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Leonard, Jay E.

Fisher, John J.

Leatherman, Stephan P.

Godfrey, Paul J.

Goldsmith, Victor

See next page for additional authors

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Authors

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Trips A-10 & B-10

COASTAL GEOLOGY AND GEOMORPHOLOGY OF CAPE COD - AN AERIAL AND GROUND VIEW

by

Jay E. Leonard* Dept. of Geology, Boston University
Boston, Mass.

John J. Fisher Dept. of Geology, Univ. of Rhode Island
Kingston, R.I.

Stephan P. Leatherman Dept. of Geology, Boston University
Boston, Mass.

Paul J. Godfrey Dept. of Botany, University of Mass.
Amherst, Mass.

Victor Goldsmith Virginia Institute of Marine Sciences,
Glouster Point, Va.

Clifford A. Kaye U.S. Geological Survey, Boston, Mass.

Harold P. Nilsson Dept. of Geology, University of Mass,
Amherst, Mass.

Robert N. Oldale U.S. Geological Survey, Woods Hole, Mass.

Peter S. Rosen Virginia Institute of Marine Sciences,
Glouster Point, Va.

INTRODUCTION

Cape Cod is a showplace of the results of the actions of geologic agents both past and present. This trip will include three separate, but integrated sections concerning modern coastal processes and past-glacial history. By means of an aerial overflight, coupled with selected ground trips, participants may view the process-response interactions of this dynamic area in a macro, meso and microscale frame of reference.

Section A (Macroscale) is an aerial overflight of the entire Cape Cod region, including the islands of Nantucket and Martha's Vineyard. Dynamic process interactions and their resultant geomorphic features will be viewed from the air. A better understanding of the complex area can be achieved through this macroscale overview.

Section B (Mesoscale) is a look at coastal geology and glacial geomorphology of the Atlantic shore of Cape Cod, north of Coast Guard Beach (Section C). On this section, the regional coastal erosion and deposition related to shoreline fulcrum, nodal points, wave refraction, and wave dynamics will be examined.

Section C (Microscale) is a detailed look at the processes occurring on Nauset spit. Through a series of cores and trenches, participants will study the area's geologic history, inlets and overwash fans. The interaction of vegetation and geological processes will also be examined with a look at plants as geological agents responding to

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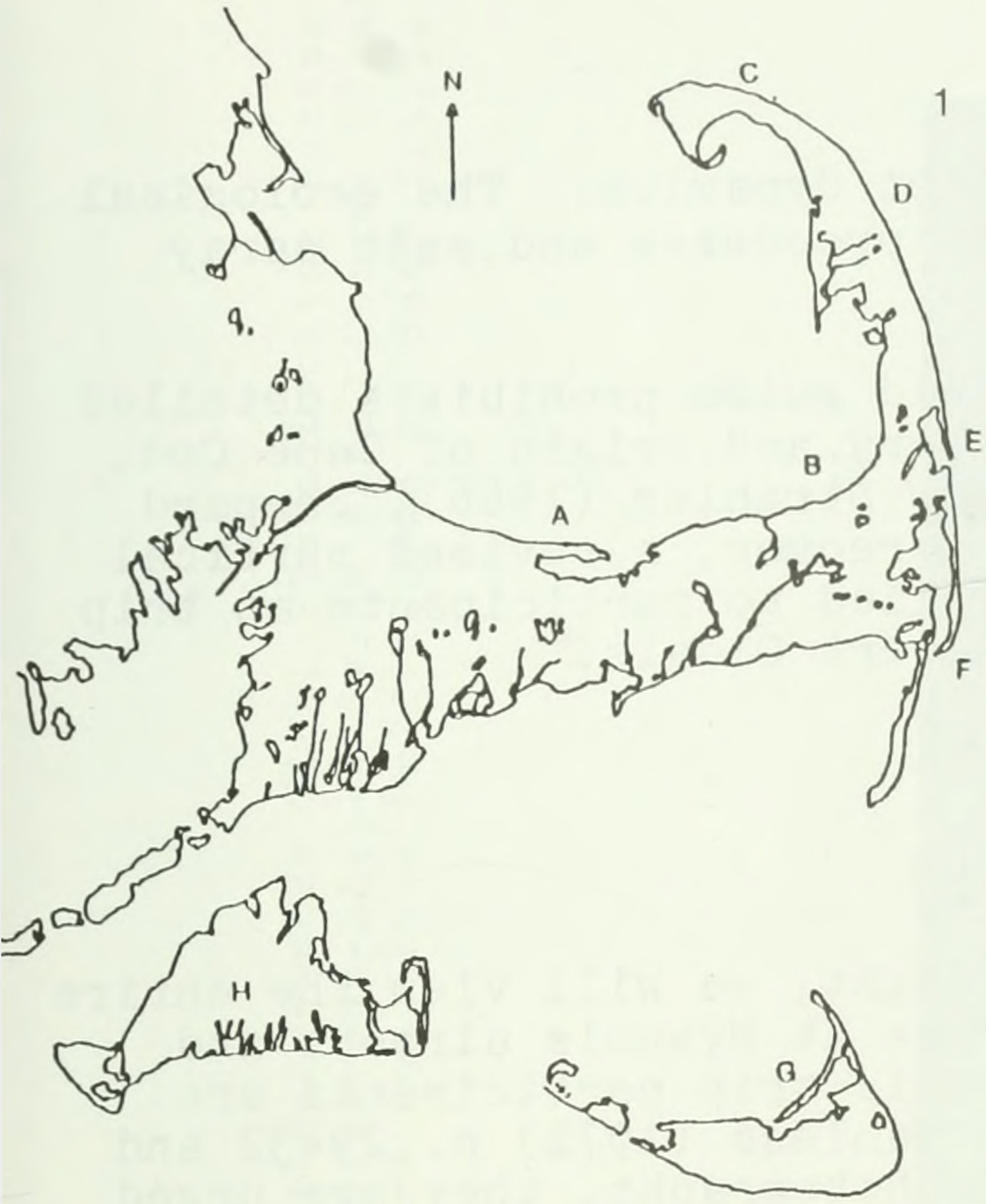
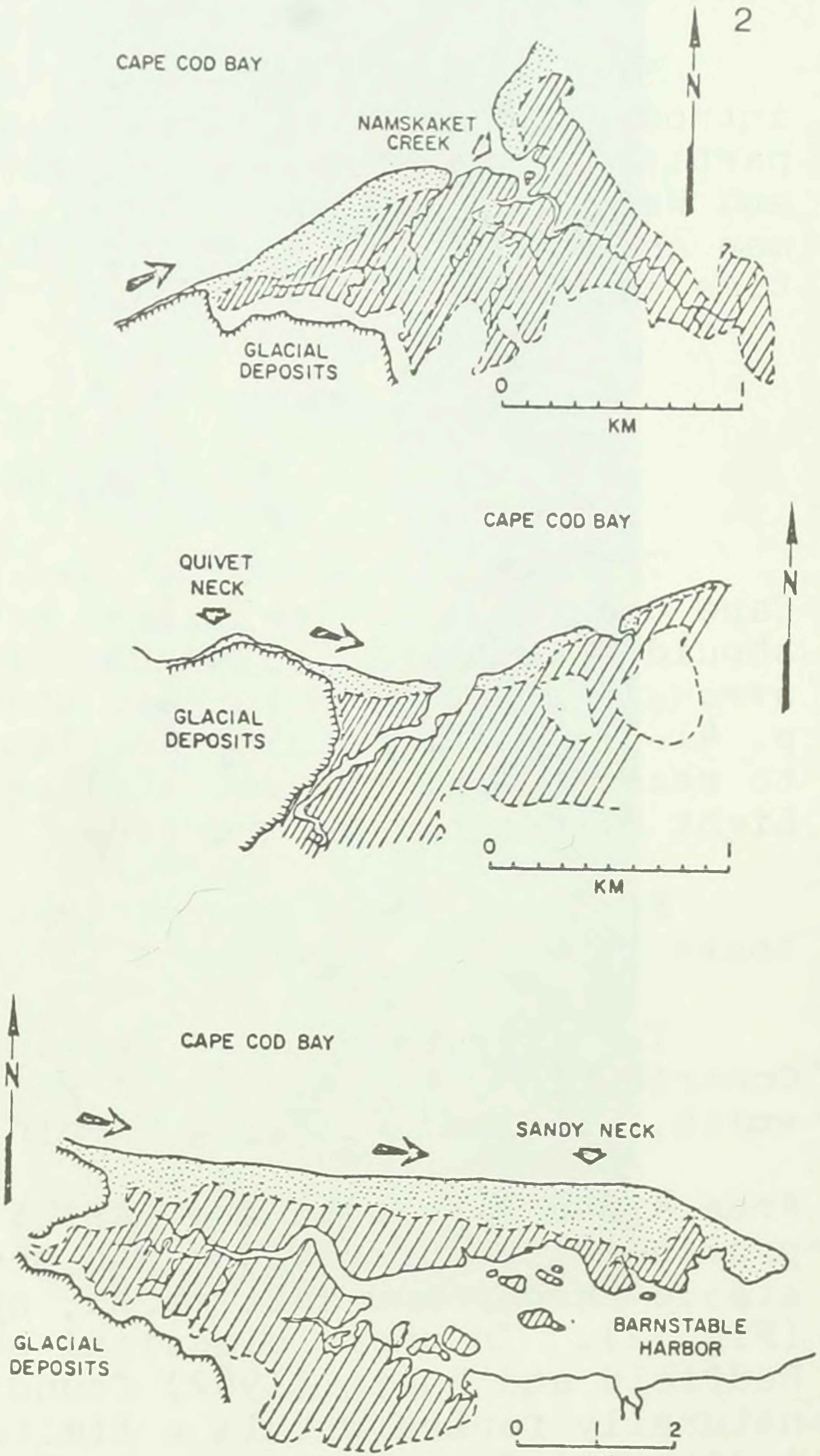
*Current address: Dept. of Geology, Bryn Mawr College, Bryn Mawr, Penn





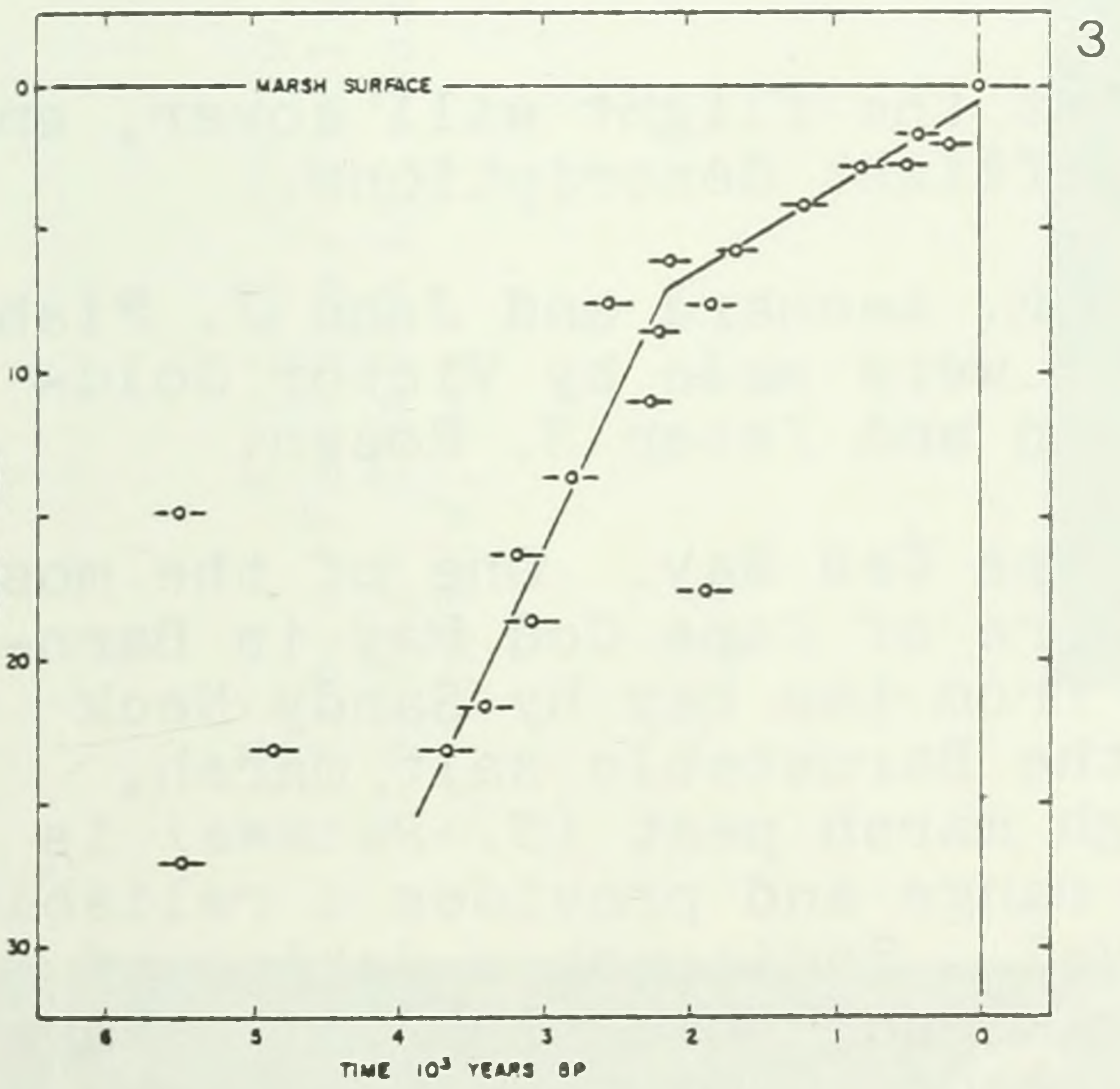


FIG. 1. Index Map to Section A (Macroscale View). Letters Indicate Areas Covered in Field Guide. Note that Areas in Between Letters Will be Discussed on the Trip.

FIG. 2. Examples of Eastward Spit Growth at Sandy Neck, Quivet Neck and Namskaket Creek. Stipled Areas are Sand Spits. The Cross-Hatched Areas are Salt Marsh Protected from Wave Action by the Sand Spits.

FIG. 3. Age and Depth Below Marsh Surface of Peat and Wood Samples Collected in the Town of Barnstable, Massachusetts. Circles with Lines are Data Points. (From Redfield and Rubin, 1962).

aeolian sand transport, overwash and inlet dynamics. The ecological zonation resulting from these geological processes and salt spray will be discussed.

Since space limitations in this field guide prohibit a detailed introduction to the general glacial history and origin of Cape Cod, participants are strongly urged to review Strahler (1966), Shepard and Wanless (1971) and Fisher (1972). Moreover, a revised surfical map and writeup of Cape Cod will be supplied to participants at trip time courtesy of the U.S.G.S. through Robert Oldale.

SECTION A

A MACROSCALE VIEW

Through the use of an aerial overflight, we will view the entire Cape Cod region. The flight will commence at Hyannis airport and should take about 1.5 hours. Prior to this trip participants are *strongly* encouraged to read Shepard and Wanless (1971) p. 29-32 and p. 41-57. If participants plan to take photographs, they are urged to read Kodak Technical publication M-5 entitled, "Photography from Light Planes and Helicopters."

Figure 1 shows the general areas that the flight will cover, and these letters are referred to in the overflight descriptions.

The leaders of this section are Jay E. Leonard and John J. Fisher. Contributions to this field guide section were made by Victor Goldsmith, Clifford A. Kaye, Harold P. Nilsson and Peter S. Rosen.

