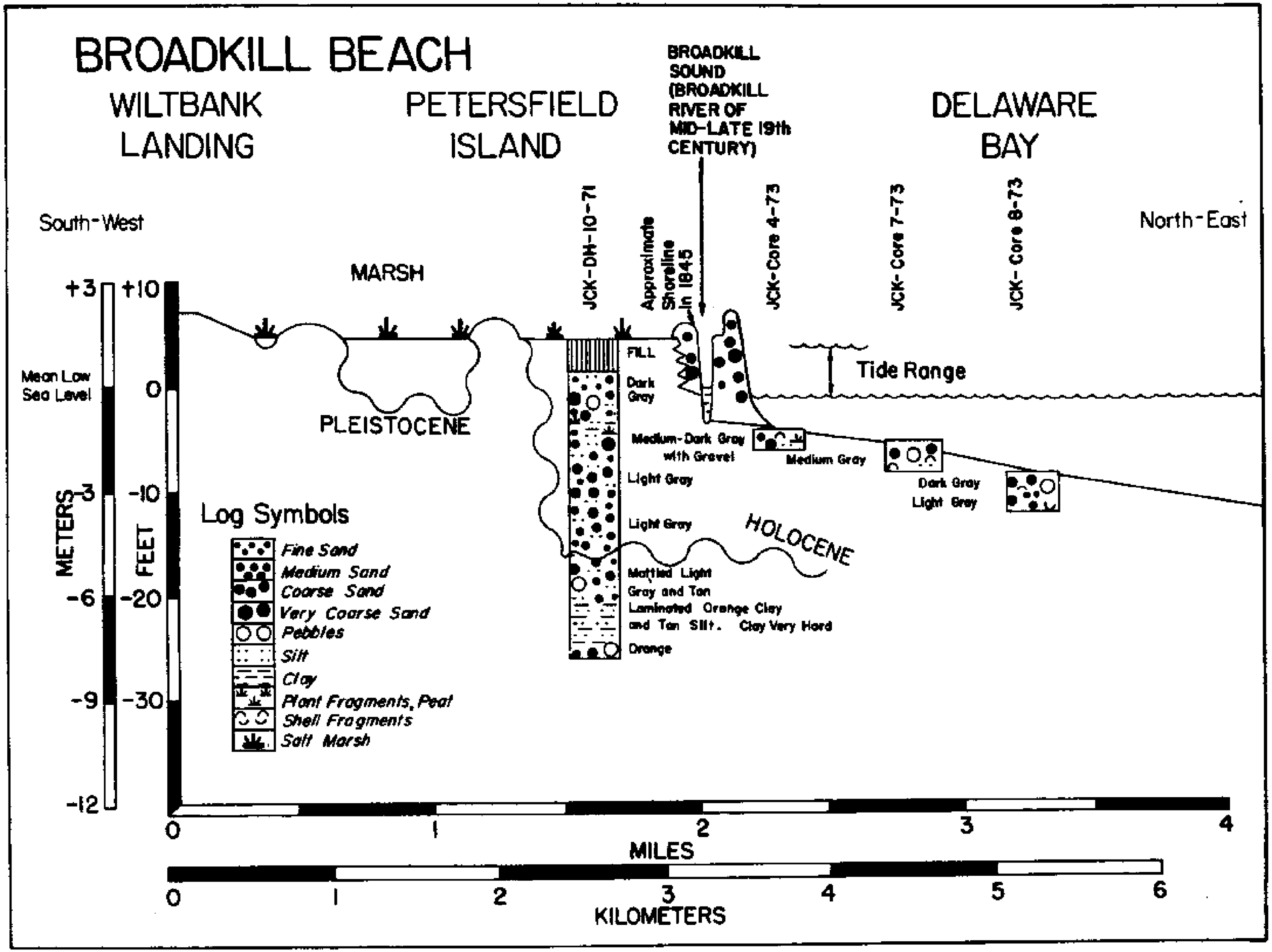


Figure 31. Geologic cross section, Broadkill Beach, Delaware.
See Figure 27 for the line of cross section.

spit-like projection around the area of Cape Henlopen into the Lewes area and on northward to Primehook. As this spit-like projection moved northward, the streams flowing into Delaware Bay in this region, namely Lewes Creek, Canary Creek, and the Broadkill River, became gradually deflected further and further to the north. Finally this very thin low-lying sandy spit reached the area of Primehook. By that time, sands flowing around the tip of Cape Henlopen had become disrupted in their flow by the construction of the inner breakwater at Lewes. Sands tended to bypass the beach area and flow into the deeper channel north of the inner breakwater and to be trapped in Lewes Harbor by a "breakwater" effect. Accordingly, the strong flow of sand around the Cape into the north stopped. The result was a relatively broad, sandy, washover-barrier-like structure at Lewes Beach, Beach Plum Island, the present area of Broadkill Beach. By examining Figure 31 one can see a remnant beach of a time previous to the flow of the Broadkill River northward to Primehook. This abandoned beach was the old shoreline of Delaware Bay for its time.

Thus it can be demonstrated that the town of Broadkill Beach is built on new land, generated since the mid-to-late 19th century. With the cut-off of the flow of sand in the littoral drift stream from the south, erosion started at a relatively rapid rate again, much as it had been in the past. However, people began to build on the town site of Broadkill Beach. By constructing a groin field, the town itself has been partially protected from this erosion. On the other hand, the areas to the north and south of the town have not been protected and have been subjected to ever-increasing rates of erosion as the shoreline tends to straighten itself out and move back to its position before the mid-19th century.

Long ago, the Broadkill River began to exit through the area known as old Broadkill Inlet, south of the present town of Broadkill Beach. Ultimately this became a problem of continuous silting or shoaling, and jetties were built in the old Broadkill Inlet. It was later decided that this was not satisfactory and a new inlet was dredged at the site of Roosevelt Inlet, further to the south at the tip of Lewes

Beach. At that time, part of the old Lewes Creek which had flowed northward along the back of the barrier was dredged out; it became the very lowest portion of the present Broadkill River which exits into Delaware Bay at Roosevelt Inlet. Thus, in summary, a back barrier system of streams that were forced to migrate and join each other in their northward flow was finally cut off by man and forced into an artificial inlet. The flow of sand was not affected by this action as it had already ceased as a result of the actions of man in Lewes Harbor itself.

Broadkill Beach is therefore constructed on an island of sand eroding more rapidly in the northern and southern portions, and tending to revert to island status in view of the swampy, relatively shallow Broadkill Sound that lies to the rear or west of the town site.

Figure 32 is an air photo of the area from the Broadkill River Great Marsh northwest of Lewes to Cape Henlopen Spit at the junction between Delaware Bay and the Atlantic Ocean and thence southward to the town of Rehoboth Beach and Atlantic coastal Delaware. In view of the fact that the coastal and oceanic processes of the Atlantic Ocean meet those processes active in Delaware Bay within the area shown in Figure 32, a unique situation occurs. A relatively larger erosion cycle occurs in the Atlantic coastal area, and an extremely large amount of sand is in motion at all times. Relatively lesser amounts of sand and gravel move from wave-generated processes along the coasts of Delaware Bay. With a dominant wave fetch from the southeast, the dominant motion of sand in Atlantic coastal Delaware is from south to north toward Cape Henlopen. Thus Cape Henlopen throughout historic time has been an area of building to the north while the shoreline of the Atlantic Ocean has been an area of erosion and migration to the west. As stated above, some of the sands previously went around the Cape and moved thence to a spit-like projection through the area of present Lewes Beach, Beach Plum Island, Broadkill Beach, and north to Primehook. This has long since ceased owing to the actions of man in the area of Breakwater Harbor and the Harbor of Refuge near Cape Henlopen Spit.

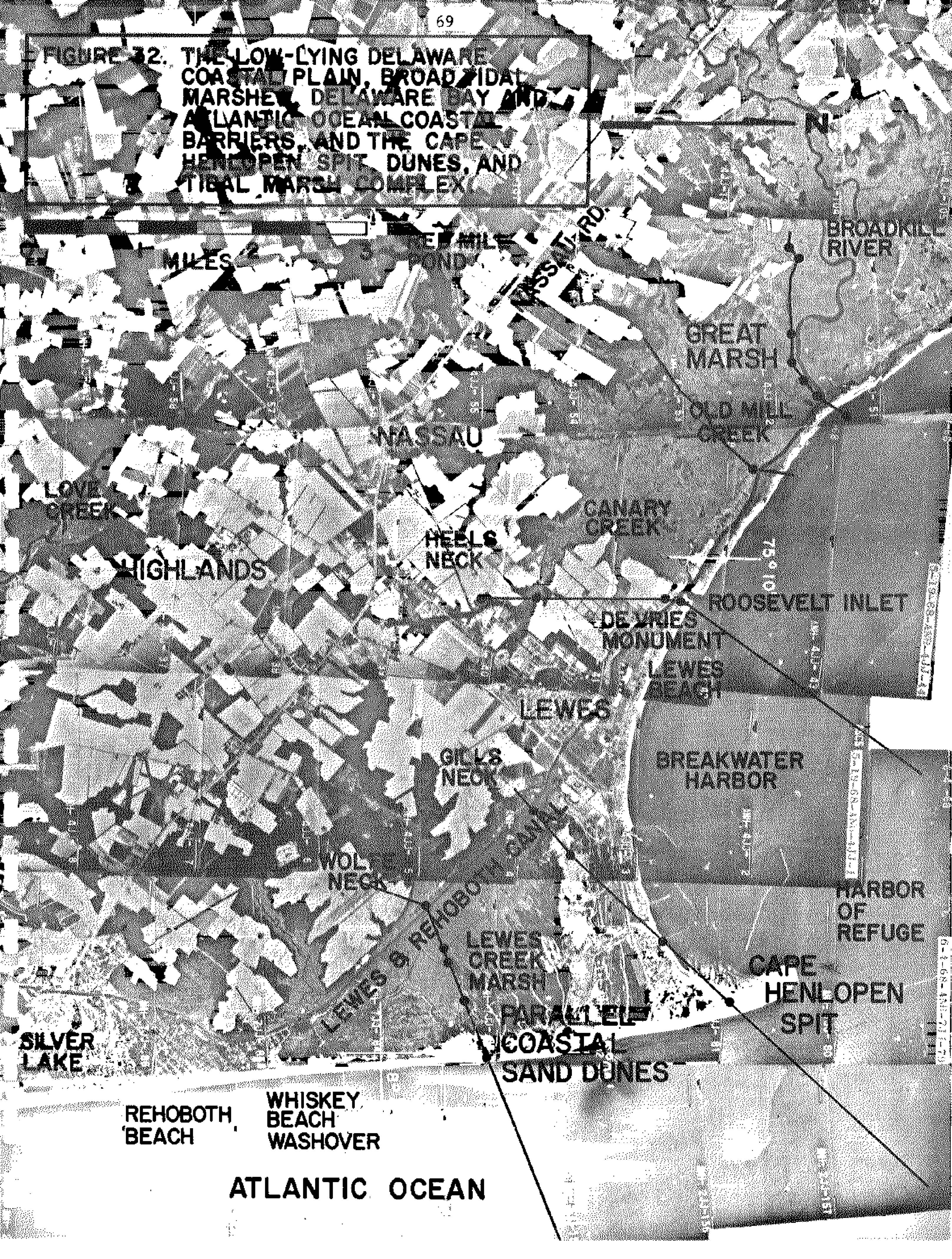
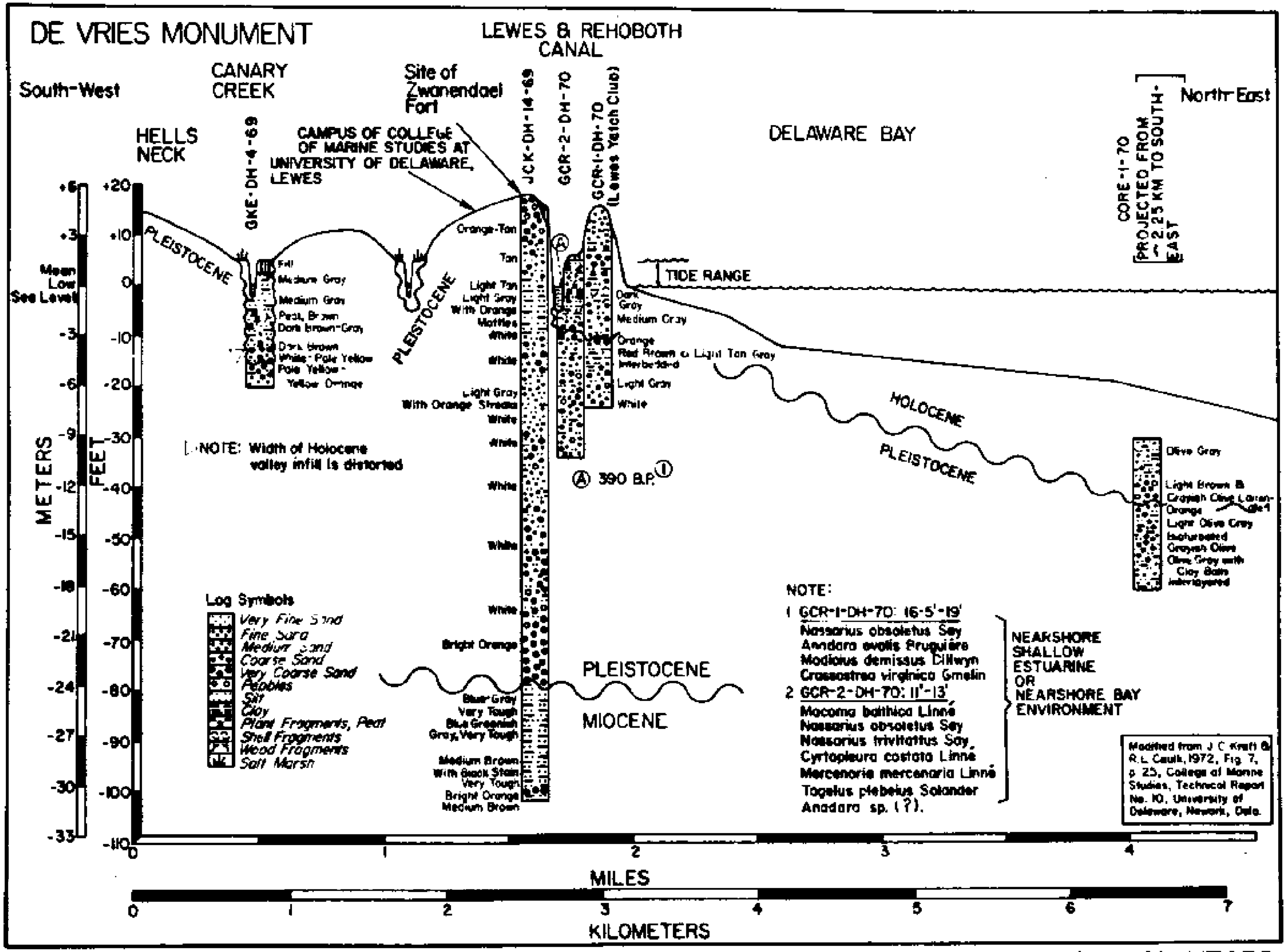


