1978

An Aerial Photogrammetric Survey of Long-Term Shoreline Changes, Nantucket Island, Massachusetts

Michael Joseph Goetz
University of Rhode Island

AN AERIAL PHOTOGRAMMETRIC SURVEY OF LONG-TERM SHORELINE CHANGES, NANTUCKET ISLAND, MASSACHUSETTS

BY

MICHAEL JOSEPH GOETZ

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

GEOLOGY

UNIVERSITY OF RHODE ISLAND

1978

ABSTRACT

The shoreline with its constantly changing patterns of erosion and accretion represents a unique problem in the area of coastal planning and development. The field collection of shoreline change data is expensive, time-consuming and presents a problem in extrapolating short-term changes into long-term trends. The use of aerial photography to make quantitave measurements is a low cost technique that provides detailed coverage of the shoreline and its transient features.

Photogrammetric areal measurements of Nantucket Island, Massachusetts were made using a Bausch and Lomb Zoom Transfer Scope for four sets of aerial photographs taken between 1938 and 1970. Sequential overlays of the shoreline were prepared and areal measurements taken for shoreline segments 305 m in length using a square grid counting technique. The accuracy of this photogrammetric technique was found to average 2.4 percent in ground truth surveys. Long-term annual changes (32 years) reveal that the eastern shoreline of Nantucket from Great Point to Tom Nevers Head was eroding at the rate of 0.56 m/yr while the south shore from Tom Nevers Head to Smith Point had a net erosion rate of 2.11 m/yr. The north shore from Smith Point to the west jetty was eroding at the rate of only 0.1 m/yr in contrast to a net accretion rate of 0.72 m/yr measured for the north shoreline from the east jetty to Great Point. The islands of Tuckernuck and Muskegat were generally eroding over the entire

32 year study period with Tuckernuck losing a net 480,000 m^2 (mostly on the south shore) and Muskegat losing 107,500 m^2. Recent shoreline changes on Nantucket and the surrounding islands as revealed by 1974 and 1976 Landsat imagery indicated changes in the position of sand spits at the end of Smith Point and on Muskegat. Satellite imagery was not found to be useful in making quantitative measurements because of its limited resolution characteristics.

Material eroded from the shoreline that is not redeposited downdrift appears to be stored in a number of shoreface connected sandwaves or ridges along the south and east shoreline.

ACKNOWLEDGEMENTS

I would like to thank my wife, Suzanne Goetz, for her patience and perserverance in helping edit and type the first draft of this paper. Theresa North typed the final copy. Special appreciation is extended to Dr. John J. Fisher for his patience and advice throughout the investigation and in the final preparation of the manuscript. Dr. Boothroyd offered helpful suggestions and insight into coastal processes.

TABLE OF CONTENTS

LIST OF FIGURES

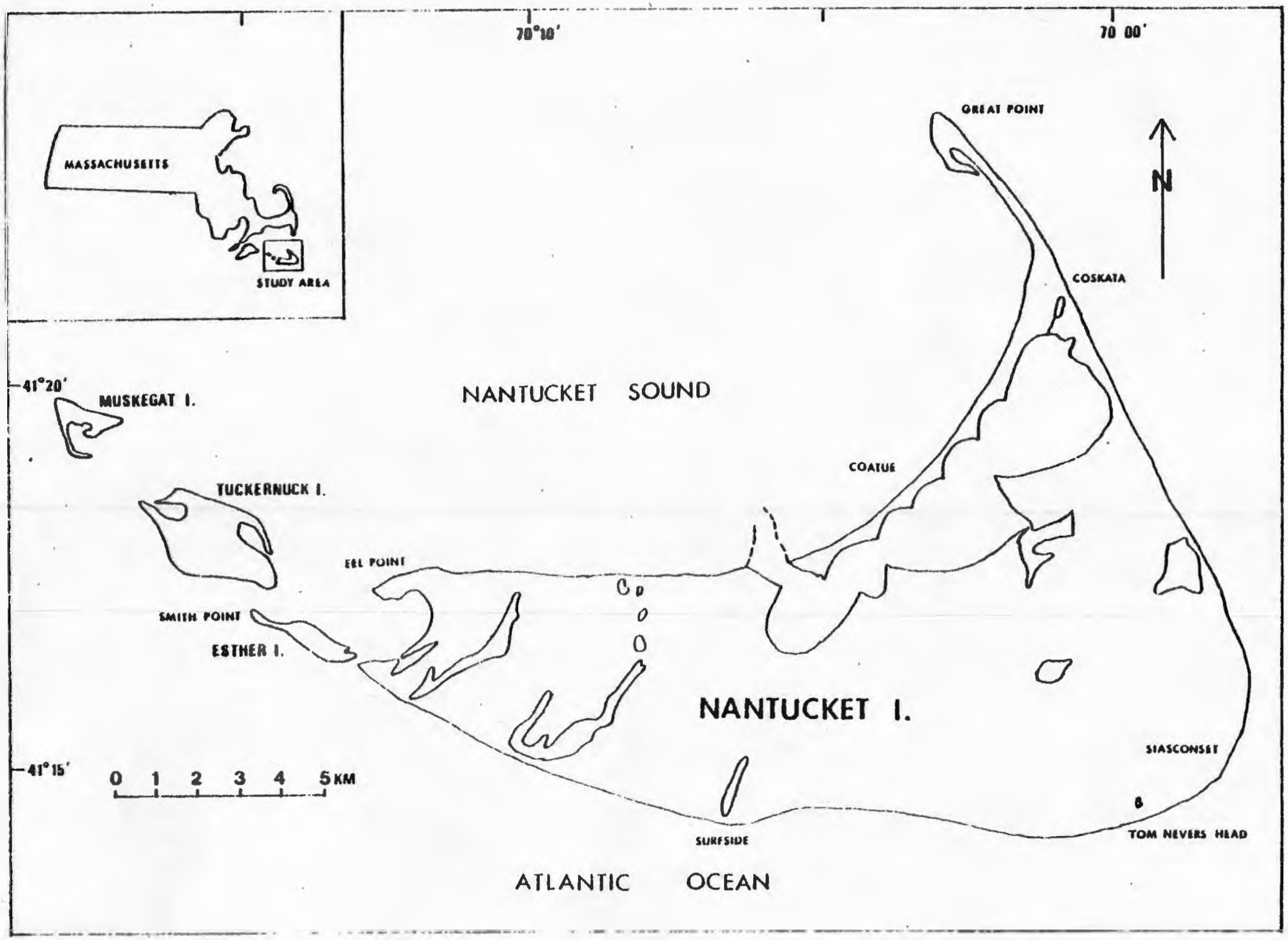
INTRODUCTION

Nantucket Island, Massachusetts is located 40 km south of Cape Cod. It is approximately 9.7 km wide and 22.5 km long with a land area of 128 km^2 (Figure 1). Nantucket has long been an important summer resort known for its many fine beaches. Consequently there has been a rapid development of its shoreline during the past 80 to 90 years. The island's constantly changing patterns of shoreline erosion and accretion have presented problems in the area of coastal planning and development. On Nantucket there have been numerous instances of buildings placed in locations where the shore was undergoing rapid erosion, resulting in the loss of this property or necessitating its removal to a more stable location. In order to insure the proper placement and protection of residential and commercial property with respect to the changing coast, information on the rate of shoreline erosion and accretion is necessary.