Area A and B - South and East Shore of Cape Cod Bay. One of the most prominent features along the southern shore of Cape Cod Bay is Barnstable Harbor and salt marsh, separated from the bay by Sandy Neck (Fig. 2). In their classical study of the Barnstable salt marsh, Redfield and Rubin (1962) found that high marsh peat (*S. Patens)* is naturally formed within a limited tidal range and provides a reliable indicator of the rate of rise in sea level. Radiocarbon dating of peat from the Barnstable marsh by Redfield and Rubin (1962) is shown in Fig. 3. The data show that in the Cape Cod area there has been a continuous rise in sea level for at least the last 3,700 years. The average rate slowed abruptly at about 2,100 B.P. Redfield and Rubin speculate that this change in the rate of sea level rise marks the termination of eustatic change and that subsequent rise was due principally to subsidence.

Eastward from Barnstable Harbor are two smaller marsh-sand-spit systems at Quivet Neck and Namskaket Creek. The origin of these systems is analogous to that of the Barnstable marsh. With rising sea level, salt marsh systems develop in topographic lows. Concurrently, sand spits accumulate between the marshes and the main water body and act as barriers to waves. The net west-to-east longshore drift along the south shore of Cape Cod Bay is responsible for the sand spit formation and generally forces tidal creek entrances to migrate eastward. Figure 2 displays maps of all three marsh-spit systems for comparison.

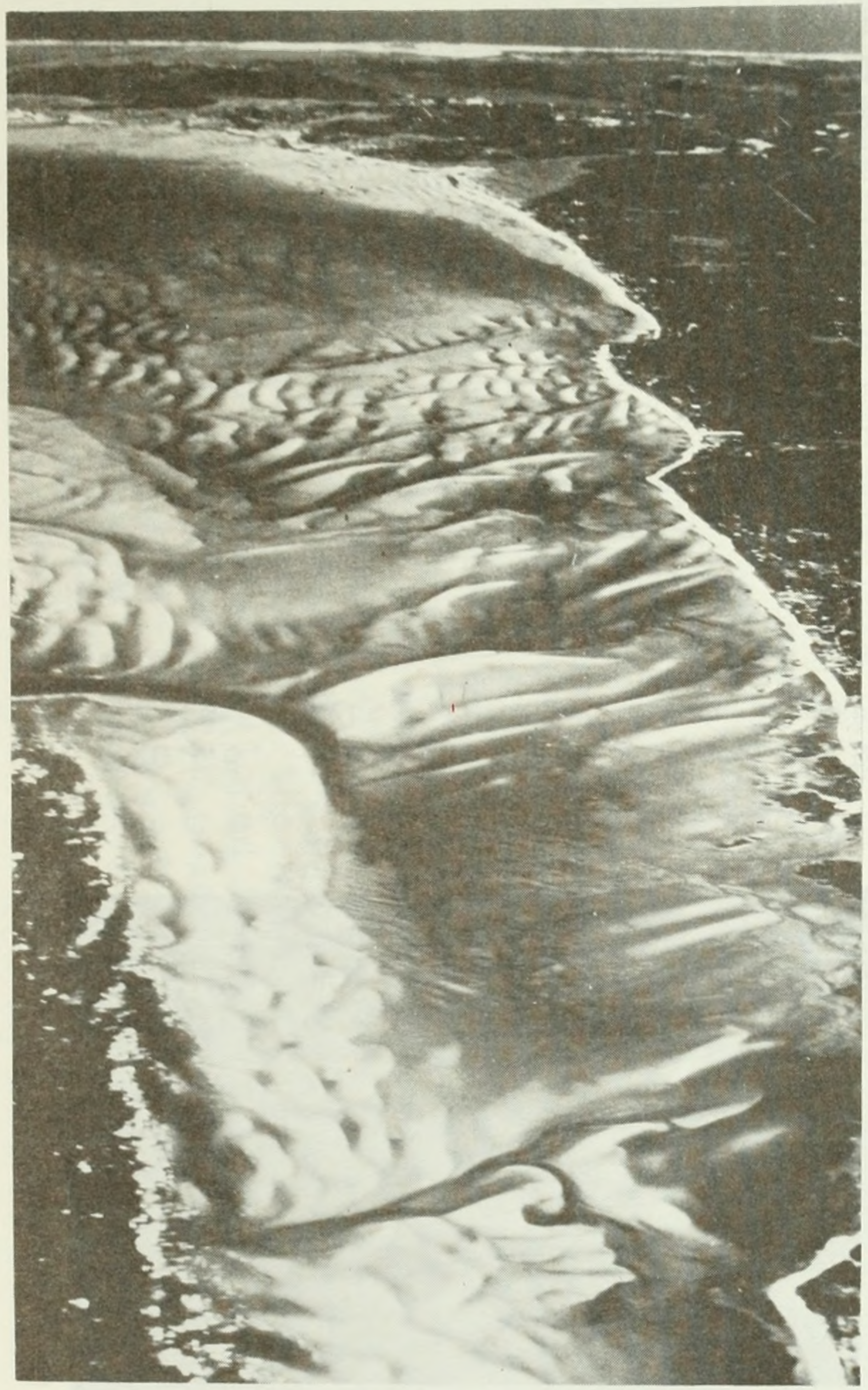


FIG. 4. Aerial Photo of the Brewster Tidal Flats Looking Eastward. Visible Features Include Crescent-Shaped Swash Bars, Curved Tidal Drainage Channels, Eastward Longshore Drift Shown by Sand Trapped by Grains.

FIG. 5. Multiple Sand Bars Parallel to the Shoreline on the Eastham Tidal Flats. Approximately 30 Bars are Visible.

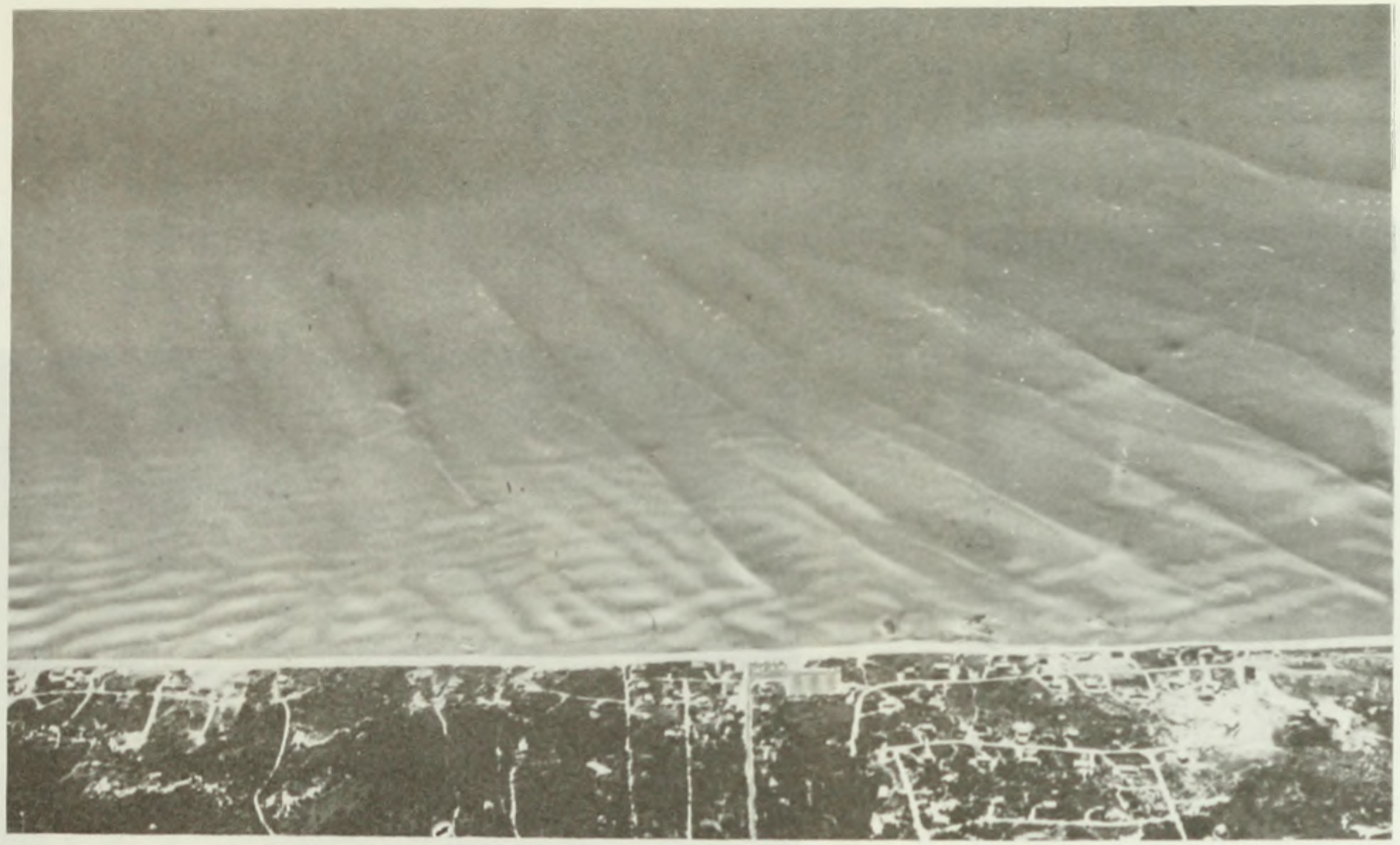


FIG. 6. Oblique or Transverse Bars on the Northern Eastham Tidal Flats. Multiple Sand Bars Intersect the Oblique Bars.

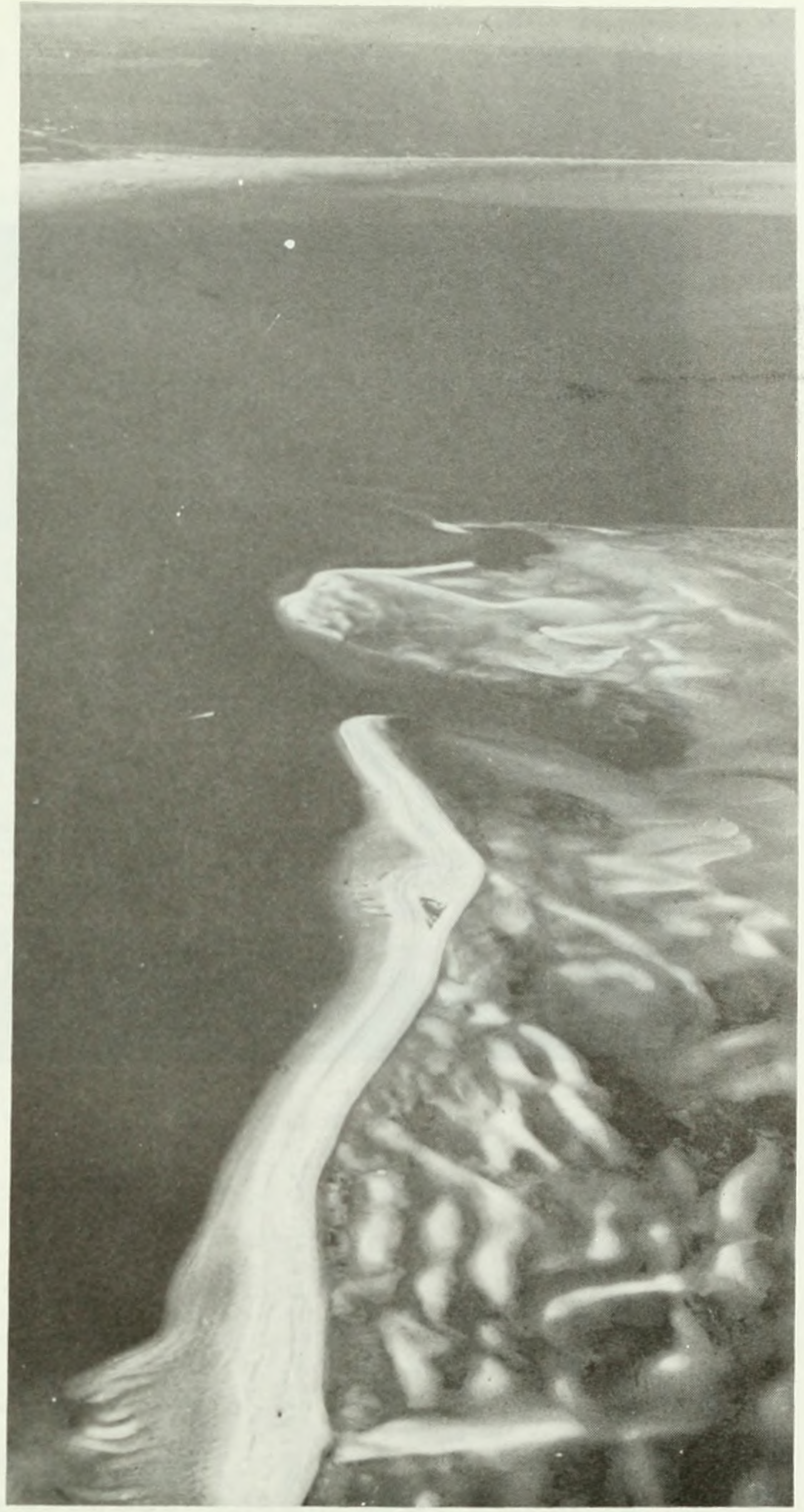


FIG. 7. Jeremy Point and Billingsgate Island Looking Southward. Two Intersecting Multiple Bar Systems are Visible. One is Formed by Westerly Winter Winds and the Other by Southwesterly Summer Winds.

Tidal Flats. Extensive tidal flats are developed in southeastern Cape Cod Bay. They begin just eastward of Sesuit Harbor and extend along the bight of the bay shoreline into Wellfleet Harbor. From Jeremy Point, the flats narrow northward toward Truro. The fundamental cause of the tidal flats is a combination of a large tidal range (approximately 3 m) and gradually sloping glacial outwash plains. Littoral processes, brought twice daily by the tides, have eroded the relatively flat outwash plains which slope gently toward the sea. The post-Pleistorene rise at sea level is also partially responsible for the lateral extent of the tidal flats.

The Brewster flats roughly begin just eastward of Sesuit Harbor and extend to Rock Harbor (Fig. 4). The Brewster tidal flats display a complex assemblage of spits, crescent-shaped sand bars and tidal channels. The complexity of the Brewster flats may be due to an originally irregular topography over which the sea has transgressed.

The Eastham tidal flats (Fig. 5) are roughly delimited by Rock Harbor to the south and Wellfleet Harbor to the north. The Eastham flats extend seaward about 2 km to mean low water. They are covered by a prominent system of multiple sand bars, parallel to the coastline. As many as thirty bars may exist which are very regular in appearance. Individual bars may be traced for over 1 km. Aiding the visual prominence of these sand bars from the air is the fact that bar troughs serve as environments for marine organisms -- especially algae. Bar crests are generally void of marine life since they are exposed to vigorous wave action.

At the northern end of the Eastham flats another type of sand bar, oblique or transverse to the shoreline, intersects the multiple sand bars (Fig. 6).

Directly westward, one may find Billingsgate Island and Jeremy Point. Billingsgate Island no longer deserves the name island, as it is now entirely submerged at high tides. In more fortunate times, Billingsgate was occupied by three lighthouses and a fishing village. The tidal flats from Jeremy Point northward exhibit systems of sand bars similar to the multiple bars of the Eastham flats (Fig. 7). One system is roughly parallel to the shoreline and the other is elongated northwest to southeast. These intersecting bar systems are developed on flats narrowing northward toward Truro.

Sand Bar Origins. Multiple sand bars, parallel to the shoreline, as displayed in Eastham, and less regularly developed on the Brewster flats have been reported from many locations. All occurrences have several features in common:

(1) Multiple sand bars are developed in relatively low energy environments (sounds, bays, lagoons, etc.).
(2) The bars exist only where there is an abundant supply of sand-sized sediment.
(3) Bars are developed on low bottom slope gradients; the less the slope, the greater the number of bars.
(4) The sand bars are developed to a depth which is approximately equal to the first break point of incident waves at mean low water.

Multiple sand bars appear to be formed by waves produced by e direction of dominant wind. In the case of southeastern Cape d, the dominant winter winds are from the west and northwest. uthwest winds are dominant in summertime.