FIGURE 32. THE LOW-LYING DELAWARE COASTAL PLAIN, BROAD TIDAL MARSHES, DELAWARE BAY AND ATLANTIC OCEAN COASTAL BARRIERS, AND THE CAPE HENLOPEN SPIT DUNES, AND TIDAL MARSH COMPLEX.



RADIOCARBON DATE IS SHOWN IN CALENDAR TIME MASCA CORRECTION: RADIOCARBON YEARS, 5568-1/2 LIFE = ① 330 ± 90 B.P.

Figure 33. Geologic cross section, DeVries Monument-Pilot Town, Delaware. The line of cross section is shown in Figure 32.

The Great Marsh and the Canary Creek Marsh west and northwest of the highlands at Lewes are broad coastal marshes constructed much in the fashion of the rest of the broad coastal tidal marshes to the north along Delaware Bay. They are bounded on the east by rapidly eroding landward-and-upward-migrating sand barriers. The barriers here have, as previously stated, trapped the Broadkill River and forced it to migrate along the barrier to Roosevelt Inlet (by the actions of man). Lewes Creek itself flows north along the Lewes and Rehoboth Canal, thence behind the barrier at Lewes Beach and into Roosevelt Inlet where it exits into Delaware Bay. The highland at the northern end of the town of Lewes, at the site of the DeVries Monument noted on the photograph (Figure 32) is an extremely important area historically. This is the first highland area that could be encountered by one sailing into Delaware Bay. As noted in the records of the Dutch who sailed into this area and constructed a fort near the DeVries Monument, it was a region of highland, fertile, with springs in the area along the low-lying Lewes Creek. Thus, Lewes early became an important port site.

Figure 33 shows a geologic cross section through the area of Canary Creek, the highlands at the DeVries Monument (site of Zwaanendael Fort), across the Lewes and Rehoboth Canal, through the sandy barrier of Lewes Beach near the Lewes Yacht Club, and thence seaward into the shallow Delaware Bay. As may be seen from this profile, the highlands again are formed of shallow marine sands and silts of an older geologic time, the time of the previous marine transgression across the lower Delaware Peninsula approximately 100,000 years ago. Lewes Beach itself and the marsh behind it, however, are the products of newly deposited sediment over the past millennium. As discussed in previous paragraphs, the sand-gravel barrier at Lewes Beach is part of the spit-like projection west and north from Cape Henlopen of three to four centuries ago. Presently, in view of the fact that little or no sand is being fed to the beach by the littoral drift stream, it tends to be eroding, particularly in the northern part, in the area of the cross section. Here again, one of geologic borings (JCK-DH-14-69) encountered Miocene-Age marine sediments at approximately 80 feet below sea level. Thus there

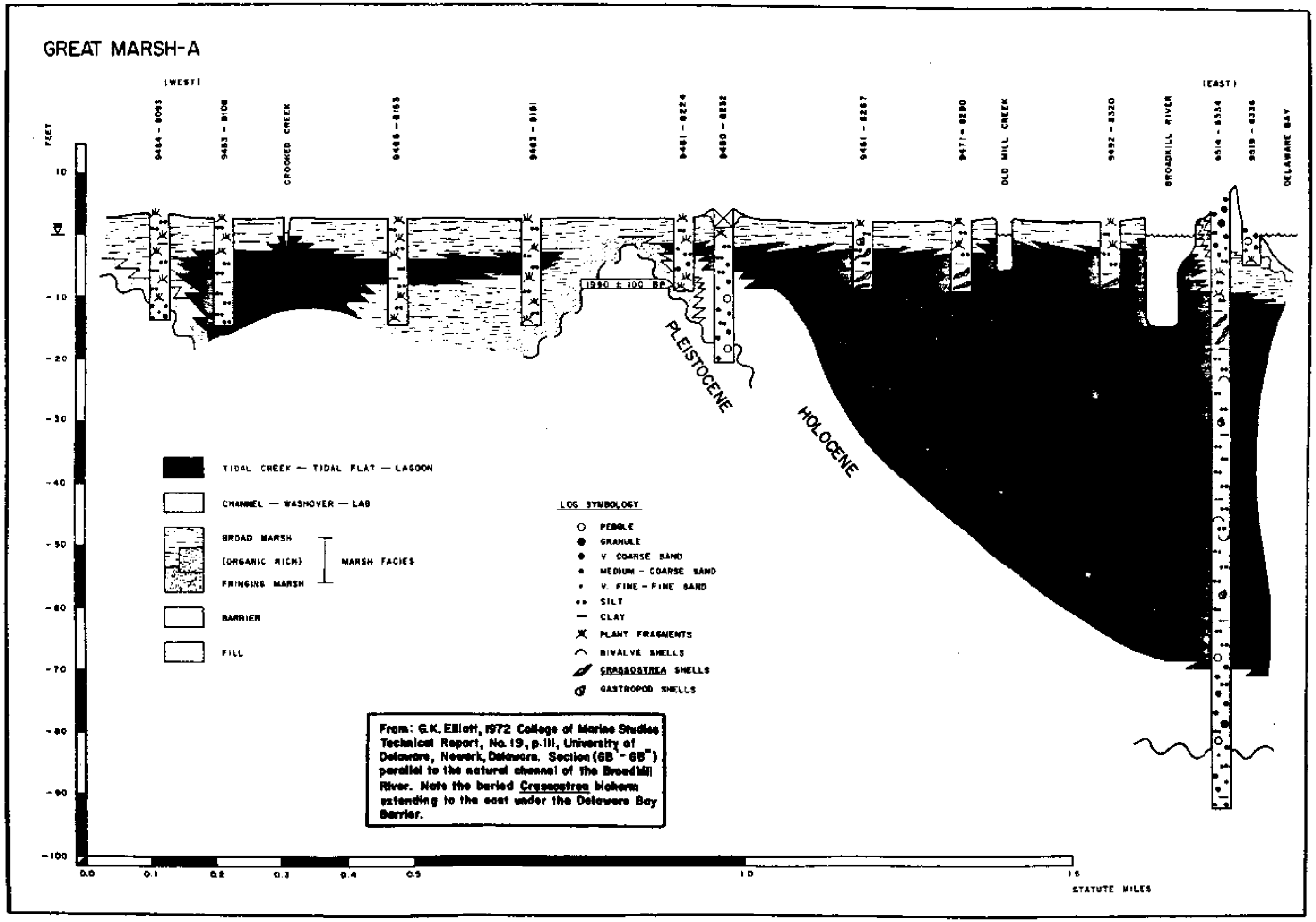


Figure 34. Geologic cross section (Part A) of the Great Marsh at Lewes, Delaware. See Figure 32 for line of cross section.

is an indication that nearly all of the lower part of the Delmarva Peninsula is comprised of relatively young geologic age sediments.

Figure 34 is a geologic cross section interpretation through Old Mill Creek in the Great Marsh to the west and north of Lewes and across the sandy washover barrier into Delaware Bay. This cross section, constructed by Elliott (1972) shows that the Great Marsh was not always a coastal tidal marsh. Much of the cross section indicates relatively young sediments deposited in a coastal lagoon. The area of Lewes Creek Marsh can thus be shown to have been a coastal lagoon over much of the past 6,000 to 7,000 years. This broad coastal lagoon must have been very much like Rehoboth Bay, to the south. Eventually it became infilled with silt and then a low-lying tidal marsh extended across it. The evidence is quite clear that a very large coastal lagoon existed here. Similar coastal lagoons, as previously stated, also existed in the Lewes Creek Marsh area, the Primehook area, and other areas further to the north. Figure 35 is another geological cross section across the Lewes Creek Marsh by Elliott (1972). Here again one can see that the greater portion of the sediment shown in the cross section is that of coastal lagoon and tidal flat rather than coastal tidal marsh. The two geological cross sections shown in Figures 34 and 35, therefore, very much support the theory of former large coastal lagoons in the lower Delaware Bay shoreline area.