The collection of data on coastal changes can be a problem. Usually it involves measurements in the field that are both time-consuming and expensive. There is a further complication in extrapolating results of field studies into long-term trends. The utilization of existing aerial photography, when it is available, can supply an excellent source of information. The photographs provide a permanent and extremely detailed record of shoreline conditions at the time they were taken. Aerial photographs allow the investi-

FIGURE 1

Location Map


70°10'
70 00'
41°20'
41°15'
MASSACHUSETTS
STUDY AREA
GREAT POINT
N
COSKATA
NANTUCKET SOUND
MUSKEGAT I.
TUCKERNUCK I.
COATUE
EEL POINT
SMITH POINT
ESTHER I.
NANTUCKET I.
SIASCONSET
TOM NEVERS HEAD
SURFSIDE
ATLANTIC OCEAN
0 1 2 3 4 5 KM

gator to locate such reference points as cliff or dune lines and high tide lines which can be used as indicators of coastal changes. Photographs provide an advantage over maps and charts in that they are taken more often than maps are revised.

The main purpose of this investigation is to determine the pattern and rate of shoreline changes on Nantucket. This was accomplished by studying the results of historical surveys from the late 1800's through the early 1900's and by preparing overlays of sequential aerial photographs from 1938 to 1970. Photography was available for the years 1938, 1951, 1961, and 1970, giving roughly ten year intervals between aerial photographs. The aerial photographs used in this study were of various scales, so in order to produce overlays it was necessary to compare the photographs at the same scale. The Bausch and Lomb Zoom Transfer Scope was used to optically enlarge and superimpose the image of a smaller scale photograph onto a larger scale base photograph. This instrument also incorporates an anamorphic system which allows compensation for such geometric anomalies in the photograph as tilt, relief, earth curvature, lens distortion or film shrinkage. Nantucket's shoreline is primarily composed of cliffs or large dunes so the cliff line and dune line were used in preparing the overlays in most instances. Where these lines were absent the high tide line was employed. Measurements were then made from these overlays and the subsequent data interpreted and analyzed. A ground control survey of Nantucket was performed in order to accurately determine photographic scale and reduce error in measurements made on the photographs.

SURFICIAL GEOLOGY OF NANTUCKET

Nearly all of the geomorphic features on Nantucket, with the exception of beaches and spits, are composed of the terminal moraine and outwash deposits of the first substage of the Wisconsinan glaciation (Woodworth and Wigglesworth, 1934). Surficial geology of Nantucket is divided into three primary units:

1. the outwash plain which occupies the southern half of the island;

2. the fosse which is a longitudinal depression between the crest of the outwash plain and moraine and the southernmost advance of the ice lobes;

3. the terminal moraine that forms the hills across the northern section of the island (elevation slightly in excess of 30 m).

Tuckernuck Island to the west of the main island has the same three surficial units, whereas Muskegat Island (to the west of Tuckernuck) appears to be a wave-leveled remnant of the terminal moraine and is presently composed entirely of sand dunes no more than 3 m in height (Woodworth and Wigglesworth, 1934).

Great Point, a spit projecting northwards on the east side of the island, is believed to have been formed as a tombolo extending from the glacial deposits on Coskata to a similar gravelly hummock to the north. Coatue Beach, a Holocene sand spit derived from the Coskata Glacial sediments, extends nearly 10 km to the south and west and separates Nantucket Harbor from Nantucket Sound. The cuspate spits on the harbor side of Coatue Beach are presently believed to be "abrasional" features formed by longshore processes within the harbor (Rosen, 1975).

PREVIOUS SHORELINE CHANGE AERIAL STUDIES

Aerial photographs have been widely employed in the past to obtain qualitative information on shoreline changes. Nichols and Marston (1939) supported field measurements of storm damage along the southern Rhode Island shoreline following the 1938 hurricane with oblique aerial photographs. Dietz (1947) utilized oblique aerial photographs taken nine years apart (1925 and 1934) to illustrate changes in the beach at Santa Monica, California resulting from man-made construction. El Ashry (1936) studied aerial photography to assess the effects of hurricanes on sections of the U.S. shoreline. El Ashry and Wanless (1965, 1968) monitored changes in coastal features such as inlet tidal deltas, capes and barrier beaches, with aerial photographs. The 1965 study used aerial photographs to measure growth of a tidal delta formed at the site of a new inlet following a 1962 storm. The 1968 study was a descriptive analysis of changes of coastal features in North Carolina from 1939 to 1962. El Ashry (1966, 1973) qualitatively studied shoreline changes resulting from severe storms and hurricanes along various sections of the Atlantic and Gulf Coasts of the United States.

A quantitative technique for measuring distances between stable reference points and the dune and high tide lines on scaled aerial photographs was developed by Stafford (1968) and used to investigate shoreline changes in Onslow and Carteret Counties in North Carolina. Stafford's technique was utilized in Langfelder, Stafford and Amein (1968) in conjunction with wave refraction and field investigations to determine erosion and accretion patterns along the entire North Carolina coast. Wahls (1973) updated mean annual erosion and accretion rates along the North Carolina shoreline. Zarillo (1974) employed Stafford's technique to study inlet changes on New Jersey in preparation for the proposed construction of an offshore nuclear power facility. Stirewalt and Ingram (1974) measured changes in the lagoonal and marsh shorelines of Pamlico Sound, North Carolina in sequential photographs between 1938 and 1971. Stephens, et al. (1975) made photogrammetric measurements of shoreline changes along the coast of South Carolina. In New England Stafford's technique was utilized to measure changes in the high tide line and cliff line along eastern Cape Cod by Gato (1975). Regan (1976) measured erosion and accretion along the southern coast of Rhode Island from four sets of aerial photographs dated 1939, 1951, 1963 and 1972.

Kaye (1973) and Ogden (1974) employed aerial photographs in conjunction with historical maps and charts, surveys, and direct field investigations to obtain quantitative data on long-term shoreline changes on the island of Martha's Vineyard, Massachusetts. Gato (1975) also incorporated Landsat satellite imagery into his aerial photogrammetric survey of eastern Cape Cod in an attempt to infer sediment transport patterns and location of the nodal point.

The Zoom Transfer Scope has been employed in an aerial photogrammetric survey by Baker (1977) in mapping shifts in the position of inlets in North Carolina. Simpson (1977) measured areal changes in depositional patterns in the back-barrier and lagoonal sections of the southern Rhode Island coast with the Zoom Transfer Scope. Simpson's technique involved mapping the 1939 and 1975 position of the feature to be measured on a ruled acetate grid and then counting squares to determine areal change.

METHODS

ADVANTAGES AND DISADVANTAGES OF AERIAL PHOTOGRAPHY IN SHORELINE STUDIES

The use of aerial photography in the study of shoreline changes has various advantages and disadvantages over other methods of collecting shoreline location data. Aerial photographs permanently record the location and conditions of the beach and its related coastal features at the time the photographs were taken. Aerial photographs also provide an almost unlimited amount of ground detail where maps and charts show only selected detail. Coastal regions of the United States have been photographed more frequently than maps or charts have been updated (Stafford and Langfelder, 1971). In the case of Nantucket, photographs have been taken at intervals of 13 years or less since 1938. Topographic maps of Nantucket have been revised roughly every 20 years. One final advantage of aerial photography is the low cost of these studies. Most 9" x 9" contact prints can be purchased for approximately three dollars each from the governmental agencies providing them. U. S. G. S. topographic maps are less expensive but do not provide the unlimited ground detail. Analysis of aerial photographs can be accomplished in the office, eliminating or reducing the number of costly field surveys. Stafford and Langfelder (1971) estimated that the acquisition of the necessary index sheets, contact prints and enlargements cost about fifteen dollars per mile of shoreline.