The very regular bars on the Eastham flats are developed by inter waves, since the area is relatively sheltered from summer waves. rthward, the shoreline is exposed to both winter and summer waves. he bars parallel to the shore are due to winter waves. The oblique ars are oriented roughly normal to southwest (summer) waves. The rs on the Brewster flats originate basically the same way as in the ther areas, but are complicated by an irregular inherited topography.

The oblique bars on the northern Eastham tidal flats are enigmatic. t appears that they are formed by tidal currents entering and leaving ellfleet Harbor (Nilsson, 1973).

The specific mechanism(s) by which the multiple sand bars are ormed are poorly understood. Carter, and others (1973) and Lau and ravis (1973) believe that the bars are formed by current cells di-ected from the troughs toward the crests. The current cells are ormed by the interference of the incident waves and a partically re-lected component of them.

rea C and D - The Provincelands and the Outershore. Participants are rged to refer to Shepard and Wanless (1971) and Section B of this ield guide for descriptions.

rea E and F - Nauset-Monomoy Island Barrier-Spit Complex. Monomoy sland and Nauset Spit are located on the "elbow" of Cape Cod, assachusetts (Fig. 1). They were formed in Holocene time as a ingle sand spit in response to the longshore currents resulting from he dominant northeast waves impinging upon the outer beach of Cape od. Since 1620, Monomoy and Nauset spits have undergone at least two, nd probably three, cycles of large-scale inlet migration (Goldsmith, 969). The latest cycle began in 1846 with a natural breach across auset Spit caused by the shoaling up of the former inlet, which in 844 was about 2 miles south of where it was in 1971. The shifting f the inlet is due to the growth of Nauset Spit approximately six iles to the south since 1846.

"Scars" remaining from this last cycle of inlet migration, and of e former inlet location, are quite apparent from the air (1, 2, 6 d 7 below):

(1) Erosion on the west side of Chatham Harbor in the Chatham Light vicinity, in the late 1800's when the inlet was opposite this location, forced the relocation of the light house.
(2) The severe offset to the west of Monomoy Island, relative to the new Nauset Spit growth.
(3) Previous to the late 1950's, Monomoy was connected to Morris Island, a glacial outwash feature. Morris Island was not connected to Chatham. The natural response to the construction of the artificial causeway between Morris Island and Chatham was a breakthrough in the Morris-Monomoy connection. An extensive flood tidal delta has formed between Morris Island and Monomoy Island since about 1960, when the breakthrough occurred. The rather extensive nature of the

deposition (and perhaps even the breakthrough) could have been predicted by consulting the tide tables which show a marked difference in times and heights of tides between the ocean and bay sides of Monomoy.

(4) The relatively small ebb tidal delta is in marked contrast to this flood delta and reflects scale in processes. Bedforms have been studied by Hine (1975).

(5) Extensive wave refraction around the ebb delta results in wave energy concentration slightly south of the landward end of the southwest part of the tidal delta, resulting in greatly increased erosion. However, because of refraction, all waves tend to approach this spot from the southeast. As a result, the end of the tidal delta is migrating northwest, and therefore, so is the zone of severe erosion. The wave refraction pattern should be visible from the air.

(6) The site of the old inlet, about 1/3 of the way down Monomoy at the narrowest portion of the island, is quite apparent. Prior to 1846, this inlet marked both the north end of Monomoy and the south end of a continuous Nauset Spit. Further evidence of the cyclic nature of this inlet cycle was apparent in December, 1974, when the ocean once again broke through in this same spot, though the new opening "healed" within 10 days. The flood delta created during this short period of opening should be apparent.

(7) Further to the west, the very extensive delta formed about 150 years ago, is quite apparent, and is now called the "commons", a site of abundant shellfish. Changes observed on Monomoy since June 1968 have been equally dynamic (Goldsmith, 1972). Large-scale accretion occurs on the southwest and southeast portions of the island. Three years of biweekly observations of twelve permanent beach profile stations on Monomoy and four on Nauset Spit has revealed major variations in the amount of erosion and deposition taking place along the shoreline (Goldsmith and Colonell, 1972). The maximum erosion observed was 151 feet of beach retreat (amounting to 2300 cubic feet of sand per linear foot of beach) between June 1968 and March 1970, which occurred at the M-6 profile location approximately 0.25 km south of this recent breakthrough. The large variations in the amount of erosion measured along these profiles are related to an unequal wave-energy distribution within wave fronts impinging on the shore.

(8) This unequal wave-energy distribution is attributed to wave refraction around the irregular bathymetry offshore from Monomoy-Nauset, resulting in five shoreline protuberances of sand in six miles of Monomoy shoreline. These protuberances are flanked updrift by erosional zones and downdrift by accretional zones. Moreover, annual changes in rates of erosion along any one profile indicate that these zones of erosion and deposition migrate along the beach. These protuberances, which are quite apparent in the air, are formed on nearly all coastlines, though the spacing varies considerably and is a function of incoming wave energy.

Wave behavior near Monomoy was analyzed with the aid of over 200 wave refraction diagrams. The results indicate that the nonuniform distribution on wave energy along the Monomoy shoreline is due primarily to refraction of long (8-12 sec) waves of low amplitude. The larger amplitude, long-period waves (height >5 ft) tend to break too far from the beach to produce zones of wave-energy concentration, and the shorter waves (<7 sec) do not refract sufficiently to produce the zones of wave-energy concentration observed on Monomoy. Furthermore, the wave refraction may have been instrumental in forming and maintaining the shape and orientation of the northeast-oriented linear depositional sand bodies which make up a large portion of the irregular offshore bathymetry.

(9) Nearshore processes have produced three distinct types of offshore bars: (a) subtidal bars oriented oblique or perpendicular to the shoreline and attached to areas of the shore undergoing large amounts of erosion; (b) subtidal bars parallel with the shoreline and located >2000 ft off portions of the shoreline undergoing relatively small amounts of beach erosion or accretion; (c) large intertidal bars oriented obliquely to the shoreline and associated with the formation of the ebb-tidal delta and the resulting wave-refraction patterns. Types (a) and (c) should be easily apparent from the air, (b) will be indicated only if there are long-period swells present.

(10) The southern 2/3 of Monomoy, marked by high vegetated dunes (about 10 m.), is much more stable, though data of unknown accuracy suggests that this portion has retreated westward since 1620 a distance equal to about two to three times its present width. Most of the present dunes are in the form of "growth rings," and formed in the second half of the nineteenth century (Shepard and Wanless, 1971). Analysis of the frequency distributions of dip angles, azimuths and elevations of 301 eolian crossbed sets shows that coastal dunes have a distinctive internal dune geometry. The crossbed dip angles are mostly low ($\overline{X}$ = 11.2° in all azimuth directions, at all dune elevations, at all sides of the dunes, and at all sample localities. Crossbeds with dip angles of 11-15° yield the most statistically representative azimuth distributions. The combined azimuths show a statistically significant correlation with the prevailing northwest, southwest, and southeast wind directions, rather than with the dominant northeast storm winds. This association is valid for crossbed sets at any dune elevation. The azimuth distribution varies between sample localities, with the crossbed sets tending to dip toward the beach all around the island.

Biweekly field observations and numerous aerial photographs of Monomoy coastal dunes made during a three-year period suggest that internal dune geometry is closely dependent on growth of dune vegetation, especially *Marram* grass. The grass acts as baffles, trapping sand moved by the prevailing winds and producing the vertical accumulation of sand behind vegetation hummocks on the gently undulatory, nearly horizontal upper surface of the dunes (Goldsmith, 1972; 1973).

(11) The growth of the recurved spits has resulted in the formation of several fresh water ponds in the southwest portion of the island, and which support an extensive floral and faunal community (including deer). In the mid-1800's one of these present ponds, Powder Hole, was an extensive harbor with room

FIG. 8. Aerial View of Coatue Beach, Nantucket Island.

for "14 sail." It can now be walked across without getting one's shirt wet.

The newest pond was formed within two years (1969-1971) by a new spit growth. Similar to the growth of Nauset Spit, growth occurs sporadically and rapidly.

The result of these dynamic processes is extensive environmental mixing via overwashing and aeolian sand transported to the beach from the island interior.

Area G - Nantucket Harbor. Nantucket Island is located 30 km south of Cape Cod, Massachusetts. Nantucket Harbor, on the north side of the island, is an elongate lagoon trending approximately northeast-southwest. The harbor is bordered on the south by Pleistocene moraine material and on the north and east by the Holocene sand spits, Coatue and Haulover beaches.

Coatue Beach (Fig. 8) is approximately 10 km long with a maximum relief of 3m. The topography consists of dune ridges, most of which are parallel to each other and oriented to the northwest. Six regularly-spaced cuspate spits project into the two southwesterly spits (First and Second Points), but truncated dune ridges on the four northeasterly spits demonstrate the erosional form of most of the shoreline.

Cuspate spits result from a shoreline being reoriented into dominant wave approach directions. They form in elongate lagoons where the basin shape is a fetch restriction that acts as a selective filter on the wave spectrum, so dominant wave approaches are at a high angle to the shoreline. The long axis of Nantucket Harbor is parallel to two opposing wind directions, the dominant northeast and prevalent southwest. The longshore processes act in both directions, each eroding sediment from the center of each of the concavities between the cuspate spits and transporting it to the spit ends, where it is deposited as subaqueous bars. The upwind half of each concavity falls in the lee of the upwind spit, preventing longshore drift before the center of the concavity.

A comparison of the shoreline of 1781 with the present reveals remarkably little change in the location of each cuspate spit. The cuspate spits in Nantucket Harbor are an equilibrium shoreline, as evidenced by a lack of long-term shoreline changes. There has been slight erosion in the centers of the concavities, which concurs with process studies and foredune ridge characteristics. The wind and waves act through longshore currents as the spit-building process, which approximately equals the action of tidal currents on the subaqueous bars as the primary erosional process. While material is eroded from the bars by tidal currents, a greater volume of sand is returned to the beach at the center of the concavities by ridge-and-runnel migration than near the spit ends.

The subaqueous vegetation throughout most of the western half of the harbor is *Zostera marina* (eel grass). This material has spread from small colonies at the Harbor mouth in the 1940's to its present extent which dominates most of the western half of the harbor. This bottom growth inhibits the formation of ridge-and-runnal systems on the westerly concavities, which may upset the equilibrium of the system.

The eel grass has also stabilized the flood-tidal delta at the harbor mouth. An ebb-dominant tidal channel flanks the tidal-delta to the north, and flood channel to the south.

Nantucket Harbor is bordered on the south by a Pleistocene moraine, and on the north and east by Holocene sand spits, Coatue and Haulover Beaches. At the junction of these spits is a Pleistocene hummock, Coskata, which is a remnant of the source material for Coatue Beach. Immediately south of Coskata are the remnants of an inlet that broke through the beach in 1896. Local fishermen cut through the dunes at the south end of Haulover spit to haul their boats over the sand as a short cut to fishing grounds. The inlet lasted 12 years, and migrated north to the present location flanking the resistant Pleistocene material before closing. While the inlet was open, tidal flow in the harbor decreased, diminishing the scour over the subaqueous bars. This resulted in an elongation of these bars until the inlet closed. This sequence of events demonstrated the trend on cuspate spit shorelines for bar growth to result in harbor segmentation in areas of lower, or zero tidal flow. An example of this can be seen in the fresh water pond between recurved dune ridges at the south end of Monomoy Island.

Cuspate spits are a common feature in the ponds, lakes and bays on Cape Cod and Martha's Vineyard, but the Nantucket cuspate spits are unique for their symmetry and rhythmicity.

Examination of the dune ridges on Coatue Beach show the presence of two unconformities (most evident on Third and Five Finger Points). This suggests that Coatue Beach is the result of at least three phases of accretion: an initial phase of spit growth (presently between the two unconformities); a phase of spit growth to the north, which extended the spit through the pulses of recurves forming First and Second Points; and a phase of accretion to the south, inside Nantucket Harbor. The border between the initial and northern phases of spit growth can be traced to north of Coskata headland, where vegetation changes delineate a change in elevation between the two growth stages.

Great Point, which projects north from Coskata headland, is a low-lying spit that is presumed to have formed as a tombolo. The north end of Great Point lies on a gravelly shoal which is the remains of a hummock similar to Coskata. The influx of sediment from the south has resulted in the formation of large (8 m) vegetated sand dunes. The Great Point Spit is migrating to the southwest over the shallow Pleistocene bench north of Coatue Beach. This migration appears to be less a function of overwash than of accretion by ridge-and-runnel migration on the southwest (landward) side of the spit and erosion on the northwest side.

Area H - Martha's Vineyard. Lying 7 miles west of Muskeget Island, the westernmost part of Nantucket, and 3.5 miles south of Woods Hole at the southwest tip of Cape Cod is the island of Martha's Vineyard (Figs. 1 and 9). Somewhat larger than Nantucket, it is approximately 18 miles from east to west and 9 miles from north to south. Its shape is roughly triangular with its long side on the south, and with a small triangular appendage (the township of Gay Head) at the western end. The southeastern angle of the triangle is Chappaquiddick, severed from the main island by Katama Bay and Edgartown Harbor.

The Pleistocene geology of Martha's Vineyard is unusually complex. Three morainic systems meet on the western part of the island and within the older moraines, three separate drifts and deposits of at least one interglacial are well preserved. With six recognizable drifts occurring in one small area, probably the most complete Pleistocene section in the United States is found here (Kaye, 1964a, b; Woodworth and Wigglesworth, 1934; Fuller, 1914) starting with Nebraskan and including late Wisconsinan. From the air, however, we can see evidence of three or possibly four.

The lobate early Wisconsinan moraine that makes up the spine of Nantucket continues west to Martha's Vineyard, where it can be seen forming the northeastern side of the island, stretching from Chappaquiddick on the southeast to Vineyard Haven, the town at the northern apex of the triangle. The moraine is somewhat subdued here and attains an altitude of 100 feet at only a few places and, in general, hovers about an altitude of 50 feet. It is not conspicuously bouldery and it lacks the well-developed corrugations found in the central part of Nantucket.

From sea cliffs and excavations, this moraine is seen to consist mainly (but not entirely by any means) of undisturbed stratified sand and gravel. This appears to be superglacial outwash, that is, outwash deposited over a slowly wasting ice front. The outwash plain extends to the south and flying in from the east we see this large outwash plain forming the large central part of the island extending as far as the south shore of the island.

Noteworthy features to be seen from the air

Chappaquiddick - superglacial outwash moraine.

Wasque Point - the southeast tip of the island. Erosion occurs at an alarming rate when the protective sandy beaches are swept away, as they occasionally are. The morainic upland is then eroded at a rate of almost 1 foot per day. The long north-south barrier beach that ties Wasque Point to Cape Poge on the north is fed by strong reversing tidal currents through Muskeget Channel. If the sea is calm, the large arcuate sand apron, or subaqueous delta, at the mouth of the channel can be seen. The surface of this is in perpetual movement. Skiffs Island, a small sandy constriction rising just a few feet above high tide, may be present about a mile southeast of Wasque Point. This island from time to time gets swept away only to reform by build-up of the sandy shoals here.

Cape Poge Elbow is the curiously curved sand spit, projecting west and then south from Cape Poge, at the north end of Chappaquiddick. The mechanics of its formation await study.

Barrier Beach along east side of island, called State and Edgartown Beaches is a fairly stable feature. Studies (Kaye, 1973) show no measurable net change in position in the past 200 years.

Lagoon Pond and Lake Tashmoo, two elongate lagoons at north end of island, are the drowned portions of a looped, or lobate depression that can be seen intersecting the north end of the outwash plain. This valley shows evidence of ice collapse and resembles a large river meander in plan.

Outwash plain in the central part of the island slopes about 8 feet per mile southward. A radiating set of shallow dry valleys that head off to the former ice margin score the surface. The lower courses of these valleys are drowned and give rise to the numerous narrow bays or lagoons along the south shore.