The Atlantic Coast

The area of Cape Henlopen, from the town of Lewes to the tip of the Cape Henlopen Spit to the town of Rehoboth Beach is roughly triangular in shape. This area is one of erosion on the east, transportation of sediments and deposition to the north, and landward and upward infill of silts to the west and southwest across Lewes Creek Marsh. Figure 36 is a geologic cross section from Gill's Neck across the Lewes and Rehoboth Canal, the Lewes Dump, the fishing pier, part of Breakwater Harbor, thence across Cape Henlopen's dunes, across the deep valley at the mouth of Delaware Bay adjacent to Cape Henlopen and on to Overfalls

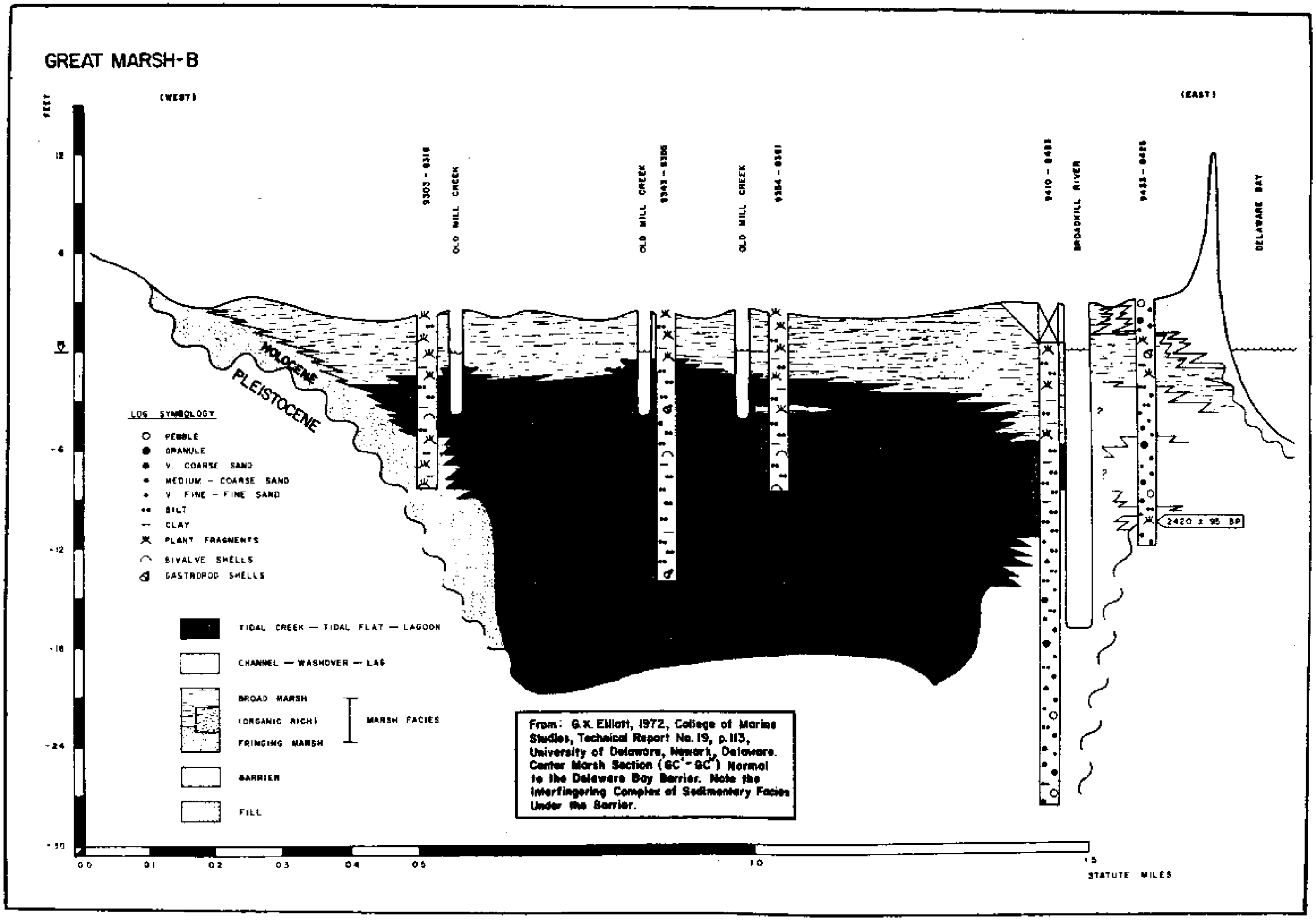


Figure 35. Geologic cross section (Part B) of the central Great Marsh at Lewes, Delaware. The line of cross section is shown in Figure 32.

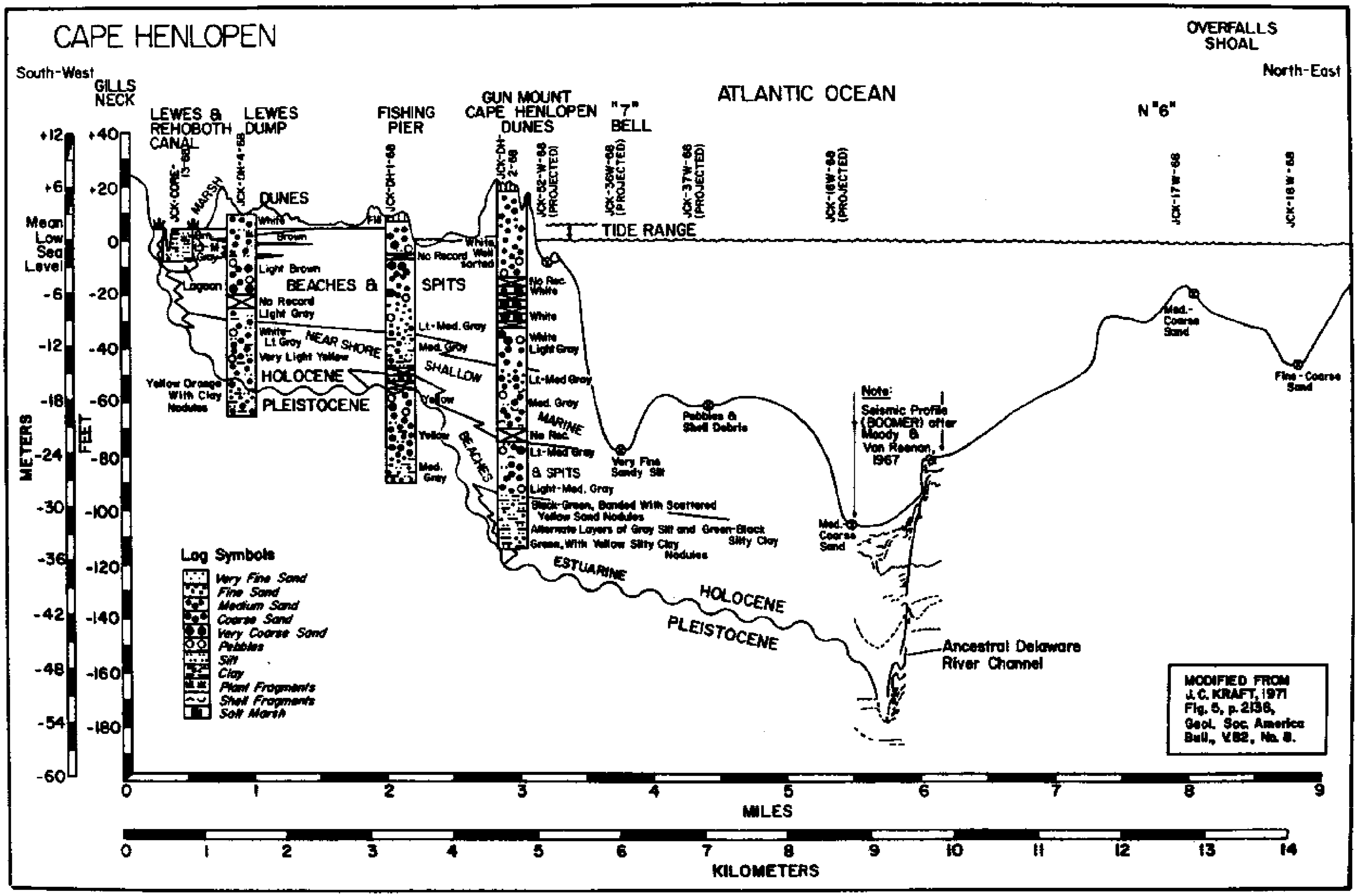


Figure 36. Geologic cross section, Cape Henlopen to Overfalls Shoal.
See Figure 32 for line of cross section.

Shoal toward New Jersey's Cape May. This cross section shows a very complex interrelationship of various types of shallow marine and coastal sediments. Toward the right side of Figure 36, the deep ancestral channel of the Delaware River has been identified, using seismic techniques by Moody and Van Reenan (1967). This ancestral channel of the Delaware River Valley was incised to approximately -180 feet below present sea level when the shoreline of Atlantic coastal Delaware lay near the outer edge of the adjacent continental shelf. Sea level approximately 12,000 to 14,000 years before present was 340 feet below present. Thus the ancestral Delaware River channel at that time was a fresh water river flowing southward along the axis of Delaware Bay. As relative sea level rose across the continental shelf it began to drown this ancestral Delaware River channel and its adjacent tributaries. The area shown in the cross section (Figure 36) is infilled with large sections of shallow nearshore marine and estuarine sands and silts.

In addition a beach is indicated along the edge of the underlying older sediment area. This beach migrated to the west and upward into the vicinity of present Lewes-Rehoboth Canal. Then, because of the very large amount of sand being eroded from the Atlantic coastal area and transported north, the beach began to move seaward and northward as a beach spit system. Beach accretion ridges may still be seen along the northeast portion of the Lewes Creek Marsh as low-lying points of sandy ridges extending into the marsh, now heavily tree-covered or as very low-lying lines or lineament elements shown on Figure 32, the air photograph.

Originally sand flowed north and around the Cape in a broad curve and thence southward again in what are known as "recurved spits" into the area of present Lewes Creek Marsh. At that time, the recurved spit tips would have flowed into a shallow water body that would have been, again, a shallow coastal lagoon. As time went on and more sand flowed north and around the Cape, the Cape became broadly rounded or blunted and sand flowed on westward in a steady stream past Lewes Beach and on to the north. At this time, the Cape would have been referred to as a broad cuspate spit. Finally, because of the construction of the inner breakwater of Breakwater Harbor, the spit migrated north to a point where the sands migrating around the Cape could no longer flow in a smooth stream into the inner harbor area and on along the Delaware Bay shoreline. Rather they began to flow around the Breakwater Harbor into the Harbor of Refuge and into deeper water. Accordingly, the spit began to become long and narrow, growing toward its present configuration which is known as a simple spit.

Figure 37 is a geologic cross section across Lewes Creek Marsh from Wolfe Neck thence across low-lying spit tips, a broad transgressing coastal dune, the beach area, and then into the shallow marine area of Hen and Chickens Shoal. This cross section in particular shows the migration of the beach and spit environment along the erosion surface of older sediments landward and westward and upward into the vicinity of Lewes Creek Marsh and thence seaward again with the migration of the spit northward. Interfingering or intertongued with these beach sediments are estuarine-shallow marine sediments clearly identified from their molluscan fauna. Eventually as the spit sands flowed smoothly around the Cape and north by Lewes Beach, the body of water behind Lewes Beach and the spit in the present vicinity of Lewes Creek Marsh formed an enclosed body of water, or coastal lagoon. This coastal lagoon did not last for a very long time. Its lagoonal muds are very thin as compared with those of the Great Marsh and other coastal lagoons to the north and south. With the infilling of the lagoon with silts, a low-lying tidal marsh, the present Lewes Creek Marsh, filled across the area. We estimate this to have occurred within the past two to three hundred years. The records of the Dutch when they arrived at the site of Zwaanendael in 1629-31 contain a clear sketch which suggests a relatively broad Lewes Creek or Lewes Creek Sound area known as Bloemaerts Kill extending southward along the present Lewes Creek and thence into the area of the Lewes Creek Marsh. Here again (Figure 37) one of the borings penetrated the relatively thin earlier Pleistocene sediments into the Miocene-Age sediments which underlie all of southern Delaware.

When Figure 32, the air photograph, is viewed with these cross sections in mind, it becomes obvious that older land upland dominates from the area of Rehoboth Beach in a relatively straight line north and west to the town site of Lewes, thence along Lewes Creek to the DeVries Monument and thence westward south of Canary Creek Marsh. This relatively straight line was carefully examined in the vicinity of North Shores, Wolfe Neck, and Gills Neck. It is broadly rounded in a relatively smooth set of arcs. These are suggestive of ancient shoreline areas of the ancestral Delaware Bay before the Atlantic coast had eroded into this area. It is hypothesized that these were highlands against the sea or shoreline areas of approximately 3,000 or 4,000 years before present, a time at which one could have stood upon Wolfe's Neck and looked north-eastward across the relatively broad Delaware Bay.

Thus all of the land from the town site of Lewes southward to the town site of Rehoboth Beach is "new land" formed within the past three millennia by erosion from the Atlantic area, building to the north, and by migration landward and upward. The processes in action continue. Present coastal erosion rates in the Atlantic coastal area of Cape Henlopen are approximately 8 to 10 feet per year averaged over a century and a half. Present coastal erosion rates in the Rehoboth Beach area averaged over a century and a half are approximately 3 feet per year.