There are disadvantages to using aerial photography for mapping shoreline features and/or shoreline changes. The conditions of the shoreline at the time the photographs were taken may not be a fair representation of the mean conditions for that section of the shoreline, and numerous ground surveys may need to be run to establish these mean conditions. Some beaches appear to undergo cyclical seasonal changes and may be influenced by storms. Aerial photographs must be chosen carefully where choice is possible, except when special damage or shoreline change aerial photographs are desired. Most aerial photography is taken during non-storm conditions. In addition, most aerial photography is obtained in the spring for topographic mapping purposes when foliage is absent from trees. During this season and the fall it is generally agreed that beach conditions approximate the average beach conditions and may be used with some reliability (Stafford and Langfelder, 1971).

Uncorrected errors in the photographic image are also a potential disadvantage. Actual scales of individual photographs may vary from the nominal scale even for a set of recent photographs. Simpson (1977) found a range of 11,620-13,163 for photographs with a nominal scale of 1:12,000 or a variation of approximately 10 percent. Errors in scale may also be introduced into the photographic image by camera tilt and relief distortions when the photographs are taken, or by paper shrinkage (Avery, 1977). Techniques can be utilized to eliminate or minimize these problems. A ground control survey can more accurately determine scale for individual photographs. By determining scale with ground control in different sections of the photography the effects of tilt, relief distortion, paper shrinkage and other errors can be reduced.

ACQUISITION OF AERIAL PHOTOGRAPHY

Four sets of aerial photographs were obtained for this study: 1938 (GSF series, taken in November, with a nominal scale of 1:24,000, obtained from the National Archives and Records Service); 1951 (DPR series, taken in October, with a nominal scale of 1:20,000, obtained from the Agricultural Stabilization and Conservation Service); 1961 (61-L series, taken in April with a nominal scale of 1:30,000, obtained from the Coastal Mapping Division of the National Oceanic and Atmospheric Administration); and 1970 (DPR series, taken in October, with a nominal scale of 1:40,000, obtained from the Agricultural Stabilization and Conservation Service). These sets of aerial photographs represent coverage of the island at approximately 10 year intervals. Some incomplete coverage of the island was available from N.O.A.A. for the 1960's and from the U.S.G.S. in 1971. More recent aerial photography was not available at the time of this study.

The photography for 1938, 1951 and 1970 was taken with standard black and white type film. The 1961 photography was taken with black and white infrared film. One minor disadvantage of black and white infrared film is its poor water penetration properties. This made it difficult to observe the shoals in the near shore. The infrared photographs did provide excellent contrast and definition of beach features.

In addition to the aerial photography. two color transparencies of satellite imagery from the ERTS-1 (now Landsat) satellite were obtained. Dr. J. Fisher provided one dated July 17, 1974. The second was obtained from the EROS Data Center of the U. S. Geological Survey and was dated May 13, 1976. These transparencies are false-color composites of the four multispectral bands scanned by the satellite, with a nominal scale of 1:1,000,000.

SCALE DETERMINATIONS FOR SHORELINE CHANGES

The most accurate scale determinations involve the measurement between stable objects in the field ("ground control surveys") and the subsequent measurement of the same distances on the photographs. The representative fraction (scale) can then be calculated by dividing the ground distance between two points by the photographic distance between the same two points. This same procedure could be used for determining photographic scale from topographic maps, but measurable distances on the maps are not always sufficiently accurate. The standards set by the U. S. Geological Survey for the horizontal accuracy only require that "at least 90 percent of well-defined map points shall be plotted correctly within one-fiftieth of an inch on a published map." (U.S.G.S., 1969). This could introduce an error in the scale of 4-10 meters on a photograph with a nominal scale of 1:20,000 (Tanner, 1977). Other variations in scale are produced by radial distortions, tilt and relief distortions. Radial distortion is produced by the lens of the camera and causes features to be distorted outward from the optical center of a photograph. Tanner (1977) suggested that for flat terrain and with modern camera lenses this may be ignored. Tilt is the variation of the optical axis of the camera from true vertical at the time of exposure. In modern air photos tilt is limited to less than two degrees, producing a displacement on the photo of less than 0.01 mm for each degree of tilt (Tanner, 1977). For a nominal scale of 1:20,000 this amounts to an error of only 0.2 m. By making measurements in the sections of the photographs where the ground changes are measured and determining a separate scale for each section, the error introduced by tilt can be further reduced. Avery (1977) has suggested making ground measurements in opposite quadrants of the photograph to determine an average scale, but in photographs that are significantly tilted this is not accurate enough. Relief distortions may introduce another error in scale. Objects that are above the average terrain are radially displaced towards the center of the photograph while objects below the average terrain elevation are displaced away from the center (Avery, 1977). This is not a problem for flat terrain, but when making measurements from the beach to a reference point landward (and often at an elevation above the beach) some error may be introduced. This study of the Nantucket shoreline does not involve making measurements from an upland reference point to the beach, but rather limits itself to a comparison of shoreline features that are close to the same elevation (less than three meters), so the effect of relief distortion should be negligible.

Ground Control Surveys

For this study, two to four ground measurements were made for each photograph where possible. Measurements in the field were made between stable objects that were easily identifiable on the photographs. Measurements between the same objects were made on the photographs using an Altender microrule to the nearest 0.001 inch. After the average scale was determined for each photograph, the accuracy of the scale was checked by using that scale to measure the distance between two other previously surveyed objects in the field. The accuracy of this method by this field checking was found to be ± 3 meters.

It was not possible to obtain field control in certain small areas of Nantucket. These areas were either inaccessible or offshore, and lacked stable objects for ground measurements. These areas included Coatue Beach and the outer islands of Tuckernuck and Muskegat. An average scale was calculated from all the photographs where measurements were made and applied to these areas. Thus, while the absolute scale of the survey may vary, the relative scales between the different series of photographs was held constant.

IDENTIFICATION OF SURVEY LINES

Three survey lines that were easily recognizable on the aerial photographs were used to map shoreline changes on Nantucket. These survey lines were the top of the cliff line, the last high tide line and the dune line.