South Beach. The long straight east-west south shore of the Vineyard is marked by barrier beaches across the mouths of the ponds, or lagoons. Erosion of this shore is appreciable and varies from an average annual rate of 11 feet on the east to about 6 feet on the west. Historical documents show that 200 years ago it was possible to go by boat from one end to the other of South Beach behind a continuous barrier beach. Since then, the shore has been pushed back to intersect the outwash plain. The dominant direction of longshore drift of the sand in the beach is west to east.

The western part of the island consists of three moraines and the topographic sag of Menemsha Pond. The early Wisconsinan moraine of the eastern part of the island becomes thin along the northwestern shore where it is squeezed against the side of the higher and longer Gay Head moraine. It is found along the entire northwest shore and its average width is about a quarter of a mile. It would appear that the larger lobe to the east that built the Nantucket and eastern Martha's Vineyard moraine. In consequence of this, it was unable to override the crest of the Gay Head moraine except at the sag in the moraine at Menemsha (see below).

The largest part of western Martha's Vineyard is the Gay Head moraine probably dating from Illinoian glaciation. The moraine is much eroded with two sizeable longitudinal valleys. The surface of the moraine has been oxidized and eroded. The structure of the moraine is very distinctive and can be studied in the large, colorful sea cliff cut into it at the western tip of the island, Gay Head. It is made up of imbricated thrust plates of pre-existing ground all drifting north. Individual thrust sheets, or plates, may be as much as 50 feet thick, but generally are less, and may be a quarter of a mile or more in length. Somehow the ground over which the ice sheet moved was detached in large plates, moved forward with the ice without significant internal disturbance and piled up in a great imbricated mass at the terminus. The major component of the thrust sheets are yellow, white, red, gray, and black Coastal Plain sediment of Late Cretaceous age. Also included in the thrust plates, is a highly fossiliferous Miocene unit and three early Pleistocene drifts with distinctive characteristics and one fossiliferous interglacial deposit (Kaye, 1964a, b).

Erosion of the Gay Head moraine has etched into relief the more resistant stratigraphic units of the thrust plates. The surface of the moraine is therefore recognizable by the many low ridges that trend parallel to it. Also noteworthy are the large boulders, some of which reach 35 feet across.

Menemsha Pond, separating Chilmark Township from that of Gay Head, was a sag in the Gay Head moraine. The subsequent Early Wisconsinan ice flowed partially through this gap and pushed up an arcuate ridge of sand and clay and some of the older deposits at the margin of its advance. These are exposed in the high cliff (Wequo (Wequobaque Cliff) on the south shore here.

Squibnocket Point is the southernmost point of the island. The cliff exposes very compact peculiarly contorted stratified till interbedded with medium yellow sand and gray clayey silt. The same type of deposits underlie No Mans Land, an island lying about three miles to the south southwest. This type of stratified till and thick sand and gravel crops out on Block Island and eastern Long Island where it is called the Montauk drift. It is very distinctive and unlike other deposits on Martha's Vineyard and is thought to constitute the third morainic system of the Vineyard (Fig. 9).

Gay Head. This spectacular colorful cliff reaches 152 feet in altitude and cuts across the large Illinoian(?) moraine. The colorful beds are all of Coastal Plain origin (Upper Cretaceous-Miocene) and make up the bulk of the cliff. White beds are mostly kaolinitic, medium-coarse sand, some gravel; black beds are lignite and lignitic silt; red is clay. The thrust plates all dip to the north and some of these can be seen from the air (slope wash masks many of these structures). The cliff is eroded largely by large slump-type landslides. Note large one heading up to lighthouse and one near north end of cliff. These can be recognized by sod-covered step-like slices. Early Wisconsinan till in upper part of cliff at north end.

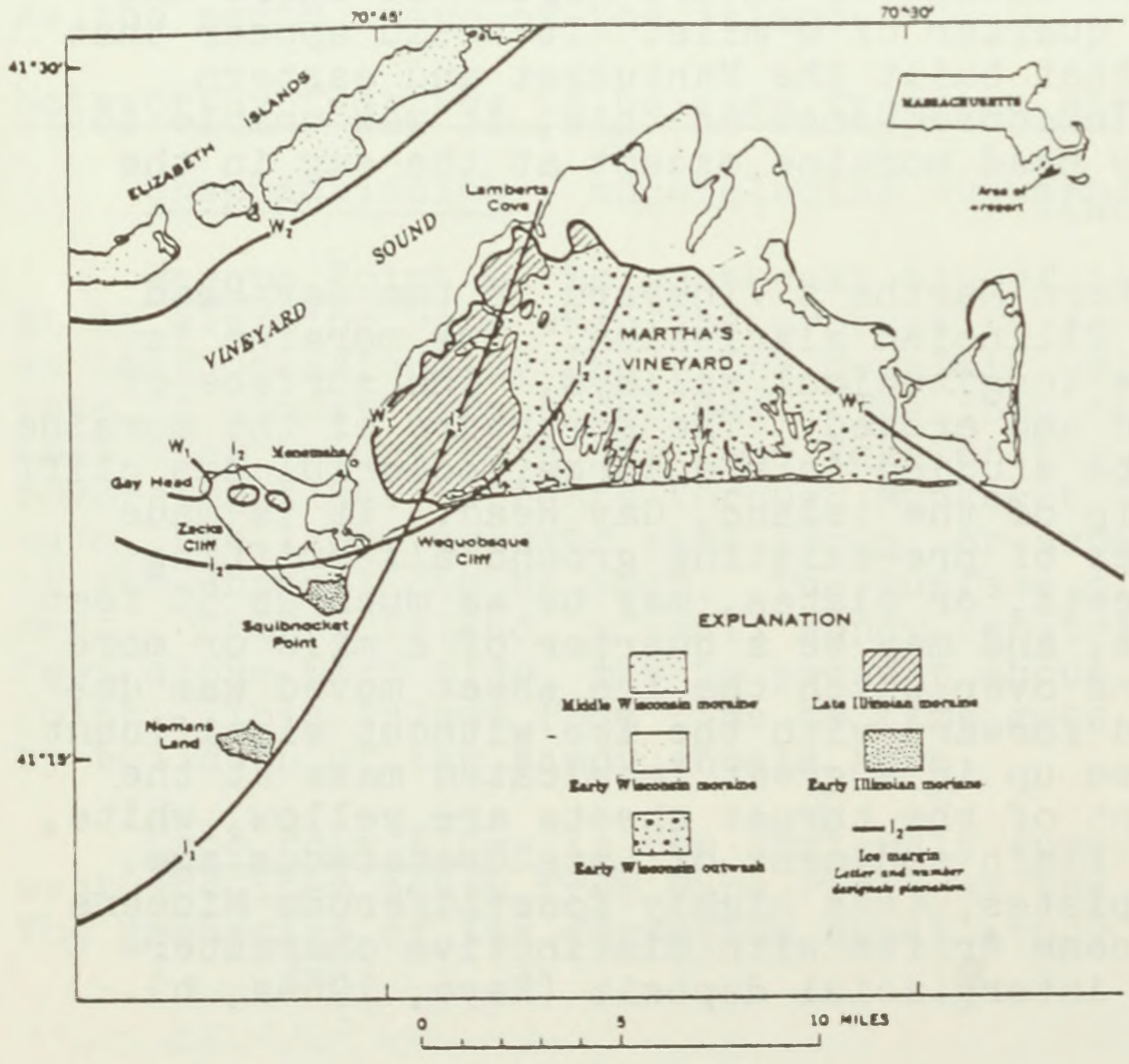


Fig. 9. Map of Martha's Vineyard and surrounding islands, showing inferred ice margins and morains of early Illinoian (I_1), late Illinoian (I_2), earl Wisconsin (W_1), and middle Wisconsin (W_2) ice sheets. (After Kaye, 1964b).

SECTION B

A MESOSCALE VIEW

In Section B of the Cape Cod field trip, we will view the Cape's outer shore from a mesoscale viewpoint. Unfortunately, the guide to the final stop concerning the environmental impact of off-road-vehicles on dune and beach vegetation, was unavailable at publication time; a supplementary handout will be supplied to participants on the trip. The leaders of this section are John J. Fisher, Paul J. Godfrey and Jay E. Leonard. John J. Fisher is principally responsible.

This section of the trip will commence at the visitors center Cape Cod National Seashore, Eastham, Mass. Mileage is logged in the margin by $\frac{xx.x}{y.y}$; where xx.x is cumulative and y.y is between stops. Participants should refer to Fig. 18 for stop locations.

$\frac{0.0}{0.0}$ **Visitors Center, Cape Cod National Seashore Park, Eastham.** This Center is 0.1 mile east of Route 6, at a point 2.8 miles north of Orleans – Eastham traffic rotary ("circle") of Route 6 and 6A. Early arrivers are recommended to visit the center for publications, movies, and special displays showing the general glacial origin of the entire Cape.

The Center's picture window overlooks Salt Pond, a drowned kettle hole, and Salt Pond Bay. In the distance, to the southeast, the beach and dunes visible is that of North Beach, a southerly prograding barrier spit beach enclosing Salt Pond Bay. Nauset Inlet is at its southern end, while the Seashore Park's Coast Guard Beach is at its northern end.

It was the naturalist-philosopher Henry David Thoreau who first studied and wrote of the "Outer Beach" of Cape Cod over 100 years ago. In several trips, he walked the beach from Nauset Inlet to Provincetown. For this "Bi-Centennial" field trip, we will, as it were, be following in Thoreau's footsteps as we make our way north along the Cape Cod Seashore Parks "Great Outer Beach." Note: On leaving the parking lot, turn right, (east) on Nauset Road.

$\frac{0.5}{0.5}$ Nauset Road bears left (north), continue ahead (northeast) on to Doane Road.

$\frac{0.8}{0.3}$ In grove to right (south) is Doane's Rock (Enos Rock), the largest glacial erratic on Cape Cod. It is 45 feet long by 25 feet wide and is 18 feet high, but continues below ground to a depth of 12 feet where it is wind polished to a depth of 5 feet (Oldale, and others, 1968). Volcanic basalt in composition, there are no similar bedrock materials beneath the Cape and some think that the ice sheet eroded and transported it from a belt of volcanic rocks beneath Massachusetts Bay to the northwest (Chamberlin, 1964, 1957). If ice-rafted to this site, the sheet of ice, 5 feet thick would need to be one-half the size of a football field.

$\frac{1.3}{0.5}$ Intersection with Oceanview Road continue ahead (east) to Coast Guard Beach.

$\frac{1.5}{0.2}$ Continue east, then south to entrance to Coast Guard Beach. Park, in parking lot, near north end (entrance).

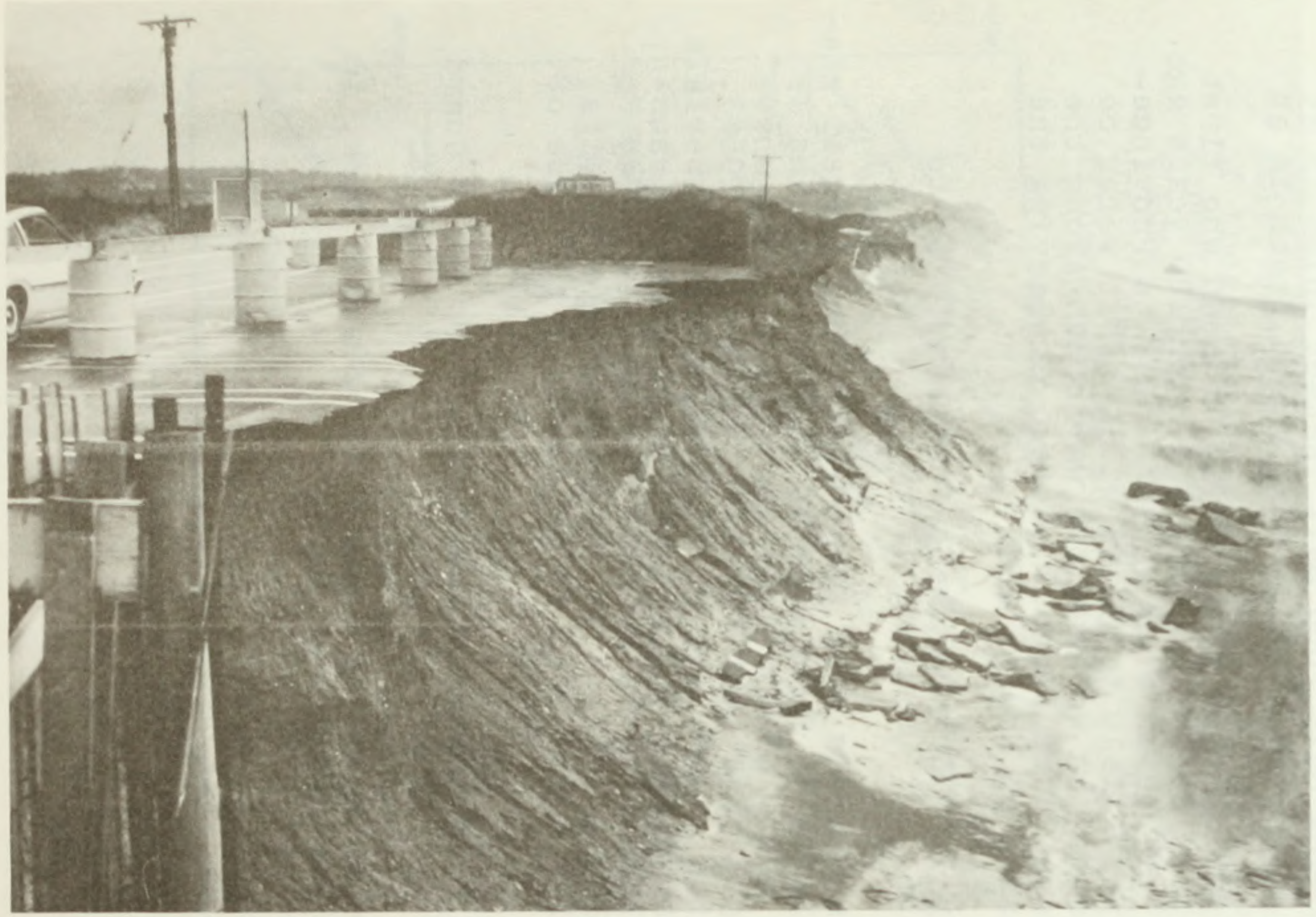


FIG. 10. Extensive Sea Cliff Erosion at Cape Cod Beach Eroding Parking Lot. Erosion Increase may be due to Migration of Fulcrum Point Between Shoreline Erosion and Deposition Segments. Emplacement of Concrete Slabs at Cliff Base did not Stop Erosion. Photo Taken April 1975, Winds from Northeast at 30 mph Causing Sand Drifting Visible on Beach.