This inevitable shoreward movement of the coast continues. Estimates made by the U.S. Army Corps of Engineers in the latter part of the last decade suggest that 450,000 cubic yards of sand pass a single point along the open Atlantic coastal area of Delaware during any single year. One-third of this sediment is estimated to go to Cape Henlopen and redeposit into the deeper waters of the Cape and around into the Lewes Harbor area. The other two-thirds is presently unaccounted for. Probably the bulk of it is carried seaward and remains as a shallow marine sand or lag deposit of the ongoing transgression. Some of the sand is washed landward across low-lying washover barriers such as at Whiskey Beach, north of Rehoboth Beach. In addition, some of the sand is caught by the winds in the coastal area and built into relatively high coastal dunes such as the coast parallel dune near the Lewes Naval Facility north of Whiskey Beach.

For a time, in the latter part of the 19th century, a large amount of this sand was transported and deposited into the area of the migrating Great Dune of Lewes. Now, however, much of the sand of the Great Dune

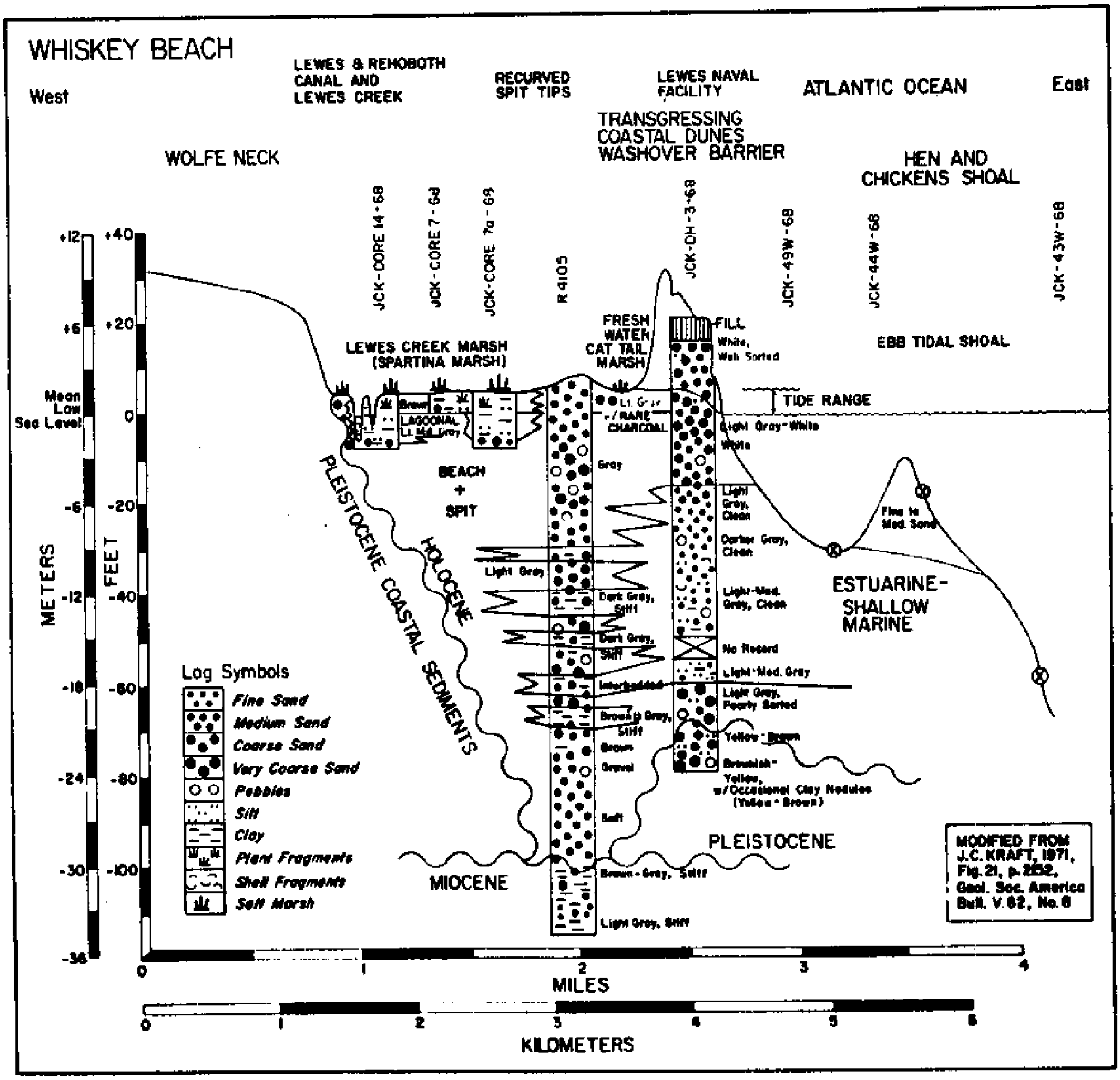


Figure 37. Geologic cross section, Lewes Creek Marsh-Whiskey Beach, Delaware. The line of section is shown in Figure 32.

has been quarried and removed from the site. The eastern part of the Great Dune has been stabilized at approximately 80 to 90 feet above present sea level and, with continued growth of vegetation in the area will probably cease to move within the next few decades. The low-lying washover feature at Whiskey Beach is extremely important. This is a point at which a storm could break through the barrier and relatively low-lying coastal dunes and send a large sheet of water into the Lewes Creek Marsh. Flooding of this type would tend to move into the area of the lowest parts of settlements north of Rehoboth Beach that extend into the low marshy area in the vicinity of North Shores.

Figure 38 is an air photograph of the lagoon barrier coastal area from Rehoboth Beach southward to just north of the town site of Bethany Beach. This lagoon barrier coast is also an area of constant change. As stated before, coastal erosion in this segment of the Atlantic coast of Delaware moves approximately 450,000 cubic yards of sand seaward, northward over the barrier and into the tidal deltas each year. This massive removal of sand from the barrier coast results in the translation of the shoreline area landward and westward and possibly slightly upward in a continuing fashion. Geological studies of the lagoon barrier coast have been continuing in the Department of Geology over the past decade.

Figures 39, 40, 41, and 42 are cross sections across Rehoboth Bay and Indian River Bay. The bays of Delaware are typical coastal lagoons behind ocean barriers. Low-lying shoreline or lagoon-barrier coasts are noteworthy for being either transgressive, with the ocean moving across the land, or regressive, with the barrier becoming wider and wider as the sea retreats from the area. The coastal barriers of Delaware are typical transgressive lagoon coastal barriers. They bear no resemblance other than a superficial geographic resemblance to the other regressive types of lagoon barrier coasts of the world. The elements of transgression are obvious from Figure 39. Numerous small streams flow into the bays and appear to be drowned by the water or the peripheral or fringing marshes. The shoreline area of the Atlantic Ocean is straight, indicating continuous smooth erosion. The small variations from a straight line are either the result of different kinds of outcroppings in the coastal

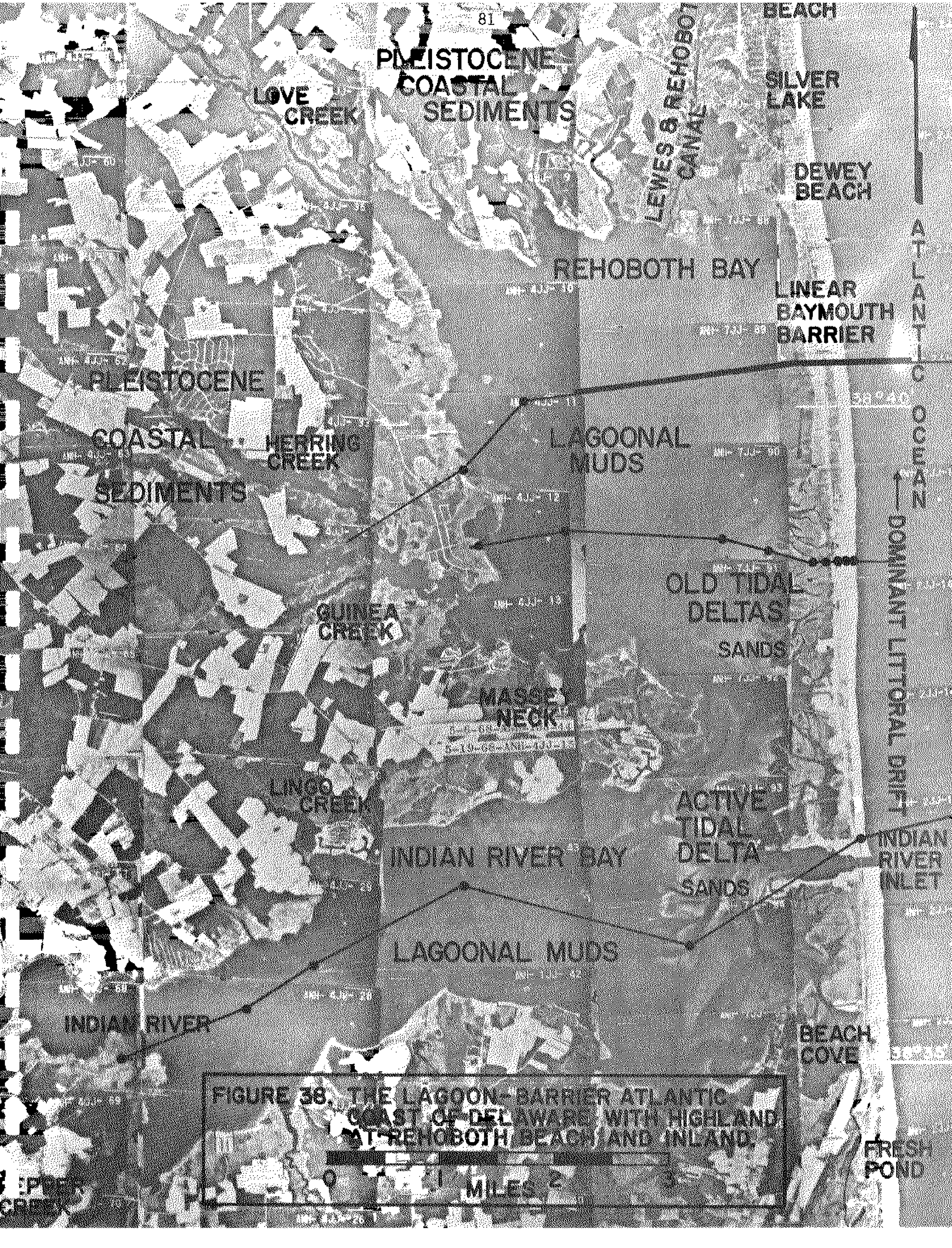
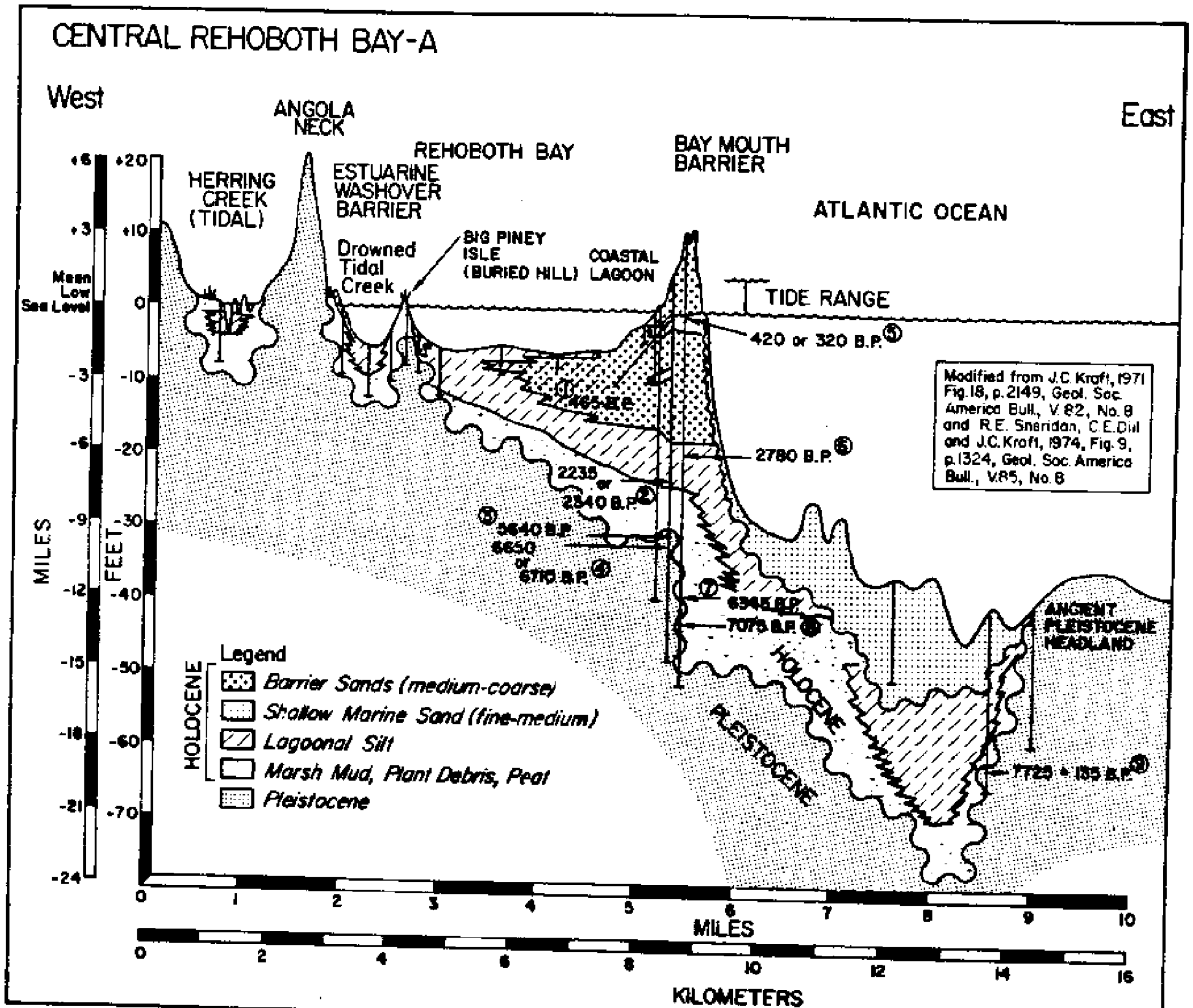