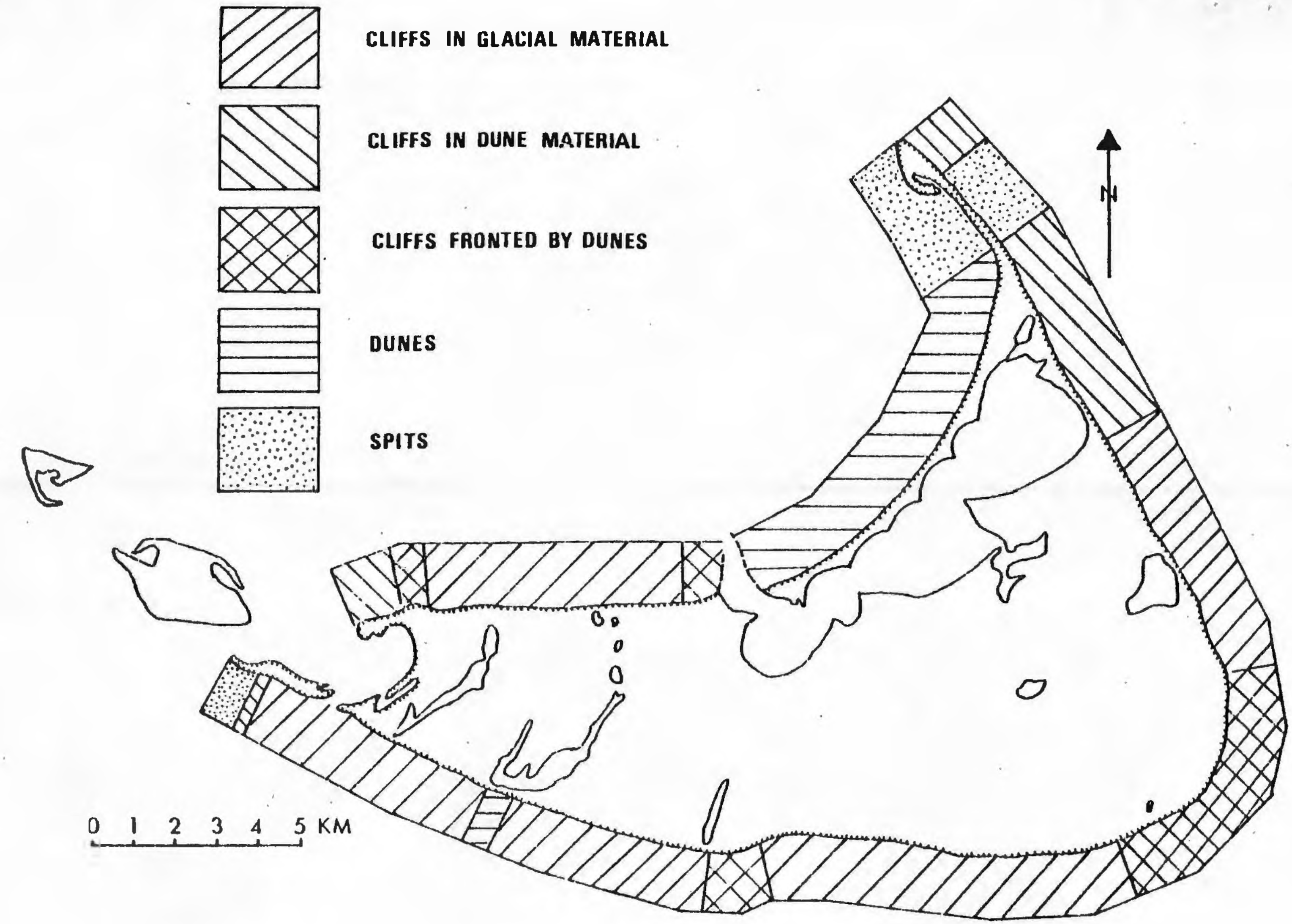
Top of the Cliff Line

The Nantucket shoreline is bordered by cliffs in glacial and dune material along approximately 75 percent of its total shoreline (Figure 2). The cliffs range upward to about 16 m in height near Siasconset and the town of Nantucket but are generally 1-5 m high. On Great Point there are cliffs in the large (10-12 m) dunes along the east side, while wave-cut cliffs in relic dune ridges of 3-5 m are visable on the east side of Coskata and at the end of Smith and Eel Points. If large-scale erosion has occurred on the island it is likely to be reflected by a retreat of these cliff lines.

The cliff line has been suggested by Tanner (1977) as being one solution to making measurements near the water's edge. The major problem in using this line is that it reflects only erosional trends and accretion is not detectable. For this reason care must be taken to measure changes in beach width especially where the cliff line appears to be stable between periods of photography. The cliff line is identified on photographs by a break in the darker tone of vegetation and the lighter tone of glacial material on the cliff face and beach. Gat (1975) utilized the cliff line

FIGURE 2

Types of Shoreline


CLIFFS IN GLACIAL MATERIAL
CLIFFS IN DUNE MATERIAL
CLIFFS FRONTED BY DUNES
DUNES
SPITS
N
0 1 2 3 4 5 KM

in measuring shoreline changes on eastern Cape Cod, Massachusetts, as one aspect of his study.

High Tide Line

The position of the last high tide line has been employed in various surveys to measure shoreline changes, including those of Stafford (1968) and Stafford and Langfelder (1971) in North Carolina, Gato (1975) on Cape Cod, and Regan (1976) and Simpson (1977) in Rhode Island. Mean high water is also used for the planimetry on many maps and charts.

The positon of the high tide line is identified on aerial photographs by a change in gray tone on the beach. This change in gray tone is a function of water content of the beach sand; the saturated protion of the beach has a darker gray tone than the unsaturated portion.

The position of the high tide line may be influenced by several factors. Abnormal wave conditions or extremely high tides associated with storms or high winds may move the position of the line higher on the beach. This problem is probably not significant for most aerial photography which is usually not taken during periods of storms or high winds (Stafford, 1968). Care must also be taken to note the position of the tide on photographs. It is possible the wetted line may vary considerably with the tidal position depending on the slope of the beach. Further fluctuations in beach energy levels may cause a beach to undergo an erosional and accretional sequence. The variation in the beach width between maximum erosion back to the depositional beach could be on the order of 100 feet (Nordstrom and Psuty, 1977).

The line of debris that sometimes accumulates at the limit of wave run-up often aids in the location of the high tide line. The debris line usually coincides with or is located slightly landward of the high tide line. Where there are two possible lines to chose from in close proximity, it is desirable to utilize the most seaward of the lines as being the high tide line. Care must be taken to ignore a debris line indicating a storm high tide which is usually located well inland from the normal high tide line.

On Nantucket the magnitude of retreat of the high tide line matches that of the cliff line in most cases. However the high tide line on the accreting forelands adjacent to Siasconset, Surfside and Eel Point and in a few isolated sections such as the end of Smith Point and the western shoreline of Coskata, often was changing at a different rate than the corresponding dune or cliff line and these changes were carefully measured. The high tide line was also used to define the limits of the spits on Great Point and at the end of Smith Point.

Dune Line

The dune line is the seaward base or top or the scarp of the vegetated sand dunes paralleling the trend of the beach. It is often represented by a wave-cut scarp or break in topography which can be seen through stereoscopic viewing of the photographs. A difference in gray line between the vegetated sand dune and the lighter beach material aids in determining position of the dune line.

The dune line is a significant indicator of erosional trends because of the protection it affords against wave damage and flooding. However the dune line tends to erode more easily than it accretes (Stafford and Langfelder, 1971). There is often a time lag between the seaward extension of the high tide line and the building out of the dunes due to the slow rate of the dune building process. Over the long term, the shoreline changes indicated by changes in the dune line correlate well with high tide changes (Stafford and Langfelder, 1971; Regan, 1976).

On Nantucket there were four regions with actively accreting dune lines (Figure 2). Along the eastern shoreline from Siasconset to Tom Nevers Head and on the forelands at Surfside and Eel Point these dunes front the glacial cliffs, protecting them from wave attack. The barrier spit, Coatue Beach, and the west side of Coskata have dune lines paralleling the beach. The large dunes on the east side of Great Point and the relic dune ridges at the end of Smith Point and Eel Point were formed before 1900 and are presently erosional features that may be more accurately classified as cliffs in dune material.

PHOTOGRAMMETRIC TECHNIQUE

The aerial photographs used in this study were of differing scales ranging from 1:20,000-1:40,000. In order to prepare accurate overlays it is necessary to map the photographs at the same scale. This was accomplished by using a Bausch and Lomb Zoom Transfer Scope. This instrument is able to optically enlarge a smaller-scale photograph and superimpose that image on a large-scale base photograph to produce a precise scale match.