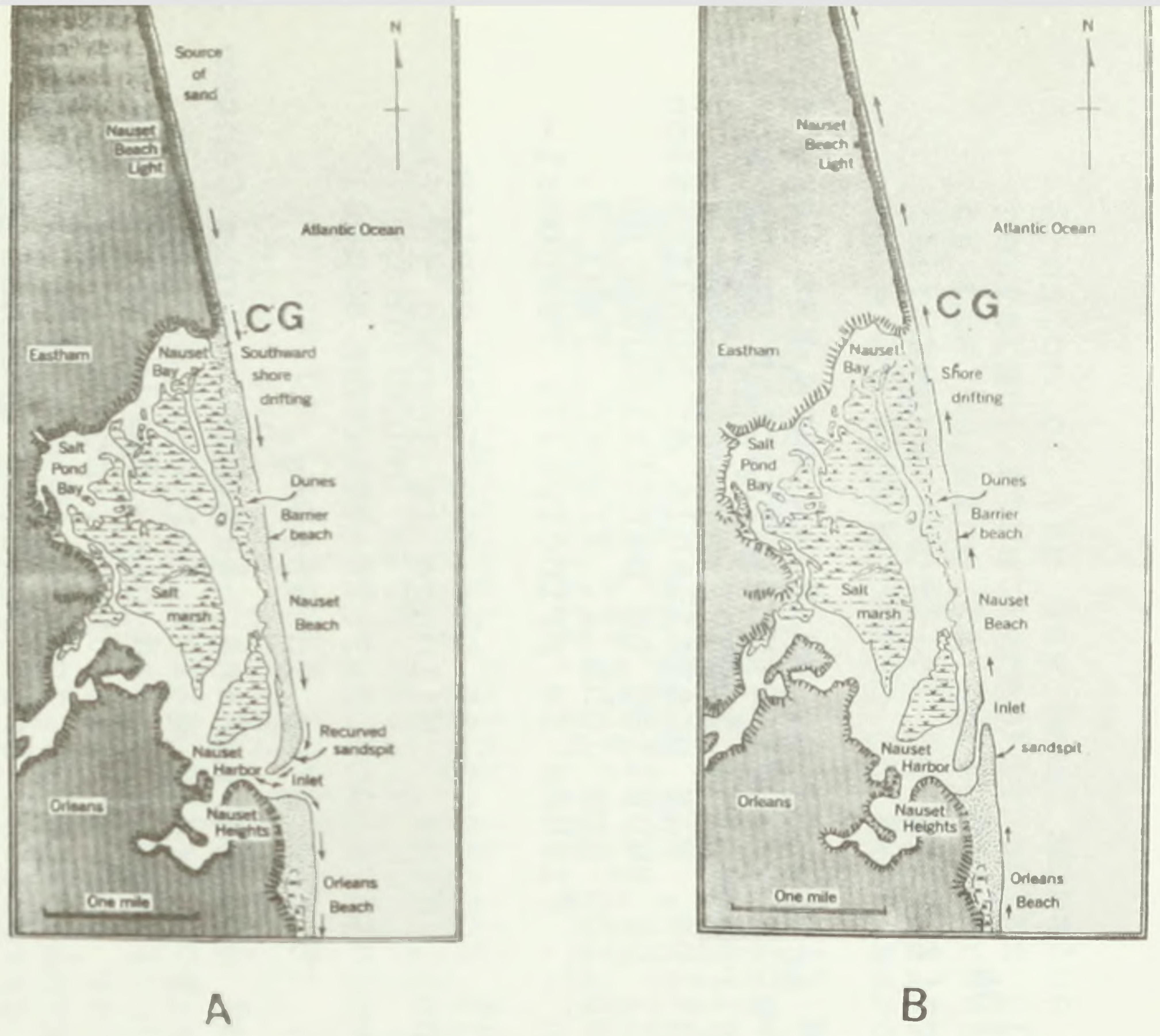


FIG. 11. A. Schematic Indicating Direction of Longshore Drift From North to South Along Nauset Cliff to Nauset Beach. Coast Guard Beach (CG) at Junction (Fulcrum) of these two Segments. Reprinted with Permission from Strahler, 1966. B. Schematic Redrawn by Strahler for Present Guidebook Indicating Change in Drift Direction from South to North as Suggested by New Development Pattern of Sandspit at Mouth of Nauset Inlet (Personal Communication A.N. Strahler, 1975).

1.6/0.1 **Stop 1 – Coast Guard Beach.** Extensive wave erosion of both the bluffs (Fig. 10) and the dunes in this recreational area over the past several years since about 1970 have been cause for concern. The question is what coastal mechanism is responsible for this increased erosion? Coast Guard Beach, as part of a spit landform, is just south of where sea cliff erosion would give way to spit deposition. A fulcrum point, is the term for this boundary between coastal erosion and deposition according to W.M. Davis' spit development model. Perhaps recently there has been a southerly shift of this fulcrum point, so that former erosion along the sea cliffs, is now shifted to erosion of the dunes of Coast Guard Beach.

This, however, does not explain increased erosion of the glacial bluff. It is possible that it is not coastal erosion that is responsible for this extensive cliff failure, near this southern fulcrum point, but rather the seasonal spring high water table and the water-filled kettle hole adjacent to the cliff, just east of the former Coast Guard Station. During the spring months, (April 1974) fresh water has been observed flowing from the base of the eroded scarp. This means that the high water table from the kettle hole could, by fluidizing the adjacent cliff and beach, allow increased erosion and this could initiate a wave of erosion moving south and north in the direction of the longshore current. The relationship of this southern fulcrum point, a coastal nodal point (longshore divergence) and the northern fulcrum point to coastal landforms, beach geometry, sediment distribution and shoreline erosion will be investigated as we continue northward along the coast.

Erosion in the Spring of 1976, of the dunes and sea cliff exposed the interior section of the deposits and dune sands; which gave way to the north, to glacial till deposits, overlain by an organic sand (bay bottom?) and then aeolian cross-bedding. Further north the till disappears and only aeolian sand is visible. This indicates that the hill on which the Coast Guard Station stands is an outline of till. The sea cliffs in the Coast Guard Beach area and the bluff on which is the Coast Guard Station are part of the Eastham glacial outwash plain. The sea cliff glacial stratigraphy have shown beds of till (5 to 10 feet thick) interlayed with beds of sand and gravel and laminated silts. These various till bodies, rather than ice-contact deposited, are probably flowtills from the South Channel ice lobe that existed to the east and which supplied the general interlobate outwash stratified drift deposits of the Eastham plain. A fabric study of the long axes of stones in the till outcropping north of the parking lot indicated a plunge direction to the west south-west which tends to support a flow till interpretation of the till beds (Oldale, and others, 1968).

1.8/0.2 Leave Coast Guard Beach entrance and turn north (right) on to Ocean View Drive.

3.7/1.9 Continue north on Ocean View Drive, and turn east (right) on Cable Road.

Stop 2 – Nauset Lighthouse Parking Lot. In 1839, three brick lighthouses occupied this site. Continuing cliff erosion toppled all three into the sea in 1892 and in 1923. Ongoing erosion can be seen along the edge of the parking lot, where an entire row of parking spaces has been lost to cliff erosion during the last half-dozen years.

Average rates of cliff erosion along these outer Cape Cod cliffs have been measured as 3 feet per year in the late 1800's (Marindin, 1891), and decreasing to 2-1/2 feet per year in the 1900's (Zeigler, and others, 1964a), and 1.8 feet in the 1970's (Chamberlain and Martin, 1974). Although this erosion supplies sand to the beach below, these beaches do not show a net increase in width, because the eroded material is carried by longshore transport to form the spit barrier beach south of Coast Guard Beach. Figure 11A (Strahler, 1966). From his book on Cape Cod Geology, he diagrams this southern longshore transport. However, in a recent diagram supplied by him for this guidebook (Strahler, 1976, personal communication), he has reversed the direction of longshore drift to the north. He bases this new interpretation on recent changes of the "sandspit" at the Nauset Inlet as shown on the new diagram (Fig. 11B).

The maximum elevation of the Eastham plain on uncollapsed glacial drift in the vicinity of Nauset Light is 80 feet. Eastham plain outwash glacial deposits north of Nauset Light are mostly fine to very coarse sand with few cobbles, in contrast to the silt and boulders present in the deposits to the south. In general, these glacial deposits have a high content of felsic volcanic rocks (Oldale, 1968).

3.8 Leaving Nauset Light Beach parking lot and heading west, continue
0.1 ahead following Cable Road.

4.7 Just past the high school on the north (right) is the Nauset Road
0.9 intersection, where Cable Road ends. Turn northwest (right) on
Nauset Road.

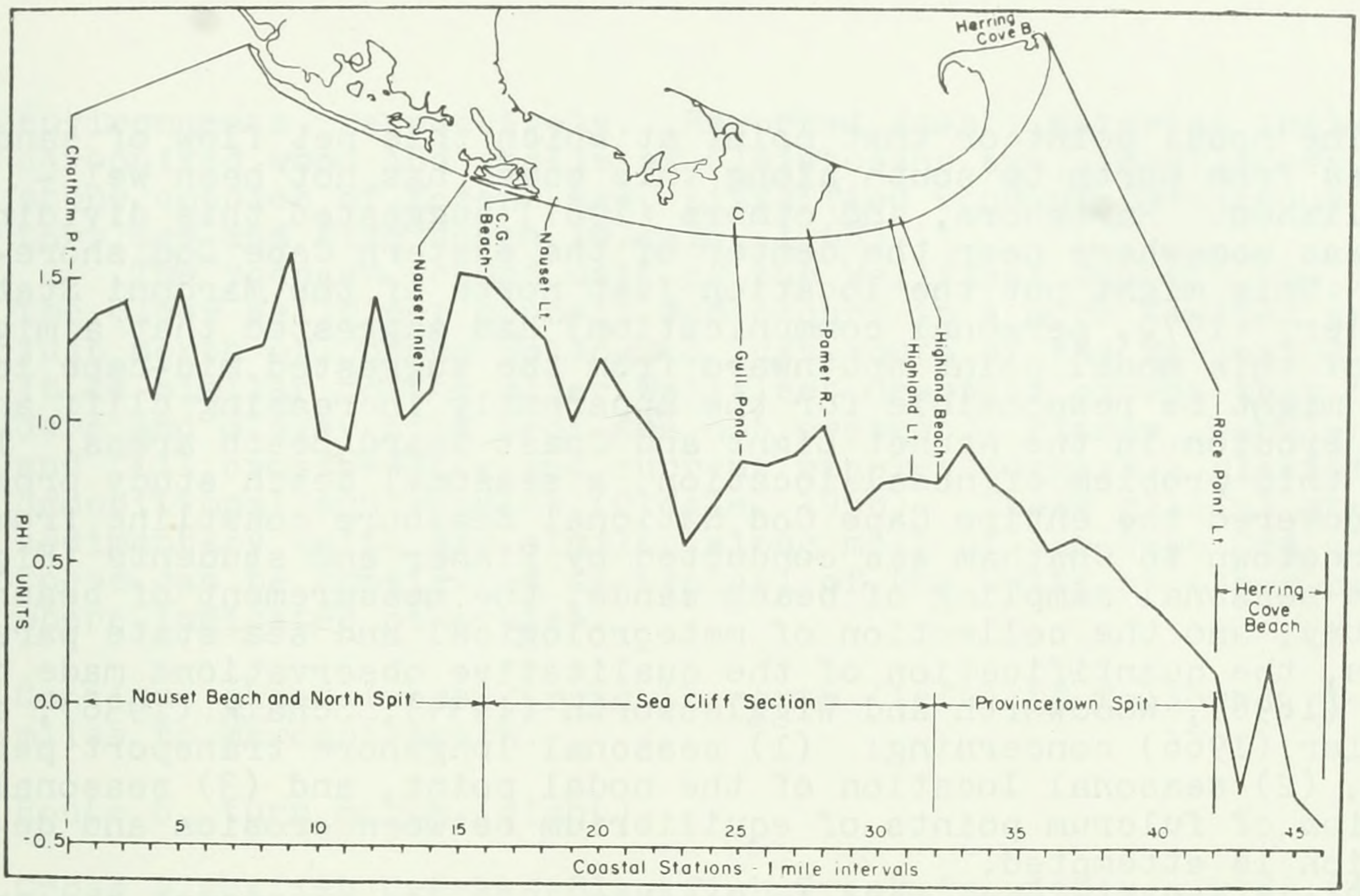
5.7 Nauset Road ends at Route 6, coming in from the south, turn north
1.0 (right) and follow Route 6 on the Eastham glacial outwash plain.

8.7 Turn east (right) on road marked Marconi Station with Seashore Park
3.0 sign.

8.8 Road to north (left) to local school, road to south (right) to Marconi
0.1 *Beach*, do not take, continue straight ahead (east) to Marconi *Station*.

One approaches the Marconi Station across the Wellfleet plain of Grabau (1897) and Woodworth and Wigglesworth (1934). A glacial outwash plain with a gentle southwestward slope, large entrenched valleys, and numerous kettle holes, it is the oldest, highest, and most extensive of the Cape glacial outwash plains.

9.8 **Stop 3 — Marconi Wireless Station.** Marconi's first antenna for his
0.7 wireless station on this spot was destroyed in a gale in September, 1901. Later four towers were erected and began transmitting in January, 1903. Since the placement of the towers, the cliff has eroded 170 feet. Presently the foundation on the edge of the cliff is undergoing erosion. This dramatic example of Cape Cod sea cliff erosion illustrates that while the cliffs continue to erode, the beach below does not increase in width because this eroded material, now, as in the past, is carried by longshore transport south to Nauset Beach and probably Monomoy Island and also north to form the Provincetown spit.



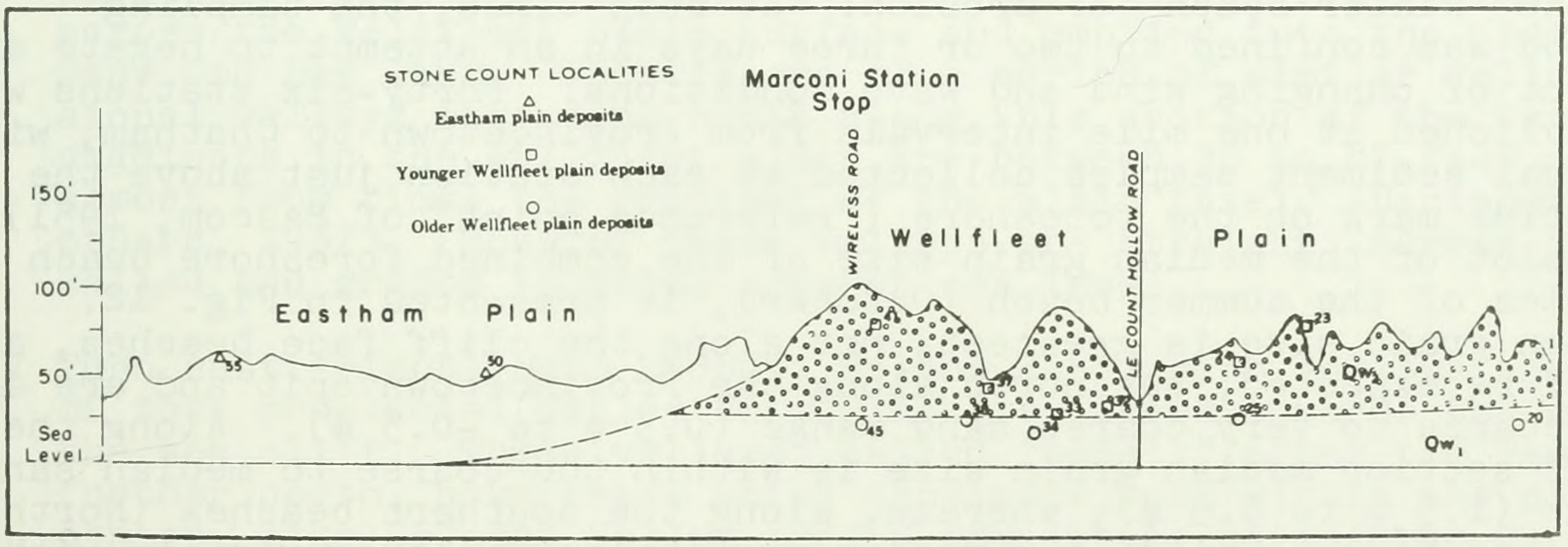


FIG. 12. Regional Pattern of Average (Median) Sediment Grain Size on Beach Foreshores of the Outer Cape Shoreline, Collected in October Representing Summer Beach Deposition. Size Varies from Medium Sand (2.0 to 1.5 ϕ) to Very Coarse Sand (0.0 to -0.5 ϕ) with Medium Sand Size Along Nauset Beach and Spit Increasing to Medium-Coarse Sand in Sea Cliff Region, the Expected Source Area. However, from the Sea Cliff Region North Towards the Provincetown Spit, the Average Sand Size *Increases* Rather than Decreases in the Supposed Direction of Longshore Drifting (from Fisher, 1972).