FIGURE 38. THE LAGOON-BARRIER ATLANTIC COAST OF DELAWARE, WITH HIGHLAND AT REHOBOTH BEACH AND INLAND.



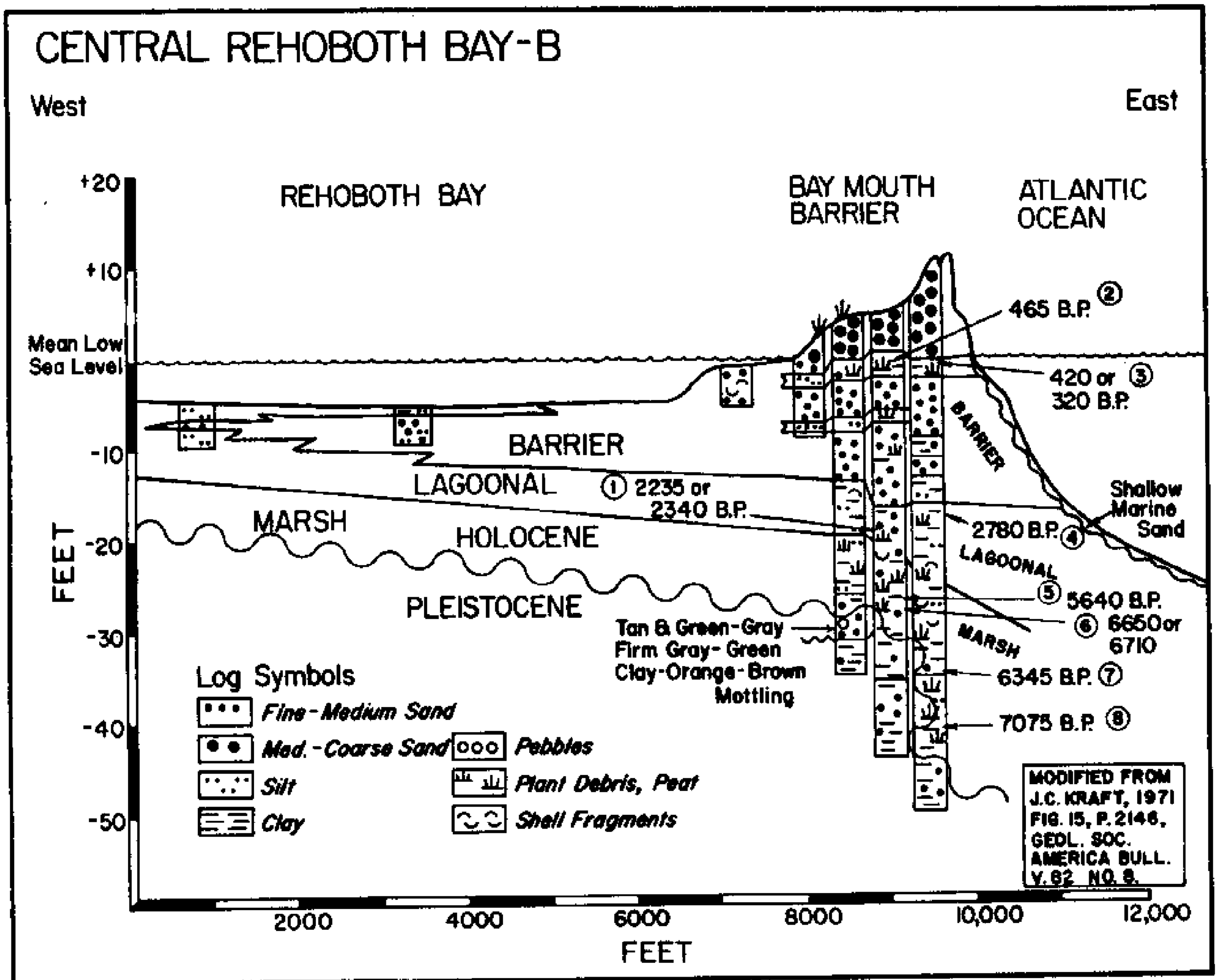
RADIOCARBON DATES ARE GIVEN IN CALENDAR TIME MASCA CORRECTIONS: RADIOCARBON YEARS, 5568-1/2 LIFE = ① 350 ± 130 B.P. ② 2180 ± 150 B.P. ③ 4860 ± 180 B.P. ④ 5860 ± 340 B.P. ⑤ 250 ± 140 B.P. ⑥ 2630 ± 190 B.P. ⑦ 5470 ± 200 B.P. ⑧ 6190 ± 190 ⑨ 5730-1/2 LIFE DATE; 5568-1/2 LIFE = 7500 ± 135 B.P.

Figure 39. Geologic cross section across Rehoboth Bay, the Atlantic barrier and into the nearshore marine area. See Figure 38 for line of cross section.

area, or are caused by the introduction by man of groins and jetties such as those at Indian River Inlet and at Rehoboth Beach.

Figure 39 is a geologic cross section from Herring Tidal Creek across a low-lying highland thence into Rehoboth Bay and across the baymouth barrier into the adjacent Atlantic Ocean. This cross section shows that the sediments of the fringing marsh, lagoon, and barrier are repeated in the subsurface as evidenced by drill-hole studies by geologists. The borings made on the baymouth barrier and the shallow marine area offshore in the Atlantic Ocean encounter the sediments and fossil remnants of mollusks and organic materials of coastal marshes, similar to those presently extant around Rehoboth Bay. Radiocarbon dating of the organic materials, and particularly the organics of the tidal marshes in the subsurface, tell us the times at which the coastal marshes were living and their positions in the past. As may be seen from Figure 39, a geologic history of the area may be constructed with some precision, of the period 7725 years before present at which time a fringing marsh around a relatively narrow coastal lagoon lay under the nearby adjacent Atlantic shoreline area.

Immediately adjacent to the east lay an ancient Pleistocene highland or hill of that time. With the continuing erosion of the coast and rise in relative sea level landward and upward, the coastal sedimentary environments have moved in the same fashion. Coastal tidal marsh and lagoon sediments have migrated from their lowest position in Figure 39 landward and upward in a sequence of correlatible layers into the vicinity of the present Rehoboth Bay. The timing is fairly precise. The rates of erosion of the coast may be projected in a fairly accurate manner, both from the historic record of the past 150 years and from the geologic record of the past 10,000 years. The lagoon barrier coast shown in cross section on Figure 39 is a normal feature of our Atlantic coastal Delaware and has been a normal feature of this coastal area for at least the past 8 millennia. Throughout that time there has been a steady and regular translation of the shoreline and of the shoreline environments in a landward direction.



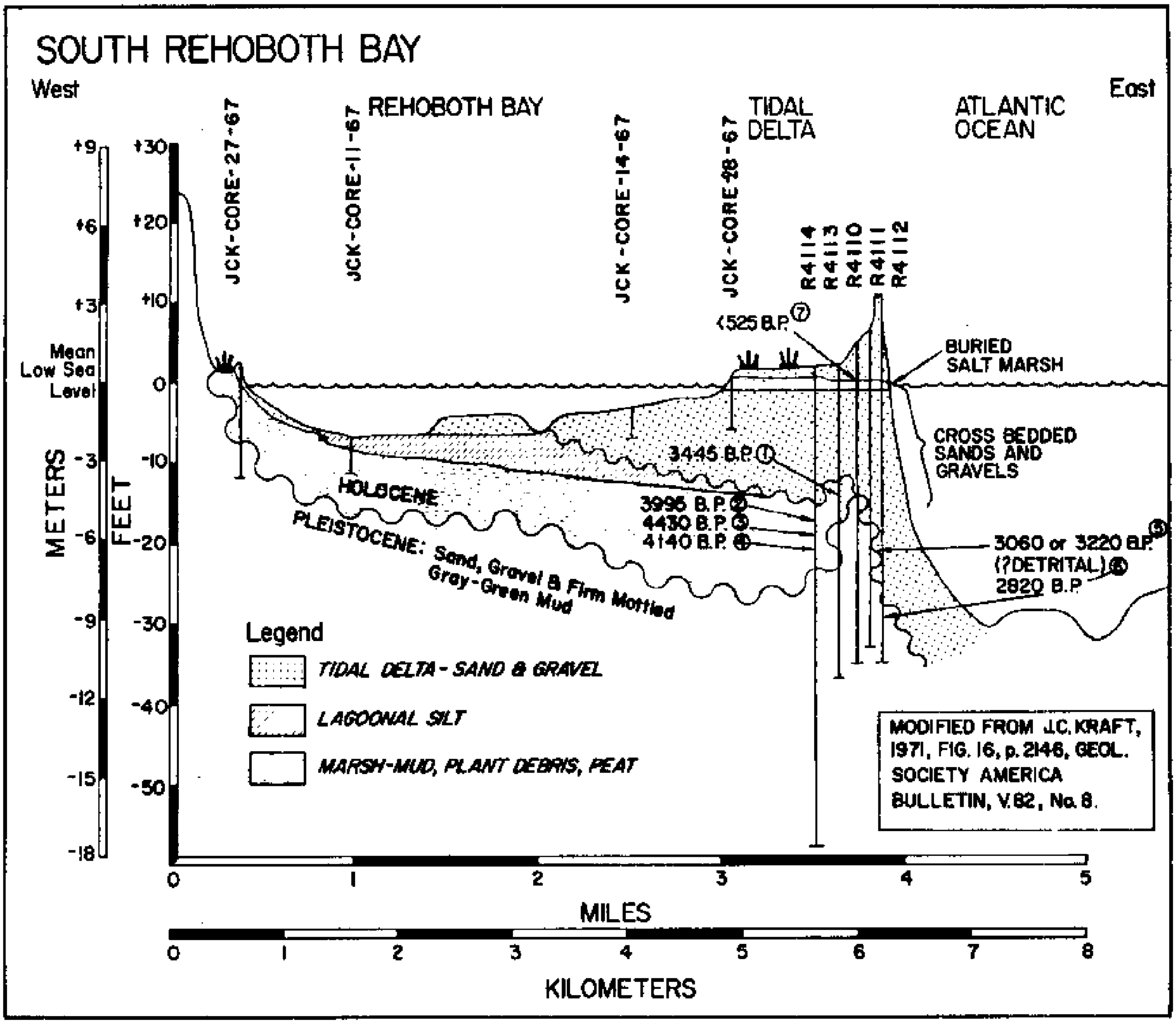
RADIOCARBON DATES ARE SHOWN IN CALENDAR TIME MASCA CORRECTIONS:
RADIOCARBON YEARS, 5568-1/2 LIFE=① 2180 ± 150 B.P. ② 350 ± 130 B.P.
③ 250 ± 140 B.P. ④ 2630 ± 190 B.P. ⑤ 4860 ± 180 B.P. ⑥ 5860 ± 340 B.P.
⑦ 5470 ± 200 B.P. ⑧ 6190 ± 190 B.P.