The 1951 photography (1:20,000) was chosen for the base map when preparing overlays because this photography had the largest scale and best tonal contrast. Overlays were traced on matte surface acetate film because of the dimensional stability of acetate.

To prepare an overlay it was necessary to determine permanent and easily identifiable registration points that appear throughout the photographic record. These registration points include roads, corners of houses and, in some areas, vegetation that has remained fixed in shape and position. The Zoom Transfer Scope was used to enlarge and correct smaller-scale photography so that these registration points matched the same points on the base photography when superimposed. The base photograph was then secured and the appropriate survey line (cliff, dune or high tide line) was traced on acetate placed over the base photograph. This procedure was repeated for each of the photographs representing that section of shoreline for the years 1938, 1961 and 1970. An overlay map on the acetate film resulted, representing the four positions of the survey line.

After overlays were prepared for the entire shoreline, the shoreline was divided into segments of equal length. Stafford (1968) indicated that a spacing of 1,000 ft (305m) would provide suitable survey accuracy, 305 meters was therefore chosen for the length of each segment on the Nantucket shoreline.

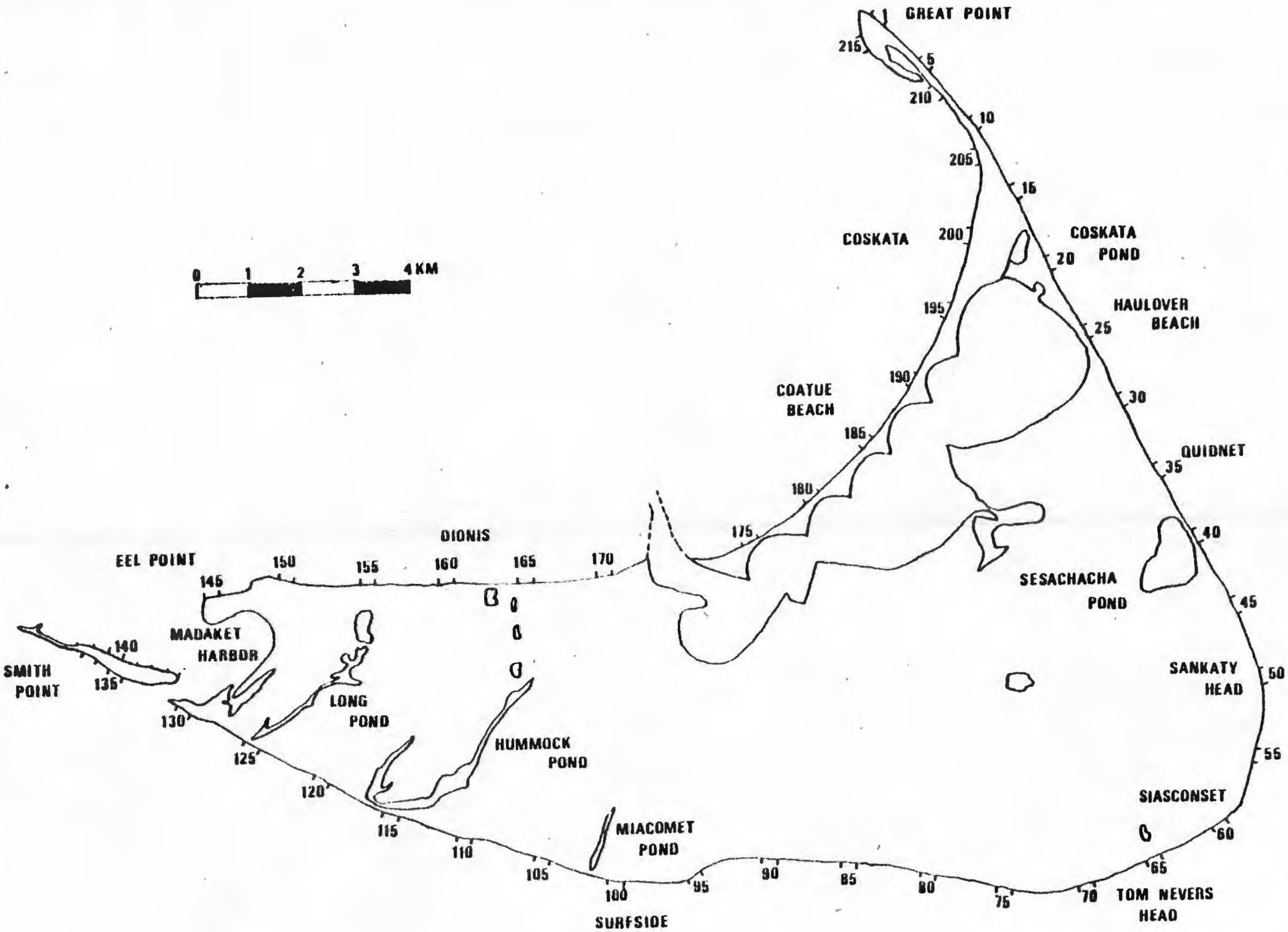
For each segment, the areal change between successive survey lines was determined. Area measurements on aerial photography can be accomplished using polar planimeters, transects or dot grids (Avery, 1977). A variation of the dot grid system was used to measure areas in this study. Instead of counting the number of dots in a given area a ruled square grid pattern on acetate was used and the number of squares tallied for each area to the nearest ¼ square. Avery (1977) recommends a dot or square grid density that will result in a conversion factor of 0.25-1.0 acres per dot or square. The grid density of the ruled acetate grid sheet used in this study was 100 squares per square inch, which results in a conversion factor of 0.64 acres per square for the 1951 scale of 1:20,000 which would be within Avery's limits. This conversion factor can be made more favorable by optically enlarging the overlay on the Zoom Transfer Scope which effectively increases the scale and increases the grid density in relation to the enlarged overlay. On Nantucket, especially along the north shore where shoreline changes were very small, the scale of the overlay could often be increased from approximately 1:20,000 to 1;10,000, resulting in a conversion factor of 0.16 acres per square. For each shoreline segment, the aerial change for 1938-1951, 1951-1961 and 1961-1970 was determined by totaling squares. The number of squares was then converted to an actual ground area (in m^2). The area of one square was determined from either the scale of the photograph or from the scale resulting from enlargement of the overlay. The enlargement technique was used primarily where areal changes were 2 squares or less (mostly on the north shore of Nantucket) and where there was sufficient ground control to determine the new scale of the enlargement.

ACCURACY OF PHOTOGRAMMETRIC TECHNIQUE

Various errors may be incorporated into the data obtained from the photogrammetric techniques employed for this study. These sources of error include: precision of the microrule and Zoom Transfer Scope, operator variability, cartographic distortion in producing overlays, precision of ruled grid, and scale variability. To determine the accuracy of the total technique field surveys were made of triangular and rectangular areas (playing fields, etc.) on the University of Rhode Island campus in Kingston. The ground measurements were used to determine ground areas to serve as "ground truth" values. The same objects were then measured on a 1972 aerial photograph of the campus (nominal scale 1:12,000) using an Altender microrule. Areal measurements were made by transfering the outline of the object or playing field onto acetate using the Zoom Transfer Scope with the square counting method. Linear photogrammetric measurements were used to determine an average scale for the photograph which was found to be 1:11,867. Comparing actual ground measurements of area to photogrammetric measurements showed a range of variation of 0.9-4.9 percent (Table IV, appendix) and averaging 2.4 percent which may be considered as the range and accuracy of this technique.