FIG. 13. Glacial Stratigraphy of Sea Cliffs Along Marconi Station Area Showing Relationship of Eastham Plain Deposits, Younger Wellfleet Plain Deposits and Older Wellfleet Plain Deposits. Sequence Determined from Field Relationships and Stone Counts of Differing Pebble Lithology in Different Plain Deposits. View is to West, North to Right (from Oldale, 1968).

The nodal point or that point at which this net flow of sand changes from north to south along this coast has not been well-established. Hartshorn, and others (1967) suggested this dividing line was somewhere near the center of the eastern Cape Cod shoreline. This might put the location just north of the Marconi Station. Strahler, (1970, personal communication) had suggested that a migration of this nodal point southward from the suggested mid-cape locations might be responsible for the apparently increasing cliff and beach erosion in the Nauset Light and Coast Guard Beach areas. To study this problem of nodal location, a seasonal beach study program that covered the entire Cape Cod National Seashore coastline from Provincetown to Chatham was conducted by Fisher and students (Fig. 12). By the seasonal sampling of beach sands, the measurement of beach geometry, and the collection of meteorological and sea state parameters, the quantification of the qualitative observations made by Davis (1896), Woodworth and Wigglesworth (1934), Schalk (1938), and Strahler (1966) concerning: (1) seasonal longshore transport patterns, (2) seasonal location of the nodal point, and (3) seasonal location of fulcrum points of equilibrium between erosion and deposition is attempted.

Field studies were made in October 1970, to represent the end of the "summer beach" of accretion and in April 1971, at the end of the "winter beach" of erosion. At both times, the sampling period was confined to two or three days in an attempt to negate any effect of changing wind and wave conditions. Forty-six stations were established at one mile intervals from Provincetown to Chatham, with several sediment samples collected at each station just above the mid-tide mark on the foreshore ("reference point" of Bascom, 1951). The plot of the median grain size of the combined foreshore beach samples of the summer beach (October), is presented in Fig. 12. Median grain size is greatest, not along the cliff face beaches, as might be expected, but north along the Provincetown spit and are in the coarse to very coarse sand range (0.5 ϕ to -0.5 ϕ). Along the cliff section median grain size is within the coarse to median sand range (1.5 ϕ to 0.5 ϕ); whereas, along the southern beaches (North Spit and Nauset Spit), the median grain size falls completely within the medium size (1.0 ϕ to 1.5 ϕ). There is a greater variability of grain size trend along this southern beach section than along the central cliff face beaches. The least variation in grain size trend actually occurs along the Provincetown spit beach proper.

From the Marconi Station overlook, one can see that 500 feet to the south is the contact between this Wellfleet plain and the lower Eastham plain of the Nauset Light area. The scarp on the west, also between the Wellfleet and Eastham plains is "thought to be an ice-contact slope developed when part of the South Channel lobe occupied the site of the Eastham plain deposits" (Oldale, and others, 1968). One-third the way down the cliff face is the contact between the younger and older Wellfleet outwash plain glacial deposits (Fig. 13). The older unit (Qw_1) is composed of fine to very coarse gravelly sand. However, within this unit are beds and lenses of pebble and cobble gravel, fine to very fine sand and clayey silt. Boulders, tens of feet in diameter are common and some pebbles in the deposit are wind-polished. Large scale deltaic foreset bedding as well as planar bedding, tabular and cut and fill crossbedding and current ripples suggest both glaciolacustrine and glaciofluvial depositional environments, respectively. Reworked fossil material includes carbonized wood and shells of Pleistocene age, fossiliferous sandstone cobbles of Eocene age, silicified wood of Cretaceous or Teritary age and fish teeth (Oldale, 1968).

The younger second unit of the Wellfleet deposit (Qw_2) overlies the older Wellfleet deposit and occurs in a more limited area from just north of Cohoon Hollow to just south of the Marconi Station. It is similar to the older Wellfleet deposits except that the boulders and clayey silt beds are not present. Planar, tabular, scour and fill crossbedding and current ripples suggest a glaciofluvial depositional environment (Oldale, 1968). These glacial stratigraphic sedimentary units are similar along most of the Cape Cod cliffs and these can be considered as typical of the units at other stops except where indicated otherwise.

10.8 Continue ahead (west), road to south (left) if followed, leads 1.5
1.0 miles to Marconi Beach.

10.9 Route 6, turn north (right).
0.1

11.6 Cross Blackfish Creek. Blackfish Creek is within a wide tidal marsh
0.7 valley that is the result of the drowning of the lower reaches of a proglacial outwash meltwater stream that flowed from the northeast across the Wellfleet plain surface and emptied into the proglacial Cape Cod Bay lake. This is one of a series of similar relict erosional valleys extending north along this section of the Cape. Their gradients in the Wellfleet plain are between 38 to 87 feet per mile, almost four times the gradient of the plain itself (Hartshorn, and others, 1967). Most of these valleys are straight, narrow and steep-walled and graded to below present sea level.

11.7 Turn east (right) onto LeCount Hollow Road which follows the extension
0.1 of this proglacial valley from Blackfish Creek towards the edge of the sea cliff. These valleys, called "pamets" after the Pamet River further north, have heads which terminate both within the plains, or others, like LeCount Hollow extend completely across the Cape from the bay to the cliffs above the ocean. The various "hollows" or lower sags along the Cape Cod sea cliff are where these "pamets" extend completely to the cliff edge. Along LeCount Hollow Road are numerous kettle holes which indicate that the valleys were cut before the ice blocks melted, evidence that the valleys were formed during late-glacial times.

12.1 To the south (right) is Wireless Road.
0.4

12.5 Intersection to north (left) with Ocean View Road, continue ahead
0.4 (east).

12.7 LeCount Hollow, the seaward extension of the Blackfish Creek pamet,
0.2 the hollow or "sag" between the sea cliff representing a proglacial valley "gap." Do not stop, unless instructed, turn around in parking lot, which is a Wellfleet Town Beach. On the beach below, the sand sediment size has been steadily increasing since Coast Guard Beach (Fig. 12) where there, the average beach sediment size was that of medium sand (.3 mm), it has been increasing in size northward along

the shoreline and along the next few stops it is between the medium and coarse sand size (0.5 mm). This sediment size change will continue to *increase* rather than *decrease* to the north towards Provincetown Spit. Even along this cliffed highland area, beach sediment size *increases* in a regular pattern to the north. This is the basic coastal geology "mystery" of the Cape's Outer Shoreline.

12.9 Turn north (right) onto Ocean View Road. From LeCount Hollow Road,
0.2 Ocean View Drive road heads north along the edge of the sea cliff on the younger Wellfleet pitted outwash plain surface. Numerous small dry kettle holes occur in this plain.

13.8 Parking area to each (right). The sediment size on this beach is
0.9 coarser than the trend along the sea cliff beaches (Station 23, Fig. 12). Its average size is about 0.7 mm while the average size of the trend in this area is 0.5 mm. This difference may not seem significant but reference to Fig. 12 does show how this 0.2 anomaly stands out. The coarser size is possibly a reflection of a local source.

14.6 Road to east (right) leads down to Cahoon Hollow, another lesser sag
0.8 in the cliff edge. No distinct pamet channel leads off to the west (left), but a number of ponds, Great Pond and Dyer Pond, may indicate the line of former subsurface ice, in such a channel. The ice then melted leaving this line of kettle hole ponds to indicate its course.

14.8 Road moves off the younger Wellfleet Plain and onto the older, lower
0.2 Wellfleet Plain.

15.7 Continue following Ocean View Road, which bears off to east (right),
0.9 to Newcomb Hollow Road.

16.1 **Stop 3a – Newcomb Hollow Beach.** This coastal sea cliff "hollow" is
0.4 again a gap developed by shore erosion of the headward section of a proglacial outwash stream channel, a pamet. On the beach below, the average sand sediment size has decreased slightly (Station 25, Fig. 12), but still follows the trend of increasing size northward. A dynamic morphologic/sedimentologic model suggests that from these erosional sea cliffs, longshore drift should be moving both north and south to form the Provincetown Spit and Nauset Spits, respectively. The *increasing* beach sediment size to the north, appears in contradiction to this model, since grain size should *decrease* in the direction of drift, especially from the erosional sea cliffs to the depositional spits. Seemingly, there is only one other situation similar to this, Chesil Beach Dorset, a spit beach along the coast of England, King (1974). King could offer no reasonable explanation for the reverse size sorting on the Chesil spit beach. The concept of diverging longshore drift directions is related to coastal nodal points or nodal zone. The nodal point is that point along a shoreline where the direction of longshore drift changes "180 degrees." It has been well-documented along the northern New Jersey coast, near Manasquan Inlet, next inlet north of the well-known Barnegat Inlet, where the longshore deposition patterns against the numerous groins and jetties along the shoreline, make location of this reversal of drift directions fairly easily. In contrast, along the Cape Cod outer shore,

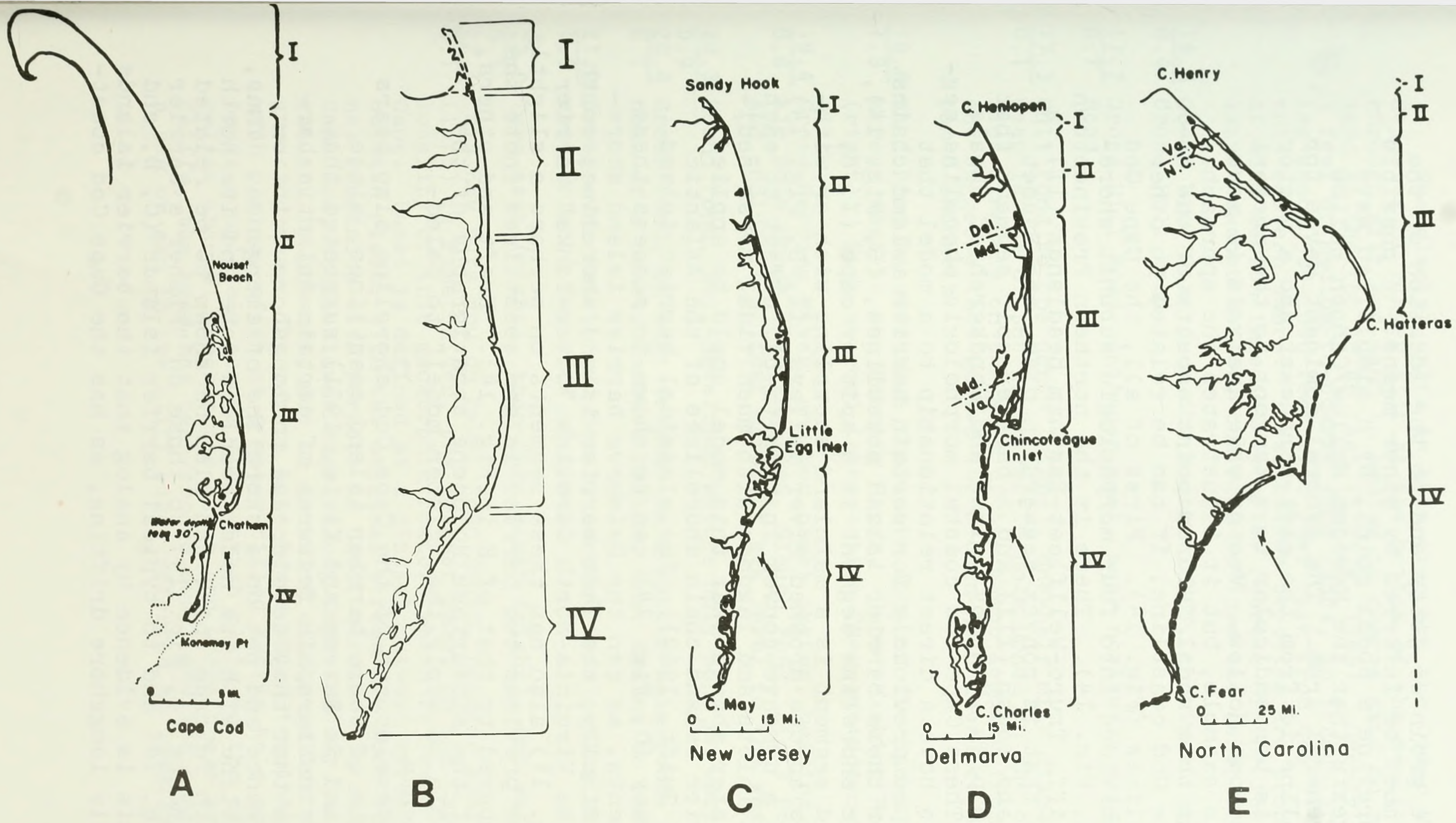


FIG. 14. Analog Relationship of Cape Cod Coastal Morphologic Units (A) to Fisher's Model of Morphologic Shoreline Compartments for Certain Barrier Islands in General (B, from Fisher, 1967) and as Applied by Analog Analysis to Atlantic Coast Barrier Islands (Fisher, 1969 *in* Swift) Including the New Jersey (C), Delmarva (D) and North Carolina (E) Barrier Island Chains. Coastal Morphologic Units as Follows: I - Spit or Cape; II - Mainland with Drowned River Valleys and Baymouth Barriers; III - Linear Barrier Islands with Few Inlets and Open Lagoon; and IV - Offset Curvilinear Barrier Islands with Numerous Inlets and Tidal Marsh Filled Lagoons.

there is not a single groin or jetty and so the location of the nodal point or zone must be inferred by other means. A possible location of this shoreline's nodal point, by a simplified wave vector analysis suggests that the Newcomb Hollow/Cahoon Hollow section may be the general area. The general dominant waves for the outer Cape shoreline is from the east-northeast and a vector from this direction is perpendicular to a tangent to the present shoreline here at Newcomb Hollow. Vector wave analysis is more complicated than this example, but it illustrates the approach.

When considering this nodal/fulcrum point aspects of the development of the Cape Cod coastline, it can be related to other Atlantic coast shorelines (Fig. 14). First of all, the Cape Cod coastline can be subdivided into four morphologic subunit shoreline compartments (A, Fig. 14). There is the northern Provincetown spit (I), the sea cliff, Truro-Wellfleet-Eastham headlands (II), a barrier spit segment that is convex seaward in plan, the Nauset Beaches, both north and south (III) and a barrier spit segment that is concave seaward in plan, Monomoy Island and Handkerchief Shoals to the south (IV). These Cape Cod coastal morphologic shoreline segments or compartments have a direct relationship to a model that Fisher (1967) developed previously for certain barrier island chains. On Fisher's model for these barrier island coastlines, (B, Fig. 14), the first morphologic shoreline segment is a spit or cape (I, B, Fig. 14). The second segment is a mainland shoreline with or without baymouth barriers across drowned river valleys (II, B, Fig. 14). The third segment is a concave-convex in plan (a-b), offset to each other, with numerous inlets and lagoons with much tidal marsh sedimentation. Fisher later showed that this model could be applied directly to the barrier island chain shorelines of the Atlantic coastline (Fisher *in* Swift, 1969). The classical barrier island shoreline of New Jersey (C, Fig. 14) can be shown to possess these model shoreline segments, as can the *Delmarva* barrier island shoreline (D, Fig. 14). Finally, the last barrier island shoreline, south of Chesapeake Bay, the Virginia-North Carolina "Outer-Banks" barrier island chain (E, Fig. 14) also has these segments on perhaps a slightly larger scale than the previous two barrier island coastlines (note the scale of C and D compared to that of E in Fig. 14). Kraft and others, (1972), in a study of the subsurface Holocene stratigraphy of the Delmarva coast was able to apply the "Fisher model" to paleosedimentary environments.

Therefore, the development of the Cape Cod shoreline also bears directly on the origin of these barrier island coastlines, since Fisher (1973, 1969, and *in* Saxena and Klein, 1971) suggested that the morphologic and stratigraphic features of certain Atlantic barrier islands indicate that they develop due to longshore drift on shorelines of submergence and not on a shoreline of emergence. Thus, if the Cape Cod coastline with its nodal headland zone and its north fulcrum spit and south fulcrum spit, can also be shown to be related in its shoreline segments (A, Fig. 14) to those on "Fisher's barrier island model" (B, Fig. 14) and to typical barrier islands (C, D, and E, Fig. 14), then this is evidence by analog that the barrier islands developed by primarily longshore drifting, as has the Cape Cod coastline.