Figure 40. A detailed geologic cross section of the barrier between Rehoboth Bay and the Atlantic Ocean. See Figure 38 for line of cross section.

Figure 40 is a detailed cross section of the baymouth barrier south of Dewey Beach between Rehoboth Bay and the Atlantic Ocean. Here a more detailed geologic interpretation of drill-hole borings is shown. The line of section is the same as in Figure 39. Erosion occurs in the beach area of the Atlantic Ocean and in the nearshore or foreshore submarine area. Shallow marine sands are left behind by part of the sediment eroded away. Another portion of the sediment is moved into the littoral drift stream parallel to the beach dominantly northward toward Cape Henlopen. Another important amount of the sand is washed across the barrier and into the lagoon. As indicated in Figure 40, where more detail can be seen of the barrier, a large wedge of sand has begun to infill the eastern half of Rehoboth Bay. This sand is part of the barrier just as much as the relatively narrow land surface that we see in the air photograph Figure 38. A barrier adjacent to a coastal lagoon is in fact a much larger feature in the subsurface than in the surface. It has an "iceberg effect" in cross section.

Figure 41 is a geologic cross section across the southern part of Rehoboth Bay. As may be seen in Figure 38, the baymouth barrier is linear along the northern side of Rehoboth Bay along the Atlantic Ocean, and sublinear along the southern part of Rehoboth Bay. Abandoned channels of old inlets that had protruded through the barrier may be seen on the air photograph. In Figure 41 there is a cross section through one of the tidal deltas of sand and gravel deposited when an old inlet existed in the southern part of Rehoboth Bay. Accordingly, this is an area in which sand and gravel have moved much further westward across the floor of Rehoboth Bay. The sequence of migration of the fringing marsh, lagoonal muds, and barrier is disrupted in this geologic cross section, in view of the fact that tidal channels through baymouth barriers tend to erode deeply as they migrate back and forth. Thus the sequence of radiocarbon dates and the sequence of sediments is not so ideal or so straightforward as presented in Figures 39 and 40.

Rehoboth Bay is relatively square in outline. It is formed by the drowning of the junction areas of a large number of relatively small stream valleys that have flowed into this area in the past. The major



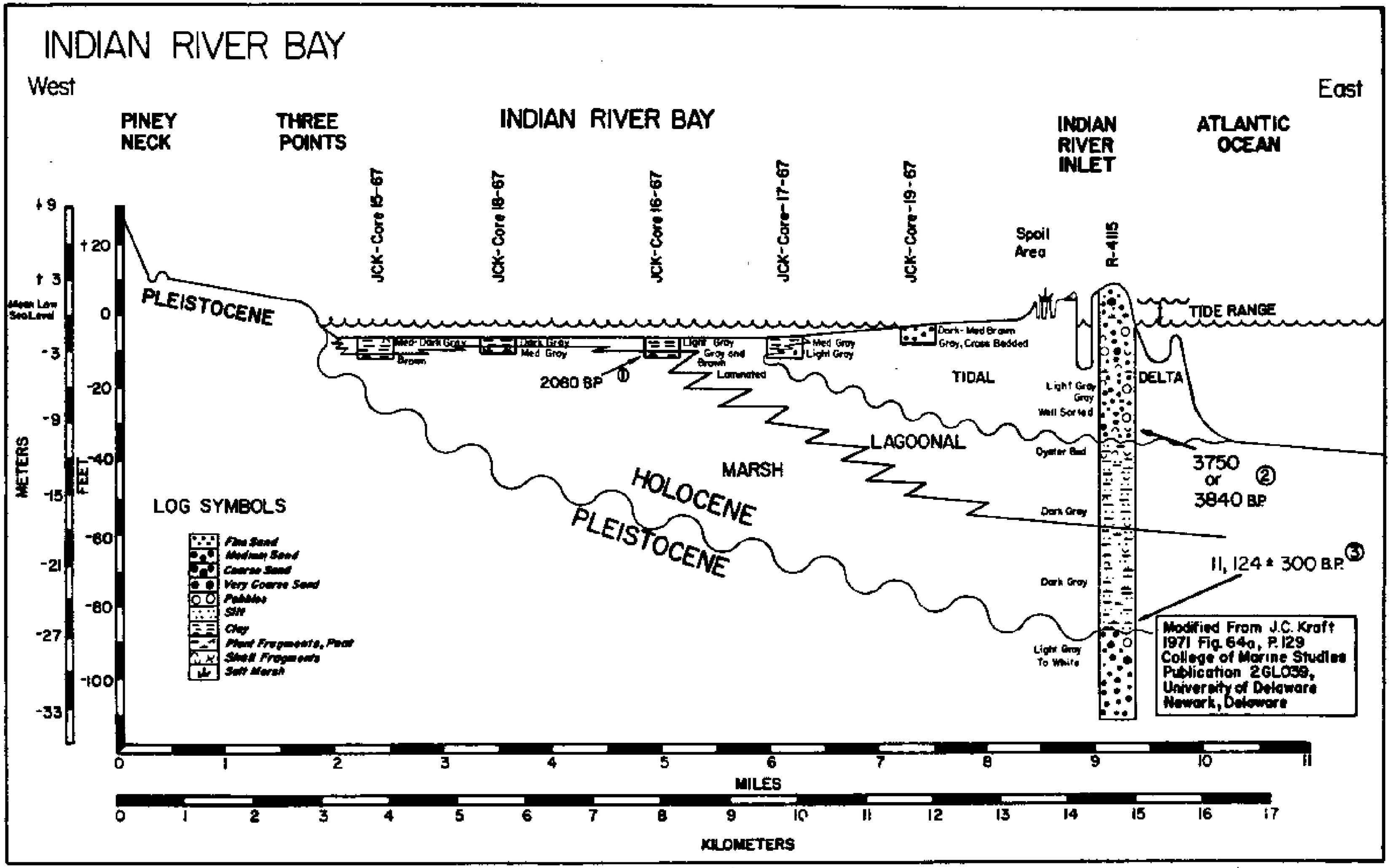
RADIOCARBON DATES ARE SHOWN IN CALENDAR TIME MASCA CORRECTIONS: RADIOCARBON YEARS, 5568-1/2 LIFE = ① 3130±170 B.P. ② 3520±160 B.P. ③ 3890±170 B.P. ④ 3780±170 B.P. ⑤ 2870±160 B.P. or 2960±180 B.P. ⑥ 2660±530 B.P. ⑦ 5730-1/2 LIFE DATE; 5568-1/2 LIFE=<510 B.P.

Figure 41. Geologic cross section, South Rehoboth Bay. The line of cross section is shown in Figure 38.

streams were Guinea Creek, Herring Creek, and Love Creek. These streams joined in the center of the area of present Rehoboth Bay and flowed through the area of the northerly barrier eastward into an ancestral coastal lagoon and thence into the ancestral Delaware River.

Indian River Bay, to the south, is an elongate east-west trending drowned river valley. The dominant valley ancestral to the bay is that of Indian River; however, Pepper Creek and Vines Creek are also important tributaries to the west. An important northward-flowing tributary is that of White Creek in the southeast portion of the bay. These creeks joined and flowed through the present vicinity of Indian River Inlet eastward into the ancestral Delaware River which was flowing southeasterly toward the outer part of the Atlantic shelf approximately 11,000 years before present. Figure 42 is a geologic cross section along the axis of Indian River lagoon. A number of shallow cores were taken within Indian River Bay illustrating the nature of the mud-silt infill and the limits of the broad tidal delta infilling the eastern part of the lagoon. Here again, under the western part of Indian River Bay a shallow tidal marsh was encountered approximately 12 feet below present surface of the water. This marsh is dated as having been alive 2,080 years before present. Thus, the broad elongate Indian River Bay that we know is again a relatively young geologic feature. On the other hand, a geologic cross section across the mouth of Indian River Bay parallel to the Atlantic coastal barrier shows a quite different story. Details of the geology of this area were delineated by Kraft (1971a).

Geologic boring R-4115 (Figure 42) by the Shell Development Corporation indicates an approximately 90-foot thick section of Holocene sediments deposited in the axis of the ancestral Indian River Valley at Indian River Inlet. Much of the base of this section is comprised of organic tidal marsh muds. The central part of this section is that of a lagoonal mud, including beds of oysters (Crassostrea virginica) and other mollusca and fossils, indicating a shallow coastal lagoon. The relatively thick sand-gravel sequence shown in this boring is the product of a tidal delta. The area of a tidal delta through a barrier



Radiocarbon Dates Are Given In Calendar Time Masca Correction:
Radiocarbon Years, 5568 1/2 Life = ① 2060 ± 110 B.P. ② 3430 ± 170 B.P. ③ = 5730 1/2 Life Date; 5568 - 1/2 Life = 10,800 ± 300 B.P.

Figure 42. Geologic cross section, Indian River. The line of cross section is shown in Figure 38.

is one of deeply entrenched or incised tidal channels. Thus, wherever a barrier includes tidal-delta-tidal-channel systems, it may be relatively thicker than at the long linear baymouth barriers. Radiocarbon dates from organic marshes at the base of the Holocene Epoch sedimentary sequence in Figure 42 indicate that the valley was beginning to be infilled by tidal waters 11,124 years before present. Thus, here again, we have a history of steady infill and rise of relative sea level in the Delaware coastal area over the past 10 to 11 millennia. The tidal marsh indicated at 11,124 years before present would have been the tidal marsh at the very head of tidal intrusion of a tidal creek for its time. Bay and lagoon systems would have lain seaward across the Atlantic continental shelf in the area now submerged. From other studies, we know that tidal waters of 11,000 years ago extended northward almost to the vicinity of the present site of Philadelphia. In addition, tidal waters lay westward and eastward along tributary creeks to the ancestral tidal Delaware River 9700 years before present in the vicinity of the mouth of the Murderkill River.

As has been mentioned above, much of the southern part of the State of Delaware is comprised of a low-lying coastal plain made up of the shallow marine sediments deposited during the Sangamon Interglacial approximately 25 to 35 feet above its present position. This broad low-lying coastal plain contains many undrained depressions. We are only now beginning to understand its origins. Some geologists feel that it is very complex in structure and of highly varied ages in origin and that it may be a long time until we know precisely the nature of the origin or formation of the lower Delaware coastal plain. Some features, however, are obvious. For instance, Thompsons Island at the north side of Rehoboth Bay is comprised of broad sheets of sand washed over a coastal barrier of an ancient sea. In the Lewes-Rehoboth Canal, near the sewage outfall, lie the remnants of an ancient coastal marsh. In the area of Fresh Pond and Beach Cove at Quillens Neck, north of Bethany Beach, lie two very linear ridges that are presently being farmed (Figure 38). These are ancient barrier beaches. It is not known at present whether they were barrier beaches 100,000 years ago, or for reasons less definite, barrier beaches of approximately 30,000 years ago. They are presently under detailed study.

Figure 43 is an air photograph of the area from just north of Bethany Beach southward to the southern border of the State of Delaware at Fenwick Island, Delaware. This area of the coast is one of a highland against the sea at Bethany Beach, and a baymouth barrier or low-lying washover barrier to the south and the north. To the north of Bethany Beach, the coastal barrier washes across into the salt marsh area of Salt Pond and Fresh Pond and Indian River Lagoon. A low-lying neck of land (a Sangamon Age? barrier) protrudes to the coast in one area just west of Fresh Pond. Bethany Beach is a relatively narrow upland area against the sea.

By examining Figure 43 carefully a slight bulge may be observed at the town site of Bethany Beach. This is an indication of the lesser erosion caused by a groin system protecting its beach; the areas north and south are subject to more rapid erosion. Just south of Bethany Beach the barrier again merges with a low-lying marsh westward to South Bethany, York Beach, and other areas. Here again the shoreline area should be classified as a low-lying coastal washover barrier. Still further south, a typical low-lying washover barrier lies adjacent to Little Assawoman Bay southward to the narrow marshes at Fenwick Island. This washover area, from South Bethany Beach southward is particularly thin and narrow because of the relatively limited supply of transported sand to the area.