FIGURE 3

Location of Shoreline Segments


GREAT POINT
COSKATA
COSKATA POND
HAULOVER BEACH
COATUE BEACH
QUIDNET
DIONIS
EEL POINT
SESACHACHA POND
MADAKET HARBOR
SMITH POINT
LONG POND
HUMMOCK POND
SANKATY HEAD
SIASCONSET
MIACOMET POND
SURFSIDE
TOM NEVERS HEAD
0 1 2 3 4 KM

RESULTS OF PHOTOGRAMMETRIC MEASUREMENT OF SHORELINE CHANGES

INTRODUCTION

The shoreline has been divided into four sections to present shoreline changes as follows (Figure 3):

1) Great Point south to Tom Nevers Head, the eastern shoreline bordering the Atlantic Ocean (segments 1-65);

2) Tom Nevers Head west to Smith Point, the southern shoreline bordering the Atlantic Ocean (segments 66-137);

3) Smith Point across the northern shoreline on Nantucket Sound to Great Point (segments 138-216);

4) The outer islands of Tuckernuck and Muskegat.

Each of the first three sections of shoreline have been divided into smaller shoreline segments (305 m in length) and defined by the type of shoreline each segment represents (e.g. glacial cliff segment). For each segment, the total areal change for a given time period (1938-1951, 1951-1961, 1961-1970) was measured using the various survey lines (cliff line, dune line, high tide line) and from these measurements, mean annual rates of changes for each time interval and for the entire 32 years (composite or net annual changes) were determined. Sequential overlay maps of Tuckernuck and Muskegat Island were prepared, and total areal change for each island over the 32 years was measured.

By dividing an areal shoreline change measurement by the length of the segment (305 m) an estimate of the average advance or retreat (in meters) for that segment can be determined.

SHORELINE CHANGES: GREAT POINT TO TOM NEVERS HEAD

The eastern Nantucket shoreline extends from Great Point to Tom Nevers Head and is represented by photogrammetric segments 1-70 (Figure 3). Great Point is the northern extension of a spit projecting north from Coskata. The dunes on Great Point are 6-8 m in height and have been cut back by wave action on the east side of the point to form 6-8 m cliffs. The spit connecting Great Point with the main island is of low relief (less than 3 m) and in 1970 had no significant vegetated dunes. The relic dunes on Coskata are wave-cut, forming cliffs approximately 3 m in height. These cliffs are replaced by cliffs eroded in glacial material, and extend from just south of Haulover Beach to Tom Nevers Head. These cliffs range in height from 3-4 m in the north to over 10 m in Siasconset and Tom Nevers Head. A beach ranging in width from 100 m to 460 m (including the dune fields) has built out from the base of the cliffs between Sankaty Head and Tom Nevers Head, isolating these cliffs from wave attack.

Shoreline Changes, Historical, 1784-1938

Woodworth and Wigglesworth (1934) reported that Great Point receded westward approximately 430 m between 1784-1874, but Marindin's (1893) surveys between 1846 and 1891 indicated accretion in the range of 0.2 m/yr to 1.4 m/yr. In contrast the shoreline between segment 6 (on the spit) and Sankaty Head (segment 45) was eroding during the same time period, with Haulover Beach showing the greatest erosion rate of approximately 2.0 m/yr. The beach built out from the base of the cliffs between Sankaty and Tom Nevers Head was actively accreting between 1846 and 1891 with rates as high as 5.5 m/yr near segment 58. This accretion was replaced by erosion just east of Tom Nevers Head (segments 60-65) where rates of 1.0 m/yr were measured during the survey period.

Gulliver (1903) observed that the east shoreline of Great Point was actively eroding after 1891. He described the formation of a succession of spits enclosing small lagoons on the west side of the point which were attributed to the migration of eroded sand up and around Great Point. During the winter of 1896-1897 there was a large amount of material eroded from the northern section of Haulover Beach (segments 20-25), with a breach eventually forming in December 1896 near segment 25. This breach was over 0.4 km wide at times before it closed in 1908 (Gulliver, 1909).

The Cooperative Extension Service (1966) of the University of Massachusetts published a report on the island's resources and included a map of storm damage and shoreline changes. This map indicated a breach in the spit extending to Great Point in the vicinity of segment 10 in 1914. There was also an indication of extreme bluff erosion during storms in 1915 and 1933 for segments 30-34.

<u>1938-1970, Shoreline Changes</u>

Great Point continued to migrate to the west with every segment losing as much as 10-20,000 m^2 (32.8-65.6 m) during each time period (1938-1951, 1951-1961 and 1961-1970) (Figures 4, 5, 6). From Coskata Pond south to Sankaty Head