The glacial units in this area are the Older Wellfleet plain deposits of clayey silt at the bottom of the section working up through silt and sand to medium to coarse sand to medium to coarse sand at the top at 48 feet (Oldale, 1968). Overlying this is 2 to 3 feet of medium-to-coarse dune sands, an irregular deposit averaging about 500-1000 feet wide just back from the cliff edge along this eastern shore. These eolian deposits are probably the result of wind action immediately after retreat of the ice sheet. As we leave Newcomb Hollow, the road follows the pamet for 0.3 mile.

16.5
0.4 Ocean View Road from the south (left), continues ahead (west) on Gross Hill Road.

17.2
0.7 Gross Hill Road continues west, bear northwest (right) on Gull Pond Road.

17.3
0.1 Gull Pond to the north (right), one-half mile diameter and 66 feet deep is one of the large kettle hole ponds on the outer Cape. It lies directly on the axis of the pamet leading from Newcomb Hollow and suggests that buried ice blocks help localize the outwash stream pamet channels.

18.6
1.3 Gull Pond Road follows the south side of the pamet in which flows a stream west to the Herring River. Upon reaching Route 6, turn north (right). Sign at road intersection "Newcomb Hollow Road."

19.4
0.8 Cross Herring River, another pamet system, heading in a number of kettle hole ponds (Herring Pond, Slough Pond, etc.) to the east (right) and ending in a tidal marsh at sea level to the west (left).

20.3
0.9 Round Pond, well-developed kettle hole pond on west (left).

20.4
0.1 Great Pond, on east (right) is a kettle hole pond, that forms the head of a pamet, Lombard Hollow, that drains to the west (left).

21.9
1.5 Cross over Pamet Road South, careful turn coming up. Quick look to east (right) for view of pamet.

22.0
0.1 Turn east (right), then turn south (right), and east (left).

22.1
0.1 This now puts you on Pamet Road South, heading east. To the north (left) is Pamet River, the largest pamet on the Cape and the type locality of this geomorphic feature which is found along the outer Cape. Pamet is defined as a glacial outwash stream channel on an outwash plain, with the original stream now gone and a relict channel remaining with perhaps an unfit stream. In some cases, as in Cape Cod, at its lower edge, along Cape Cod Bay, a tidal stream or estuary is present, due to drowning of the relict channel by a transgressing sea. The pamets have heads which terminate within the outwash plains, often at a water-filled kettle hole or the channel extends completely across the outwash plain to the ocean. Where this relict channel reaches the ocean and where there are eroding sea cliffs, the head has been eroded away, and the channel itself creates a sag or gap in the cliff edge, referred to locally as "hollows."

The presence and location of these hollows are important locally, since they are often the only means of reaching the beaches below from the top of the sea cliffs along the outer Cape.

Numerous kettle holes along many pamets suggest that the valleys were cut before the ice blocks melted and that the ice forming these kettle holes was buried below the surface and were not ice blocks on the surface. This also suggests that the pamets formed during the later stages of the glacial retreat. At Pamet River, the largest pamet on the Cape, the valley is wider (0.5 mile) and deeper (50 feet minimum) than any other pamet on the Cape, there may have been more dead ice present. The question arises then, to what extent is this wide valley due primarily to fluvial meltwater or the buried ice collapse? Along the Pamet River pamet channel valley walls there are what appear to be incomplete terraces, if these are terraces, the question arises as to whether they are fluvia terraces, indicative of extensive meltwater deposition and erosion or perhaps they are kame terraces, and if kame terraces, they then suggest a greater influence of ice rather than water on the development of these larger pamets.

22.9 Straight ahead (east), intersection with Collins Road.
0.8

23.8 **Stop 4 — Ballston Beach.** Park here for excellent view, down valley,
0.9 south/southeast of Pamet River pamet. This pamet may also have reached to the ice lobe's edge, where Ballston Beach at the ocean edge forms a low hollow that is actually longshore drifted beach sands and wind action developed dunes. Since the Pamet River, from its harbor to these dunes, here, are both at sea level elevation, this pamet was once considered as a possible site for the Cape Cod Canal. On the beach itself, the average size of the sands are slightly finer than those 5 miles north and south of this site (Station 28, Fig. 12). The increase in the finer fraction is probably supplied from these dunes backing the beach. Upon leaving the parking area, continue ahead (north) onto North Pamet Road going west

24.1 On the north (right), there is a well-formed almost circular kettle
0.3 hole, just about 150 feet in diameter.

24.3 Again, to the north (right) there is a larger, elongated kettle hole,
0.2 that has, in the past, been ditched and drained on its north side as a cranberry bog.

24.6 North (right) again a cranberry bog and the road climbs up what may
0.3 be an incomplete erosional terrace and onto the Wellfleet plain.

25.5
0.9 At first intersection of "cloverleaf," turn right and immediately right onto Route 6. There may be a short stop to view the pamet, to the east towards the ocean, and west to the bay.

27.4 On the east (right) is Long Nook Road, again another pamet, which
1.9 leads some 1.3 miles to the North Truro town beach, which was infamous a couple of years ago, as Cape Cod's nudie beach.

28.4 East (right), South Highland Road.
1.0

28.9 Leave Wellfleet Outwash Plain (150-175 feet above sea level) and
0.5 enter onto the lower Truro Outwash Plain (50-75 feet above sea level).

29.1 Turn east (right) onto South Hollow Road. Immediately to south
0.2 (right) are town wells. All of Cape towns get their water from a ground water supply. The highly porous and permeable outwash glacial deposits are excellent ground water reservoirs and all surface water goes almost immediately underground. There are no streams on the Cape, except for some tidal "streams" and the water level observed in most kettle hole ponds is at the local water table level.

29.4 South Hollow Road, leaves lower Truro Plain and enters onto contact
0.3 between highest Wellfleet Plain to south (right) and intermediate height, Highland Outwash Plain (100-125 feet above sea level) to north (left).

29.8 Turn north (left) on South Highland Road. Sand quarrying ahead in
0.4 "undifferentiated sand deposits of uncertain origin, chiefly valley-bottom deposits" (Oldale, and others, 1967).

30.2 Turn east (right) onto "Highland Light Road." To south (right) is
0.4 Highland Golf Course. Road is on Highland Outwash Plain.

30.5 **Stop 5 — Highland Light.** Follow trail south (right) to overlook.
0.3 Please do not enter onto lighthouse property.

The wave-cut cliffs at Highland Light are remnants of a once more extensive land mass to the east. The original extent of the Cape Cod offshore land mass can be estimated by multiplying the average rate of cliff erosion of 3 feet per year (Zeigler, 1960) by the length of time the sea has been at its present level. Curry's sea level rise curve (1965) indicates that about 3,500 years ago sea level was close to the present level and has been rising slowly but steadily since then. These figures suggest that the original Cape Cod shoreline extended some 2 miles offshore (3,500 × 3 = 10,500 feet). Shaler (1897) claimed that "slope extension" indicates that this original shoreline could not be less than one half mile or more than four miles. Davis (1896) suggested that the "greatest retreat of the original shore to the present shore" was about 2-1/2 miles based on fulcrum retreat and reconstructed the initial shoreline on this basis. He also suggested that this erosion would have occurred within the past 3,000 years based on average rates of erosion. Erosion still continues along these cliffs, both by wave erosion below, where at high tide, the water reaches the cliff base and at the top where landslides occur. To the north (left) of the overlook, fissures or "mole-tracks" are often visible, paralleling the cliff from 5 to 10 feet back from the edge. These are fractures, the beginning of the fault on which a landslide block fails. In September 1972, a 200 square foot section of this cliff failed and 10,000 cubic feet of sediment was deposited on the beach below (Giese and Giese, 1974). The average size of sediment on the beach itself is not unusually coarse (Station 29, Fig. 12) being between medium and coarse sand. In fact, the finer material of this station and those north and south is probably due to an input from the finer silts that make up the "blue clays" of Truro. Highland Light, 120 feet above the beach, is situated on the Highland Plain (Qh), a small triangular area, bordered on the south by the

50 foot higher Wellfleet plain (Qw, Fig. 18). These Highland Light glacial deposits are among the most well-known of the various Cape Cod glacial features. While Grabau (1897) was the first to describe the Wellfleet and Truro plains, the Highland plain, (lower than the Wellfleet plain to the south and higher than the Truro plain to the north) was first recognized by Wilson (1906).

The stratigraphic section of the Highland plain deposits exposed in the sea cliff at Highland Light has been known for many years (Woodworth and Wigglesworth, 1934) although there are now differences in interpretation as to age and depositional environments. At the base of the cliff, 30 to 70 feet of iron stained coarse sand to pebbles and cobble gravel is overlain by 0 to 45 feet of gray clay and silty clay, which is then overlain by 15 to 40 feet of yellowish-gray, fine to medium grained sand. This upper sand unit is ripple-laminated, however the upper section of the clay unit is contorted into rolls and faulted and contains "clastic" dikes which penetrate into the upper sand unit. Similar deformation features, probably due to slump during deposition, are found within the main body of this clay unit (Hartshorn, and others, 1967; Oldale, and others, 1968).

In the past, these three glacial units were correlated with the Jameco Gravel, Gardiners Clay and Jacob Sand on Long Island (Woodworth and Wigglesworth, 1934). The silt-clay unit, in particular, has been correlated with the Gardiners Clay by numerous early workers (Fuller, 1906, 1914; Woodworth and Wigglesworth, 1934; and Hyyppa, 1955). Hyyppa pointed out the marine character of the clay on the bases of diatoms; but, since the type Gardiners Clay on eastern Long Island is considered interglacial in age, it does not seem likely that this late Wisconian age glacial clay on Cape Cod is correlative with the Gardiners Clay.

Oldale, and others (1968) show that, in general, these Highland plain glacial deposits were laid down in a body of water (marine?), dammed by the Wellfleet plain to the south, the Cape Cod Bay ice lobe to the west and the South Channel ice lobe to the east. South Channel ice is shown to be the source of the sediments by the westerly slope of the surface of the plain and stone counts within the deposits itself (Koteff, and others, 1967). The clay unit interfingers with the sand unit, as it pinches out to the south, while it is truncated by erosion to the north. This stratigraphic relationship is evidence of both its local and glacial character and thus again, could not be correlative with the Long Island interglacial Gardiners Clay.

30.8 / 0.3 At South Highland Road, turn north (right), leaving the Highland Outwash Plain.

30.9 / 0.1 On Highland Road, (sign indicating "To Route 6 and 6A") turn west (left).

31.7 / 0.8 Just before the Route 6 overpass, turn south (left) onto the approach and then north (right) onto Route 6.

32.0 / 0.3 Road east (right) leads to Head of Meadow Beach, a "hollow" leading to the shore.

33.3 Stop 5a – Pilgrim Springs - Head of Meadow will be made. Leaving
1.3 Route 6, the road to Pilgrim Spring passes over the Truro plain. Truro plain is the most northern of the glacial outwash plains of the outer Cape and is about 50 feet lower than the Highland plain. Less ice collapse and meltwater erosion features are found on this plain. Truro plain deposits overlie the Highland plain deposits with an unconformable contact, indicating that it is younger than both the Highland and Wellfleet deposits. These Truro sediments are primarily fine-grained, yellowish-gray flat-bedded ripple laminated sand with scattered pebbles and cobbles. No till was found, although a till-like material is found in the cliff near Highland Light. Its origin is uncertain, it may be a landslide, ice rafted or a turbidity flow, and has been called "diamicton" (Flint, and others, 1960a, 1960b). In addition, steeply dipping deltaic foreset beds are found in the Truro deposits (Hartshorn, and others, 1967).

From the parking lot, a short walk along the Pilgrim Spring trail leads to a relict or "fossil" sea cliff above the "Head of the Meadow." The meadow referred to, is the salt meadow below that, separates the Truro plain from the Provincelands spit that has grown from a junction to the south along the sea cliffs. This junction on the initial Cape Cod shoreline must have been southeast of the present junction at Head of the Meadow beach. Davis (1896) pointed out that as this spit grows by accretion and the cliff retreats by erosion, there is a neutral point of "fulcrum" of no change along the shoreline; but, with time, on the initial seaward Cape Cod shoreline, this fulcrum will shift toward the spit as the cliff erodes.

Below the Pilgrim Spring overlook, this cliff, above the present meadow, was originally a marine sea cliff above the open ocean until the first Provincetown spit was built from the Highland Light area to the south (right).

Sand dunes visible to the north, on the outer shoreline of this spit are parabolic or "U" in shape with the open end of the dune facing into the dominant prevailing wind which along this section is from the northwest. Parabolic dunes generally develop where there are large amounts of sand together with some vegetation, in this case, beach grass and various low salt tolerant shrubs such as bayberry.

33.7 Route 6 drops down the face of the former marine sea cliff "High Head,"
0.4 which was open to the sea until spits growing from the ocean and bay side isolated it from the sea.

34.1 High Head Road to north (right) follows the base of this relict sea
0.4 cliff and leads to a trail over the dunes on the spit.

34.7 Route 6 follows along a spit enclosing Pilgrim Lake to the north
0.6 (right). This shallow water lake (depth 3-5 feet) was originally a salt water bay, into which the Pilgrims sailed to find fresh water before crossing Cape Cod Bay to find their settlement at Plymouth. The inlet originally at this point, closed in 1869 and its tidal delta is visible to the north (right).

35.8 North (right) at the western end of the lake is the Mt. Ararat dune
1.1 field parking lot.

The climb up the sand trail from the parking lot to the top of Mt. Ararat is only 50 feet, but the loose sand makes the climb difficult. From the dunes, the view to the southeast illustrates the concept of High Head as an ancestral marine cliff with the Provinceland spit, now covered by parabolic dunes, growing from a fulcrum along its present oceanic cliffed shoreline. Perhaps the earliest spit that was formed, reached from High Head on the east, passed through this Mt. Ararat area and continued west to form the land on which Provincetown is situated.

Dunes in the Mt. Ararat area are not as recognizably parabolic as those on the far side of Pilgrim Lake, and are more open or semicircular in shape with their central axis oriented to the northwest.

36.7 / 0.9 Dunes migrating from the north (right) onto the highway. The dunes have developed from the sand of relict spit ridges. Under the dominant northeasterly winds, these sands move across the highway at a rate of 12 feet per year.

37.8 / 1.1 Road intersection, at traffic light, turn north (right) onto Race Point Road, sign indicates "Provinceland." From Route 6, Race Point Road heads northeast towards the ocean. The road passes through a forested lowland that lies between the ancestral Provincetown spit and the older of the more recognizable relict beach spits. This lowland area, about one-half mile wide, perhaps represents a past change in the rate of sea level rise, with the sand forming a wide foreshore or nearshore but not a series of narrow spit frontal ridges. Other, less likely factors, might be change in sediment supply or meteorological patterns.

38.2 / 0.4 Just before the road enters the relict beach spits, a trail to the west (left) leads through Beech Forest.

39.0 / 0.8 Road to east (right) leads to the Seashore Park Ocean View Shelter. If time is available, we may stop there. Ocean View Interpretive Shelter is directly on what is perhaps the third relict spit ridge. To the south, on perhaps the oldest spit ridge, can be seen the Pilgrim Monument, together with the intervening forested lowland of the Beech Forest area.

39.2 / 0.2 Road to west (left) leads to Herring Cove. Continue north on Race Point Road with relict spits and intervening ridges curving off into the distance. From this vantage point it is easy to visualize each of the relict ridges as "lines of growth." To the northeast and north, a wide trough between the most recent relict ridges begins to appear, and in the view to the northwest along Race Point Road, we see that the Provincetown Airport occupies this wide trough. This trough probably represents a very wide relict beach formed before the frontal or foredune ridge on the growing spit, much like the wide beach in front of present-day Race Point Beach. Undulations in Race Point Road as it heads northwest towards the beach indicates the ridge and trough topography of these relict spits.