The average littoral drift flow in this area has tended to be southward toward Ocean City and thence southward into the Assateague area. Thus, lying at the nodal point of Bethany Beach, the sand-gravel barriers tend to be extremely narrow and very much subject to washover and storms such as the frequent northeasters that hit this coast. All the elements are indicative of very rapid landward transgression of the barrier across the low-lying coastal marsh and Little Assawoman Bay. Here, in the beachface area after any storm, one can see outcroppings of marsh muds on the beachface itself, an indication of extremely rapid rates of erosion. Similar erosion of marsh muds in the foreshore-lower beach area may be observed after a storm at Whiskey Beach, to the north of Rehoboth Beach, and elsewhere. Such features are less well and more

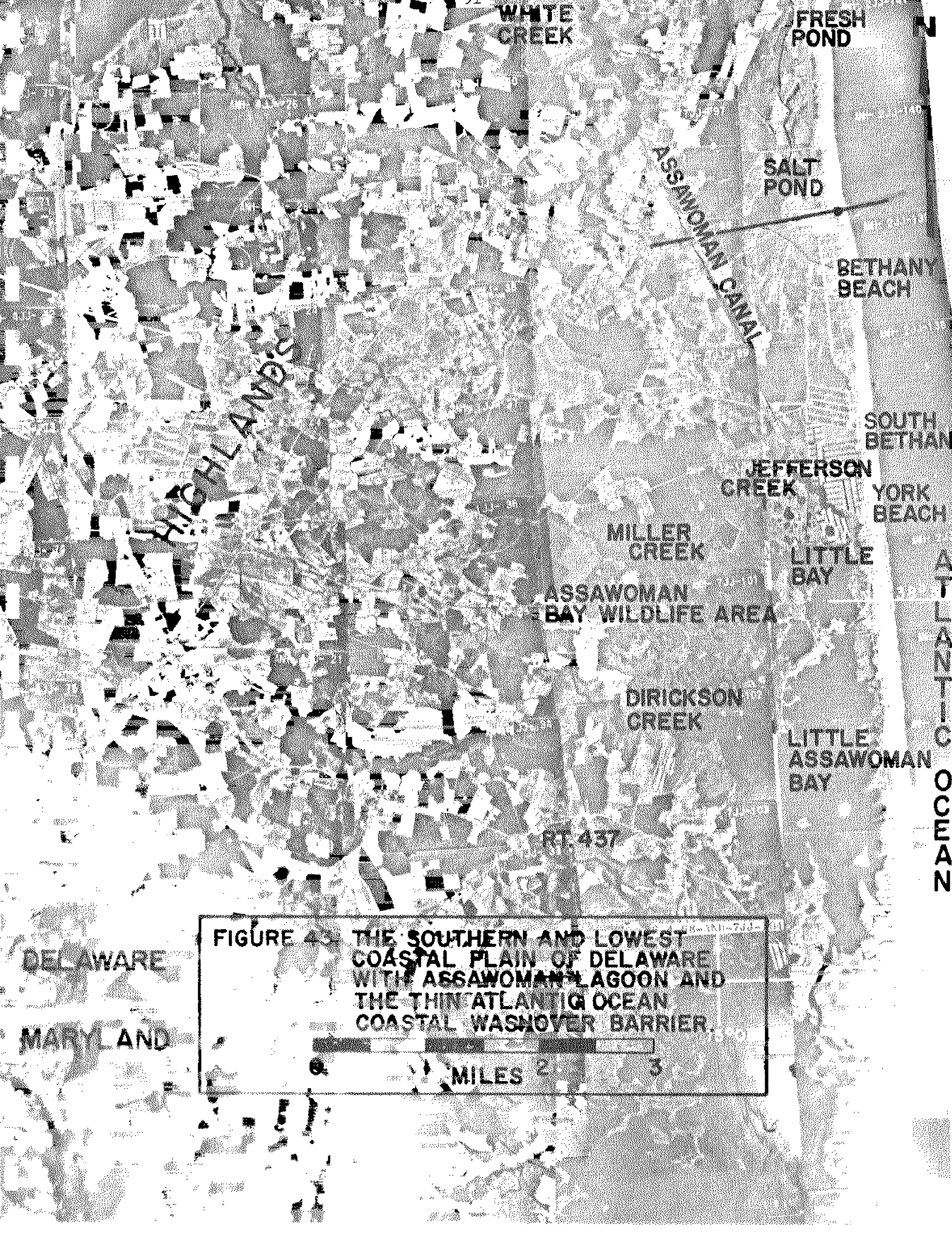


FIGURE 43- THE SOUTHERN AND LOWEST COASTAL PLAIN OF DELAWARE WITH ASSAWOMAN LAGOON AND THE THIN ATLANTIC OCEAN COASTAL WASHOVER BARRIER.

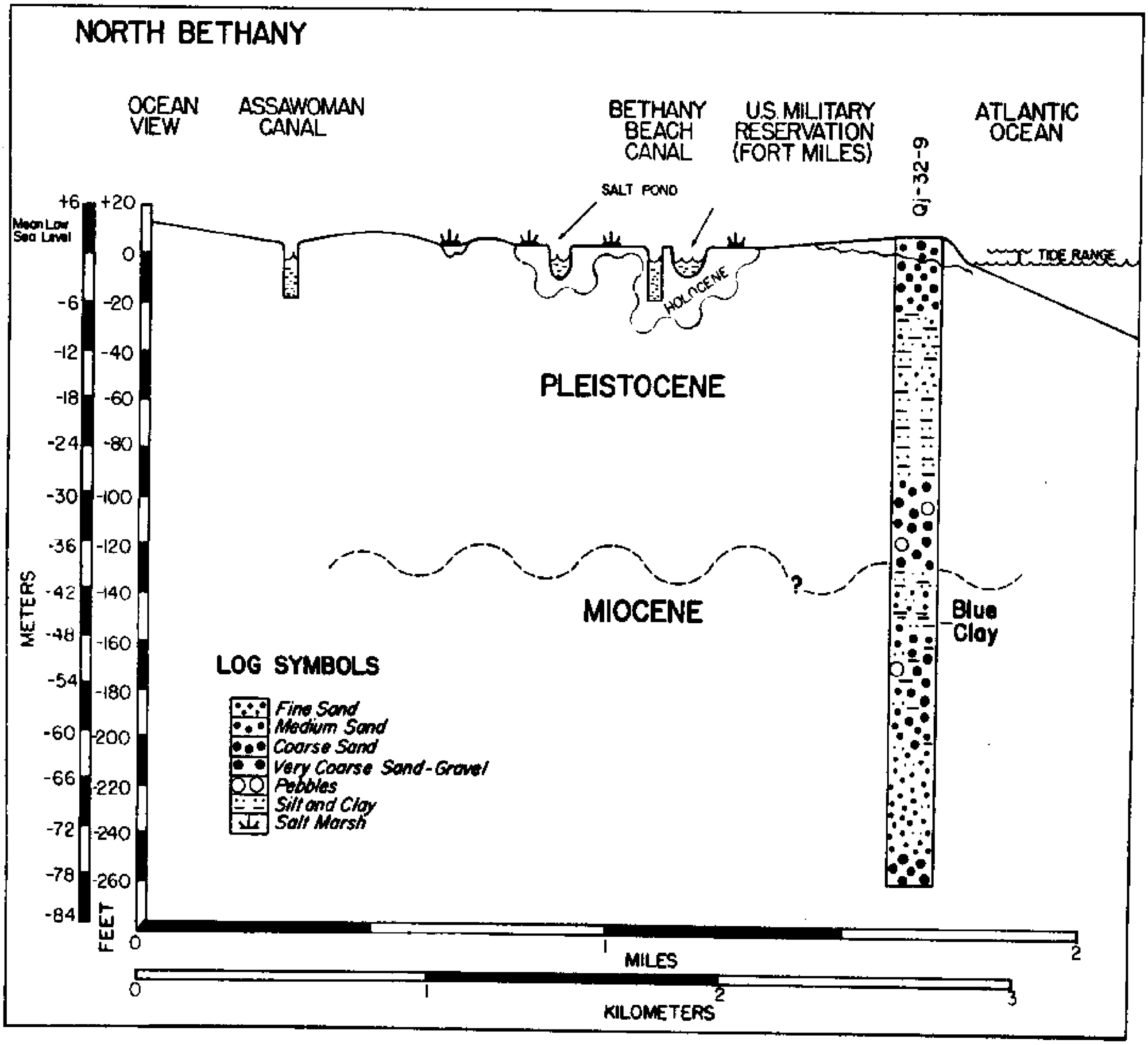


Figure 44. Geologic cross section at North Bethany Beach, Delaware. The line of cross section is shown in Figure 43.

infrequently exposed in the foreshore area just beneath mean-low sea level opposite Rehoboth lagoon. However, at that site, a larger amount of sand is in motion along the beach and washover area, and the low marshy erosion surface tends to be hidden by the sands of the beach.

Figure 44 is a geologic cross section from Ocean View and the Assawoman Canal area eastward through Bethany Beach and into the adjacent nearshore Atlantic coastal area. The sediments are almost totally Pleistocene shallow marine sediments underlain by Miocene shallow marine sediments, as indicated. In the vicinity of Salt Pond, a very thin section of coastal marsh has been deposited. Thus the area is geologically very similar to the interfluve areas northward at Rehoboth Beach and north and westward along the Delaware Bay coastal area.

Figure 45* is a geologic cross section across the Delmarva Peninsula from the vicinity of Newark and northwest Delaware southward across the Atlantic coastal plain in the vicinity of Bethany Beach-Ocean City, Maryland. This geologic cross section, previously published (Kraft and Maisano, 1968), presents the stratigraphy of the Delmarva Peninsula in the Delaware area. The relatively thick section of sediments (over 8,000 feet thick in the southern coastal area) becomes ever thinner until it merges with the Piedmont Crystalline Province near Newark-Wilmington in the north. The sediments shown in the cross section vary in age from the Triassic Period of geologic time 225,000,000 years before present to the presently depositing sands-silts and muds of coastal Delaware. The rapidly thinning section of sediments shown is part of the northwestern flank of the Baltimore Canyon Trough geosyncline, the axis of which lies offshore on the outer continental shelf (Figure 4). At its greatest depth, the thickness of sediment in the axis of the Baltimore Canyon Trough geosyncline is believed to be over 40,000 feet. Thus we can see that the Delmarva Peninsula has only a relatively thin section of sediments in relation to the larger geologic structure of which it is a part. The sands and silts in clays of the geologic cross section shown have strongly compacted throughout geologic time. In addition they have been gradually sinking over the longer period of time.

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* At end of book

The majority of the sediments shown in the geologic cross section were deposited either on terrestial coastal plain-flood plain environments or in shallow marine environments. Nearly all of them were formed at or near sea level of their time. Exceptions, such as the Hornerstown formation, were probably deposited in an inner to mid-shelf marine environment. The fact that some of the sediments in the geologic cross section are now 8,000 feet below present and in the axis of the geosyncline are 40,000 feet below present is indicative of the fact that the Atlantic coastal plain-continental shelf is submerging over the longer geologic period of time. We can estimate that the rate of sinking is somewhat on the order of 40,000 feet over a period of 200 $\pm$ million years. However, this longer-term rate is not the important one in terms of present coastal erosion problems in Delaware. The shorter-term rate, determined by drill-hole evidence presented throughout this report and the radiocarbon dates taken, gives a precise indication of relative change for coastal Delaware over the past 10,000 years. The net movement of sea relative to land is upward, just as it is in the geologic cross section shown in Figure 45.

Over the longer geologic term, it has been more normal for the Delmarva Peninsula to be under water than above water. This is strongly indicated in Figure 45. At a time known as Oligocene time, approximately 40 million years before present, the entire Atlantic coastal plain-continental shelf was exposed for a brief period. Aside from that, at all times part of the Atlantic coastal plain-continental shelf has been submerged. The more permanent shoreline position for the Atlantic coastal plain-continental shelf is a line from Baltimore to Newark to Wilmington to Philadelphia rather than its present position, which is a happenstance of relative levels of sea at a halfway state between melting of the great ice caps that covered the earth approximately 14,000 to 16,000 years ago. It cannot presently be said whether or not this process will continue indefinitely into the future. Even a brief reversal of a thousand years or so could lead to a retreat of the ocean and expansion of land area. However, the geologic history as indicated by the drill-hole records of coastal Delaware suggests that the present marine transgression over the land has been a continuous one although at various rates over the past 10,000-year period and will probably continue.