FIGURE 4

Total Shoreline Changes:
Great Point to Tom Nevers Head, 1938-1951

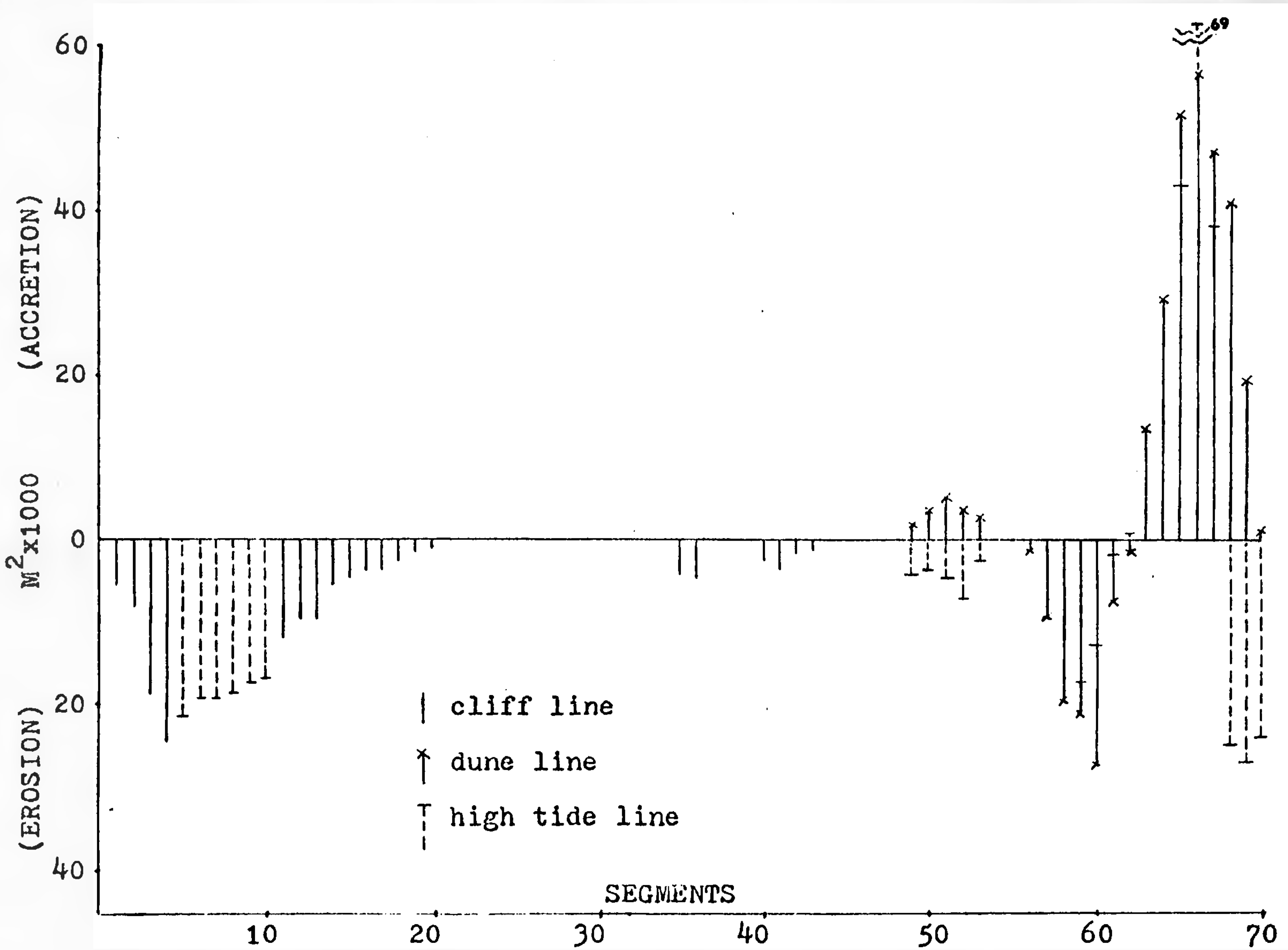
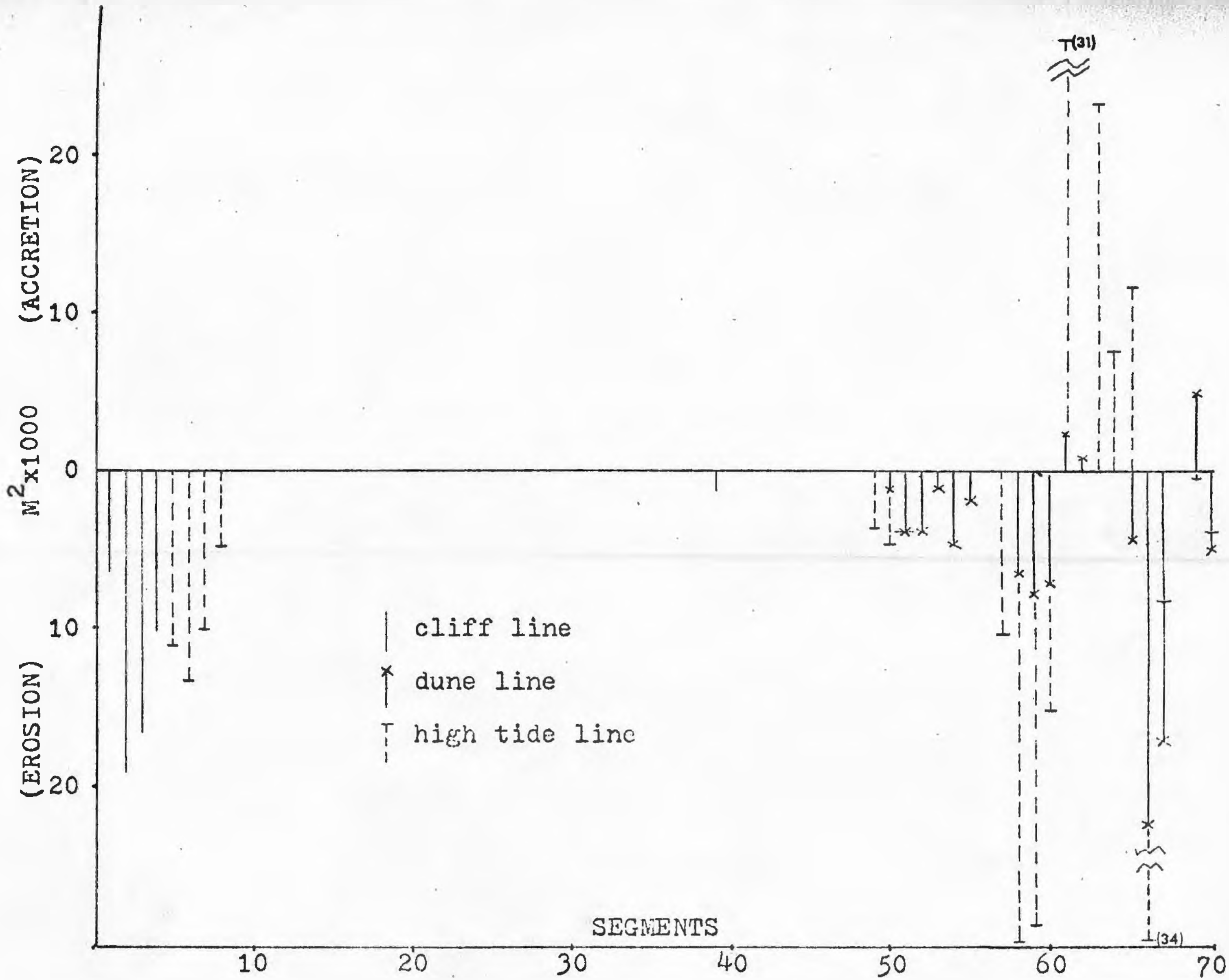

60
40
20
0
20
40
(ACCRETION)
M²x1000
(EROSION)
T 69
cliff line
dune line
high tide line
SEGMENTS
10
20
30
40
50
60
70

FIGURE 5

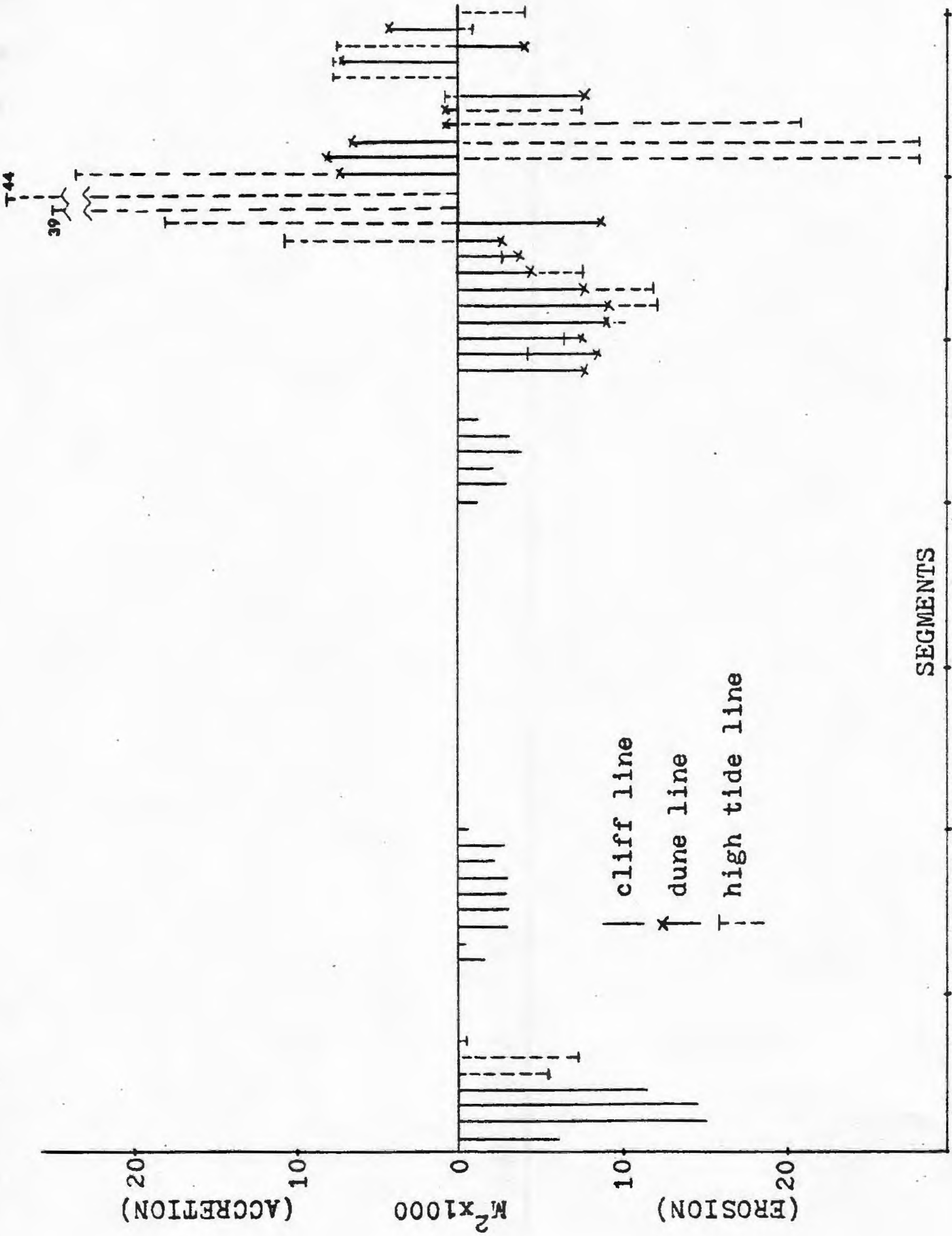
Total Shoreline Changes:
Great Point to Tom Nevers Head, 1951-1961