39.8 / 0.6 **Stop 6 — Race Point Beach.** The most recent of these growing spit beaches is, of course, present-day Race Point Beach. Race Point Beach usually exhibits "abrupt day-to-day changes" and measurements of seasonal beach changes have ranged from a maximum elevation of over 18 feet above mean low water to a minimum of 3.5 feet (Zeigler and Tuttle, 1961). Offshore from Race Point Beach there is a fairly permanent longshore bar, Peaked Hill Bar. The dynamics of this bar are probably responsible for most of the abrupt changes along this beach. Peaked Hill Bar actually begins tangent to the beach at Highland to the east and extends westward, terminating at Race Point. This bar is offshore, a distance of 2,000 feet, and as the shore makes a sharp turn to the south at Race Point, the Peaked Hill Bar also turns, but gradually merges into the shoreline.

Between Peaked Hill Bar and the Race Point Beach, observations indicate that at times the sand moves onto the beach as a series of giant ripples or bars. Sometimes these smaller bars are also transverse to the beach as they migrate along the shoreline (Zeigler and Tuttle, 1961).

The coarsest beach sediment size on the Cape Cod outer beach is found here at Race Point Beach. The average sediment size is almost that of very coarse sand (Stations 40 to 42, Fig. 12). If this sediment is transported by longshore drifting from the highland cliffs to the south, one would expect the sediment size to decrease away from the source area. The beach sediments along the southern part of the Cape, Nauset Beach, do decrease in size in the direction of longshore drift, but not here to the north in the Provincetown spit shoreline. Changes in the direction of longshore drifting were thought to occur some 18,000 and 6,000 years ago when sea level was lower. At that time, sand eroded from the highlands, further offshore, was moved from the north to the south, but as sea level rose, and Georges Bank, to the east, was submerged, more waves could reach the Cape from the east and southeast and the Provincetown spit could begin to form (Zeigler, and others, 1965). That reversal in littoral drift direction occurred many years ago and does not seem to explain the reverse trend in present-day beach sediment size along the Provincetown Race Point beaches.

SECTION C

A MICROSCALE VIEW

In Section C, we will view the microscale coastal processes and resulting geomorphic structures and bedforms occurring on Coast Guard Beach and Nauset Spit. Transportation will be by four-wheel drive vehicles. The leaders of this section are Stephan P. Leatherman and Paul J. Godfrey.

Barrier beaches, islands and spits, are common features along the Atlantic and Gulf Coasts of North America. Their exposed position and low physiography make them highly vulnerable to severe storms. With the present eustatic rise in sea level (Hicks, 1972), these barriers are presently being eroded (National Shoreline Study, 1971). Overwash, the transport of sea water and sediment across the island during storms, is a major component of the barrier islands response to these high energy conditions. In addition, overwash processes may be important to the possible landward migration of these islands.

Overwash is defined as the continuation of the uprush over the crest of the most landward (storm) berm (after Shepard, 1973; Leatherman, 1976). The resulting deposit is not subject to reworking on the active beach by normal wave and tidal action.

FIG. 15. Nauset Spit Washover Fan with Sand Deposited Over High Salt Marsh.

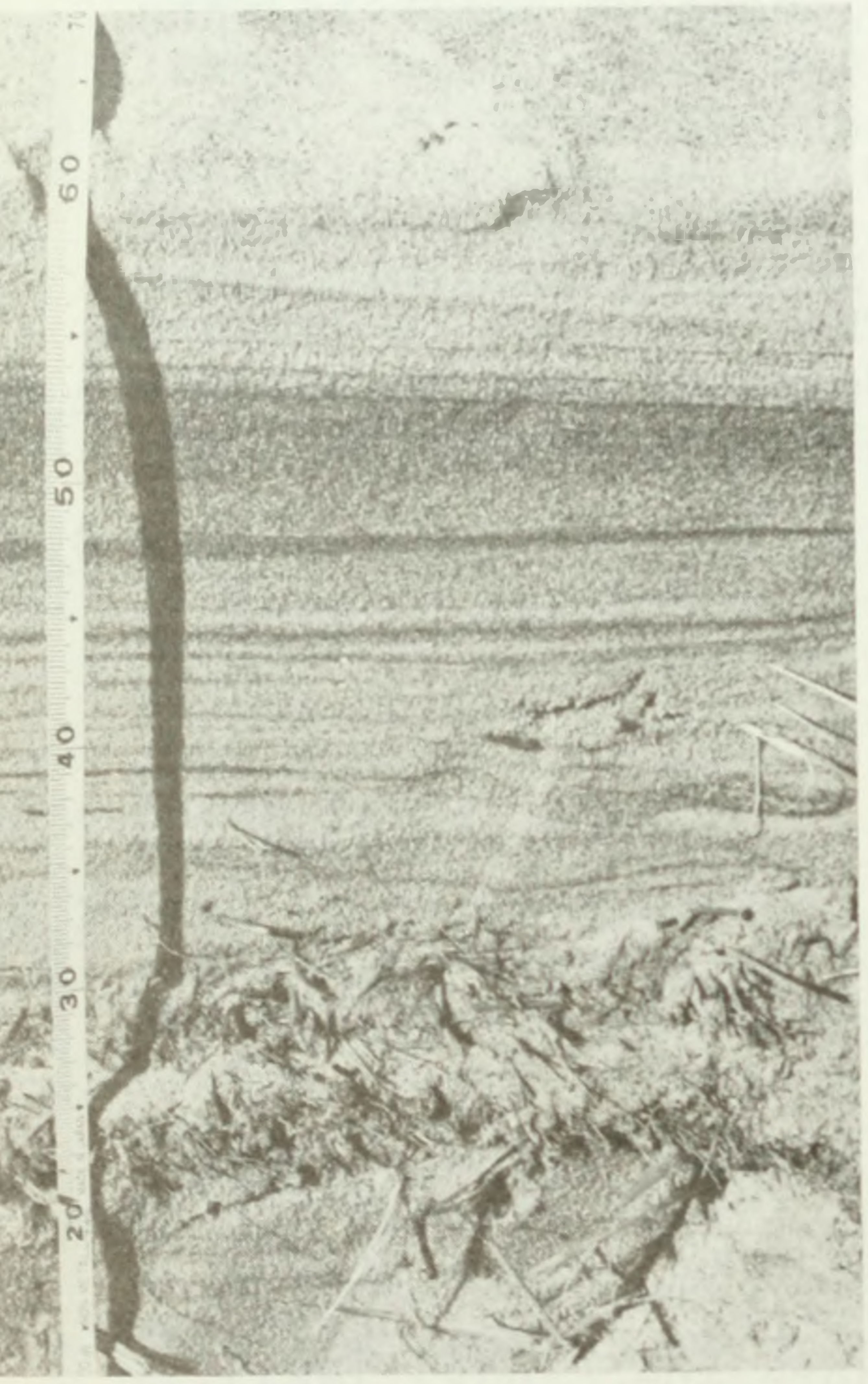


FIG. 16. Overwash Sedimentary Sequence from a Single Storm Event.

FIG. 17. Eroding Peat Outcropping on the Beach Face in Front of a Washover.

The surges transport sediment to the eolian flats or marsh, depending on their magnitude and the island's width. The narrow breach through the dune field is referred to as the throat or neck. The fan is that portion of the washover where the deposit is allowed to flare due to the lack of horizontal constraints. Broad washover flats, as contrasted to discrete fans with flanking barrier dunes, generally mark the position of previous inlets.

Overwash is important in terms of its ecological and geological implications. Godfrey and Godfrey (1972) found that overwash is partly responsible for creating new marshes and providing nutrients to the salt marsh system. The *Spartina alterniflora* that colonizes the new sediment has been shown to be more than twice as productive as older marshes in North Carolina. Therefore, overwash is deemed significant on the short-term basis.

The geological implications of overwash are more difficult to evaluate. After 26 months and seven discrete overwash events, there was no net gain of material on the back-dune area for the washover fans on Assateague Island, Md. (Leatherman, 1976). One of these storms, the December 1, 1974 northeaster, was one of the largest storms to affect these shores in the past 25 years from wave hindcast analysis. The prevailing northwest wind transported the bulk of the material back onto the beach face before it could be colonized by the Spring growth. Therefore, the washover fan is viewed as a temporary reservoir for the eventual redistribution of the material by the wind. Overwash appears to be relatively unimportant on the short-term basis, at least for the area cited. This viewpoint agrees with the Corps of Engineers position that island maintainence by overwash processes is probably only significant within the context of a geologic time frame (Corps of Engineers, 1974).

Coast Guard Beach parking lot in Eastham marks the end of the eroding glacial material and the beginning of Nauset Spit, a coastal accretionary landform. The National Park Service built Coast Guard Beach parking lot and bathhouse in 1964. Shoreline recession threatens to close off this area, and the bathhouse remains unprotected due to the rampant erosion. The sand derived from these eroding cliffs has served to create and nourish Nauset Spit and Monomoy Island.

The segment of shoreline between the parking lot and Nauset Inlet (Fig. 10) is also eroding as marked by narrow beaches, wave-scarped dunes and numerous washover fans. A large breach in the frontal dunes occurred in 1972 as a result of a severe northeaster. Sand was deposited to a depth of several feet over the *Spartina patens* salt marsh as a fan (Fig. 15). Much of this sediment was derived from erosion of the dune itself, the remainder supplied from the beach and shoreface. To a large degree, the *Spartina* has not recovered, much of the area remains bare, except for some colonization by American Beach grass (*Ammophila*). Once the grass becomes established, it acts as a baffle to the eolian-transported sand, and a small dune is now forming. This revegetation pattern is unlike that found along the North Carolina shoreline (Godfrey, 1970).

A trench, dug into the overwash sand in the throat section, revealed the characteristic horizontal laminations (Fig. 16). Measurements taken at Assateague Island during storm conditions showed that the overwash surges move across the threshold at high velocities due to the initial momentum imparted to the surge by the breaking wave. Maximum instantaneous velocities of 9 feet per second at 2 inches from the bottom for a one foot surge were recorded at Nauset Spit for the March 16-17, 1976 northeaster. Froude numbers indicate that subcritical to critical flow regimes persist, resulting in parallel bedding (Leatherman, 1976).

Between 20-30 cm. there exists a mat of debris. This vegetal material is concentrated as the prevailing northwest winds strip off the sand, transporting large quantities of the overwash sediment back to the beach. Therefore, this debris represents an old surface and marks the position of the base of the new material. At 50-54 cm. there exists a concentrate of heavy minerals, principally ilmenite and garnet. Previous analysis of storm deposits illustrated that this concentrate is negatively skewed and therefore hydraulically-lagged (Leatherman, 1976). The heavy mineral band represents the height of storm surge when the waves were allowed to advance closer inshore before breaking and the surges reached their maximum flow conditions. The heavy sand layer is found at approximately mid-section in a fresh overwash deposit, but subsequent (post-storm) wind erosion is much in evidence (note small wind shadow dunes in Fig. 15). As one proceeds southward, the laterally spacing between fans decreases until a barrier flat is encountered over 500 meters north of the inlet. This area was planned off by a temporary inlet in 1972 that moved southward until it merged with the present day inlet. Overwash processes and eolian transport, acting principally in opposite directions, tend to keep this area low and non-vegetated.

At the first distinct fan north of the washover flats, a large section of salt marsh peat is exposed at low tide following storm-induced beach erosion (Fig. 17). The peat is underlain by very coarse sand which is poorly size-sorted, suggesting it is of inlet origin. This peat material is being dated by the U.S.G.S. - Woods Hole, and further investigations are currently in progress. Figure 17 also shows the seaside scarping of the barrier dunes and small wind shadow sand accumulations tailing toward the East.

Nauset Inlet is anomalous in its behavior since it is migrating northward even with a predicted net southward littoral drift. The flood tidal delta is left stranded with this movement, and it serves as a substrate for marsh development and expansion. The ebb tidal delta is well-defined by the position of the breakers seaward of the inlet.

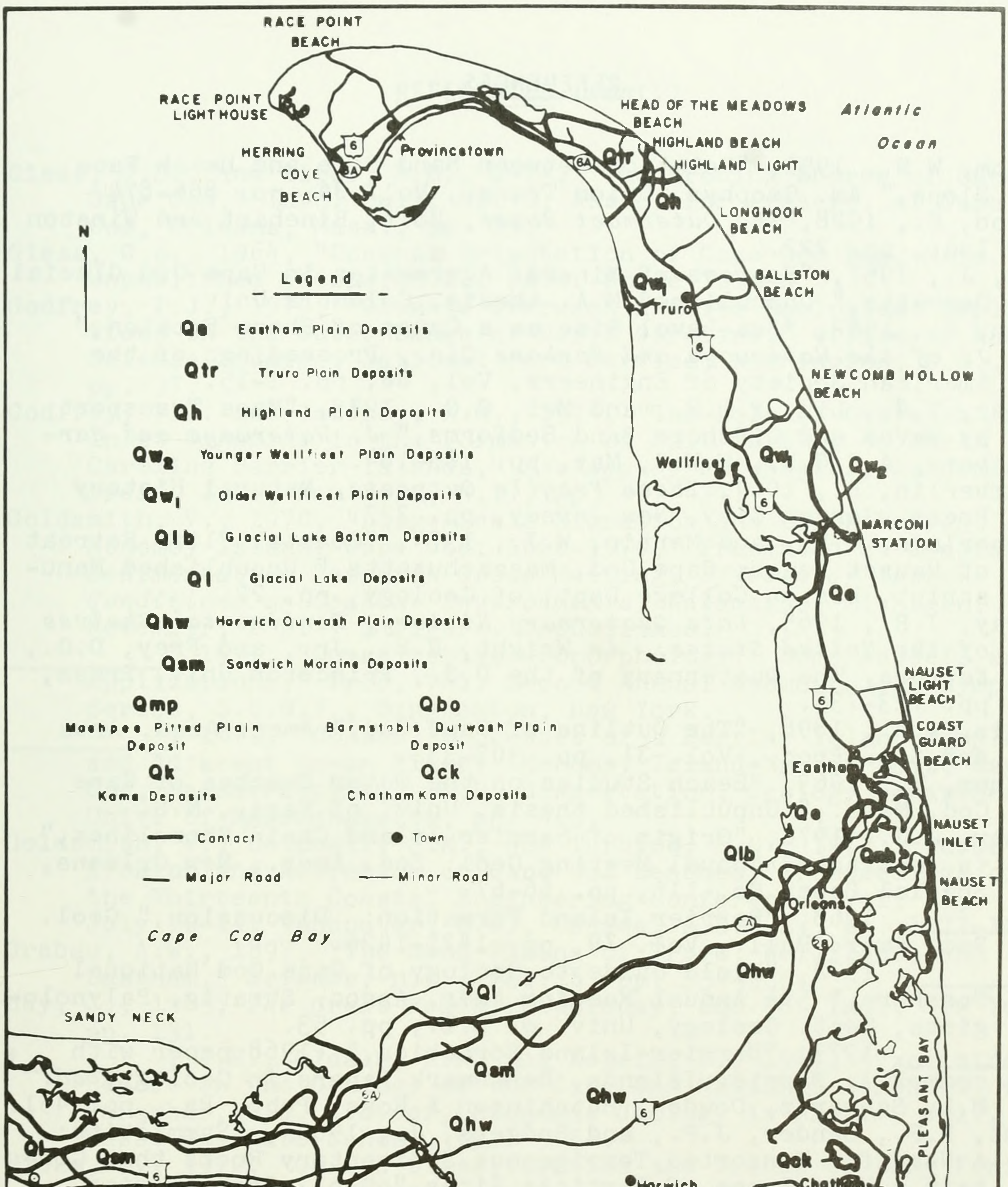


FIG. 18. Generalized Geological Map and Section B Route Map of Cape Cod.

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