GEOLOGIC ZONATION OF DELAWARE'S COASTS

The coast of Delaware, extending from Claymont on the tidal Delaware River southward along the western shoreline of Delaware Bay around Cape Henlopen and then south along the Atlantic coast of Fenwick Island may be classified into various geomorphic elements. In the north, the Piedmont Crystalline surface rises relatively rapidly from the relatively narrow coastal plain of the tidal Delaware River to elevations of greater than 300 feet above sea level. This Piedmont Crystalline Province lies from Claymont to Wilmington and thence westward to Newark. The narrow coastal marshes along the tidal river delta of the Christina River in this area have been almost destroyed by the development of highways, industrial plants, and other man-made structures such as the Penn Central Railroad system.

From Wilmington, at the mouth of the Christina River and the broad Cherry Island Marsh, southward to the vicinity of Augustine Beach, the coastal plain of Delaware is relatively high and undulating. The coastal zone of Delaware in this vicinity might be labeled as a high coastal plain adjacent to tidal waters. The coastal marshes may be narrow or broad but are always a product of intrusion along the axes of drowned stream valleys such as the Christina River and its tidal intrusion westward beyond the town of Christiana. This area is one of large numbers of upland surfaces merging with the shoreline of Delaware Bay. In view of the fact that coastal processes such as wave action and currents are relatively weak in this area, massive coastal erosion does not occur, and therefore large amounts of sand and gravel are not moved along the shoreline. The upland surface of this high coastal plain is deeply incised by the ancestral valley along which the tidal marshes are presently infilling.

As one proceeds southward from Augustine Creek and the Appoquinimink River area to the Kent County border, the coastal marshes of Delaware become much broader. In this area, lesser and lesser highland areas merge with the edge of coastal Delaware-Delaware Bay. However, the stream valleys are still deeply incised into the highland area. Further south, in the areas where highlands are immediately adjacent to the lower Delaware River and upper Delaware Bay, thin sandy washover barriers form. However, they are limited and discontinuous as is typical of the area of the Appoquinimink River marsh, the Black Bird Creek marsh and Bombay Hook. The area from the Appoquinimink River and Augustine Creek southward to Bombay Hook might be labeled as a mid-coastal plain low-lying marshy coast of the lower Delaware tidal river with rivers inland still deeply incised. From Bombay Hook southward, the Delaware River widens rapidly into Delaware Bay. The low-lying marshy coast continues to the town of Lewes, Delaware. The tidal streams are boarded by low-lying banks and flow across an almost flat surface of a Sangamon Age sea bottom. The number of highlands that merge with the sea and are presently actively undergoing erosion are very limited. A typical case is the upland surface at Bowers. A great number of coastal towns such as Kitts Hummock and Big Stone Beach have upland surfaces immediately underlying them and are subject to erosion from time to time, thus providing small amounts of sand and gravel to the littoral drift stream.

From the area of Bowers southward to the northern portion of the town of Lewes, at Roosevelt Inlet, lie the broadest low-lying coastal marshes of Delaware and the very low coastal Delaware plain. The upland surface of this plain is extremely flat and relatively poorly drained. It is characterized by thousands of small depressions that become slightly swampy during a heavy rainy season. Some of the depressions are deep enough to hold fresh water swamps of ponds permanently. Here again relatively deeply incised pre-Holocene or ancestral rivers of 14,000 to 15,000 years before present have cut a drainage pattern that persists to present. With relative sea level rise and infill of sediments along the axes of these rivers and their tributaries, a "drowning effect" has tended to subdivide the low-lying coastal plain into upland surfaces, very flat but fairly well-drained, known as "necks." This segment of Delaware's coastal zone may be considered to be the low-lying coastal plain with broad coastal marshes and thin sandy barriers. Larger amounts of sand and gravel sediment are available to the littoral drift stream in this area. In addition, another important factor occurs. Delaware Bay is relatively broad and the fetch is wide. Accordingly, winds and storms such as northeasters can develop enough wave activity to cause a winnowing action in the shoreline area, clean the sand and gravel and transport it in a littoral drift stream. In addition, the washover process of sand and gravel across the marsh surface occurs and the barrier tends to maintain itself although in a tenuous, thin, and very ephemeral fashion.

From the north end of Lewes Beach to the area of Whiskey Beach occur transitional coasts from Delaware Bay washover barriers to the simple spit Cape Henlopen, to the broad dune and washover barrier coastline of the Atlantic Ocean near the naval facility at Lewes and Whiskey Beach immediately adjacent to the south. This section of coast is the one of most active change. Coastal erosion rates are up to 10 feet per year averaged over a century and a half. The area of the inner Lewes Harbor is rapidly infilling with sediment moving around the Cape and into the Harbor. In addition, the presence of the inner breakwater tends to cause sediment to deflect around the breakwater. Possibly in the short-term (one decade or less) future, the Cape will join the inner breakwater, and sand eroded from the Atlantic shoreline area will very rapidly move around the breakwater toward the town of Lewes. The spit-dune and barrier segment of Delaware's coast is very rapidly migrating in time and space. Paleogeographic reconstructions in the area indicate that the entire triangular spit area was approximately 17 kilometers to the southeast about 6,000 to 7,000 years ago. Even three to four millennia ago it is probable that the triangular area of land between Rehoboth-Cape Henlopen-Lewes, was in a shallow southerly portion of Delaware Bay.

The shoreline area from Rehoboth Beach southward to Fenwick Island may be classified as a lagoon-barrier oceanic coast. This shoreline is prone to massive erosion during storms. The littoral drift stream, set up by waves approaching the coast, transports most of this eroded sand along the shore. Some material is carried into the shallow marine offshore area, while some sand from the shoreline area is washed landward into dune fields across washover barriers. The lagoon barrier coast is clearly one of a major transgression of the Atlantic Ocean over the land area. All elements observed along this coast indicate major migration of shoreline landward. The average rate of erosion determined historically over a century and a half is 10 feet per year in the north and decreases southward to 3 feet per year in the vicinity of Rehoboth Beach, and to 2 feet per year near Bethany Beach. From there northward during the major portion of the past 150 years, the littoral drift stream has tended to move to the north toward Cape Henlopen. South of Bethany Beach over most of the past 150 years the littoral drift system has been flowing to the south. Accordingly, the sand washover barrier south of Bethany Beach is relatively thin and narrow. Very little sediment is eroded and provided into the littoral drift stream in this area. On the other hand, the more rapidly eroding beach area to the north, eroding from Bethany Beach highland, highlands near the Indian River Inlet, and Rehoboth Beach area itself, provides a continuing stream of sediment flowing to the north.

In summary, then, the Delaware coastal area may be divided into five coastal zones as follows:

(1) A tidal coast against Piedmont area. Here an upper deeply incised coastal plain with highlands merges with the tidal Delaware River;

(2) A middle coastal plain area. In this region lesser numbers of highlands merge with the edge of the shoreline area in the vicinity of the lower Delaware River. The wave fetch is relatively narrow and therefore wave action is not severe;

(3) The broad low-lying coastal plain of southern Delaware adjacent to Delaware Bay. Here there is a broad wave fetch which results in wave action and littoral drift systems which help to maintain a barrier beach between the broad coastal marshes and the Delaware Bay.

(4) The spit-dune-marsh tract of Cape Henlopen covering the area from the tip of Lewes Beach to Cape Henlopen to Whiskey Beach; and

(5) The lagoon-barrier shoreline area extending from Rehoboth Beach southward to Fenwick Island.

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Figure 45. A geologic cross section across the Delmarva Peninsula from Newark, Delaware to Ocean City, Maryland showing the stratigraphy and geology of subsurface formations on the northwest flank of the Baltimore Canyon Trough geosyncline. This section was originally published in 1968. It is presented here to place Delaware's coasts in their geologic perspective on the northwest flank of the Baltimore Canyon Trough geosyncline. The correlations are essentially up-to-date; however, the enclosed block diagram is known to be out-of-date. Depths to basement in the axis of the geosyncline have long been known to be up to 35,000-40,000 feet, but at the time of original publication of the section, the senior author knew this as privileged information and thus a minimal depth configuration was published.

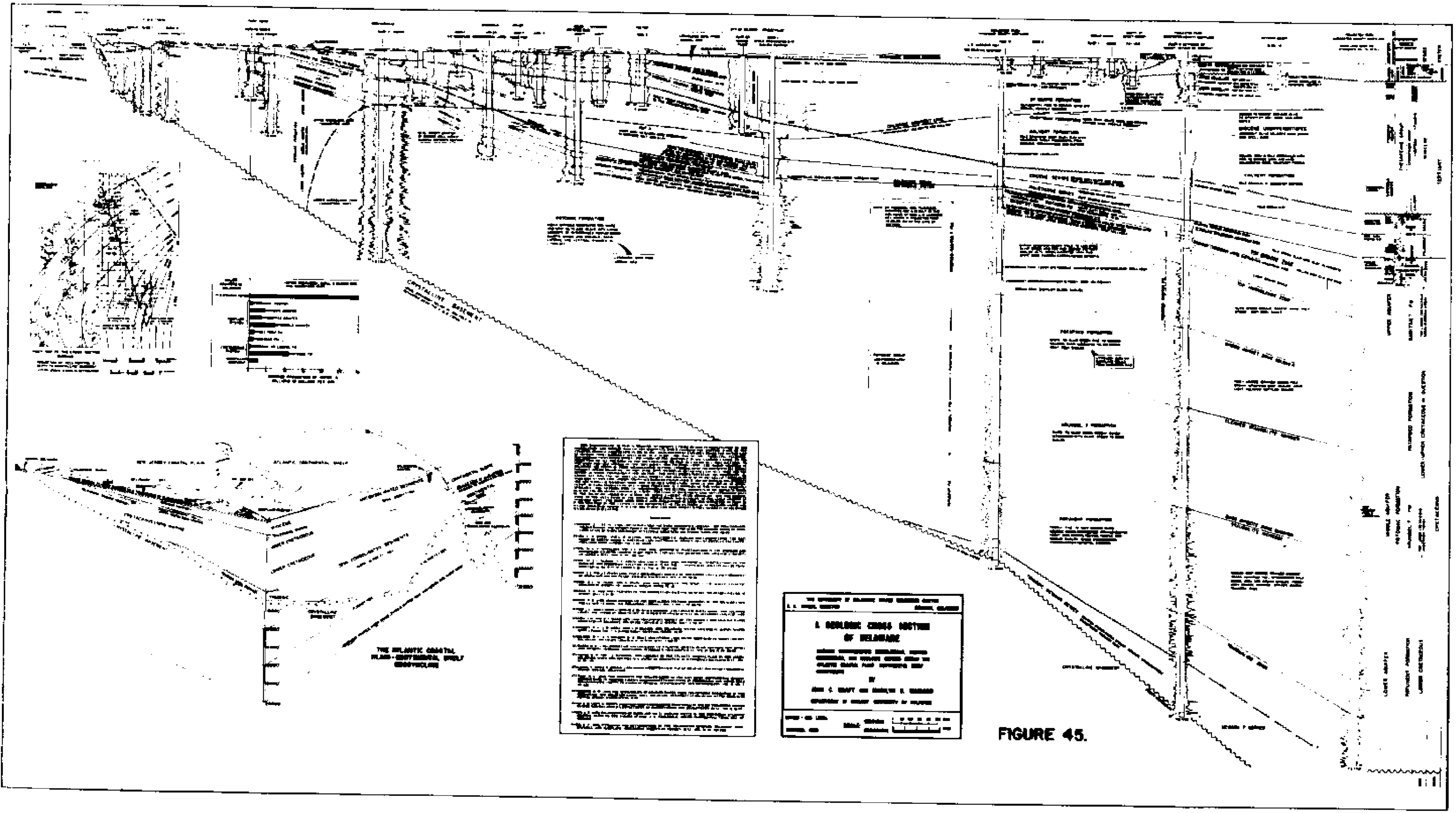

FIGURE 45.