(ACCRETION)
(EROSION)
M²x1000
20
10
0
10
20
T(31)
(34)
cliff line
dune line
high tide line
SEGMENTS
10
20
30
40
50
60
70

FIGURE 6

Total Shoreline Changes:
Great Point to Tom Nevers Head, 1961-1970



(ACCRETION)
M²x1000
(EROSION)
20
10
0
10
20
SEGMENTS
10
20
30
40
50
60
70
cliff line
dune line
high tide line
44
39

(Figures 4, 5, 6). From Coskata Pond south to Sankaty Head (segments 21-50) the cliffs in the dune and glacial material along the eastern shoreline were stable over the entire 32 year period.

The section of shoreline stretching south and west from Sankaty Head to Tom Nevers Head was highly variable. Accretion dominated in dune line segments 60-70 in 1938-1951 (Figure 4). Erosion was more typical of all dune line segments in 1951-1960. However, the beaches just east of Tom Nevers Head (high tide segments 61-65) were building out considerably, probably resulting from some erosion of the beach and dune line just to the east (Figure 5). The erosional trend continued in 1961-1970 for most of cliff and dune line segments 48-55 but with some significant accretion of the beaches and dune lines measured for segments 55-70 (Figure 6). The beaches that were accreting during 1951-1961 (segments 61-65) were eroding heavily during 1961-1970.

Mean Annual Shoreline Changes: Great Point to Tom Nevers Head

Mean annual shoreline changes enable a direct comparison of the total shoreline changes measured for time periods of different lengths by reducing the changes to a yearly rate of change. Mean annual shoreline changes are presented in Table II of the appendix.

Cliffs in the dune material on Great Point (segments 1-4) had an average erosion rate of approximately 1,100 m^2/yr during the 1938-1951 period, decreasing slightly to an average of 1,000 m^2/yr (3.3 m/y) in 1951-1961 and an average of 900 m^2/yr (3.0 m/yr) in 1961-1970. The high tide segments 5-7 on the spit connecting Great Point had erosion rates decreasing from approximately 1,400 m^2/yr (4.6 m/yr) in 1938-1951 to approximately 1,150 m^2/yr (3.8 m/yr) in 1951-1961. High tide segments 9-10 on the spit were stable in 1951-1961 and 1961-1970.

On Coskata, cliffs in the relic dune had erosion rates averaging 400 m^2/yr during 1938-1951. In 1951-1961 cliff (in dune material) segments 11-21 were stable but erosion returned in 1961-1970 with rates of generally 300 m^2/yr in each segment, representing a slight overall decline in erosion compared to 1938-1951. Cliffs in the dune material of segments 21-30 and glacial cliff segments 31-39, across Haulover Beach into Quidnet, generally remained stable over the 32 years with only glacial cliff segments 35 and 36 showing erosion rates of approximately 300 m^2/yr (1.0 m/yr) in 1938-1951. Glacial Cliff segments 40-49 showed some erosion in 1938-1951 and again in 1961-1970 but were stable in 1951-1961. Glacial cliff segments 40-43 had erosion rates on the order of 100-280 m^2/yr (0.3-0. m) increasing to between 140 and 450 m^2 (0.5-1.4 m/yr) in 1961-1970 with a period of stability from 1951-1961.

The dune line for segments 49-53 had accretion rates of between 200 and 400 m^2/yr (0.6-1.3 m/yr) in 1938-1951, reversing to erosion rates of approximately 400 m^2/yr (1.3 m/yr) in 1951-1961 with the erosion rates increasing to 500-1,200 m^2/yr (1.6-3.9 m/yr) in 1961-1971. The high tide line for segments 49-53 generally showed increasing erosion rates in each successive time period. For example, segment 50 had an erosion rate of 300 m^2/yr (1.0 m/yr) in 1938-1951 increasing to 470 m^2/yr (1.5 m/yr) in 1951-1961 and again in 1961-1970 to over 700 m^2/yr (2.3 m/yr). The dune line in segments 54 and 55 were stable in 1938-1951 but showed similar increases in erosion rates in 1951-1961 and 1961-1970 as in dune segments 49-53.

Erosion rates for dune line segments 58-60 decreased in each successive time period. The dune line erosion rates were in the order of 1,600-1,700 m^2/yr (5.2-5.6 m/yr) in 1938-1951, decreasing to approximately 700 m^2/yr (2.3 m/yr) in 1951-1961 and becoming stable in 1961-1970. High tide line segments 58-60 had erosion rates increased from 900-1,300 m^2/yr (3.0-4.3 m/yr) in 1938-1951 to 1,500-3,000 m^2/yr (4.9-9.8 m/yr) in 1951-1961 before reversing in 1961-1970 to accretion rates of 2,600-4,900 m^2/yr (8.5-16.0 m/yr). Generally accretion rates for dune segments 61-70 of 1,000-4,000 m^2/yr (3.3-13.1 m/yr) in 1938-1951 decreased significantly or even reversed in segments 65-67 and 70 to show erosion rates in 1951-1961 before a return to accretion rates of 50-700 m^2/yr (0.2-2.3 m/yr) with dune line segments 65 and 69 showing slight erosion rates in 1961-1970.

Readjustment of the beach width along high tide line segments 61-70 caused a great deal of variability in erosion and accretion rates between successive time periods. High accretion rates along high tide line segments 63-67 ranging from 850-5,300 m^2/yr (2.7-17.4 m/yr) shifted east slightly to high tide line segments 61-65 and decreased to 800-3,500 m^2/yr (2.6-11.5 m/yr) in 1951-1961. Accretion rates decreased again in 1961-1970 to less than 800 m^2/yr and shifted west to high tide line segments 65-68. Erosion rates in the high tide line generally ranged from 1,000-1,300 m^2/yr (3.3-4.3 m/yr) for segments 60 and 68-70 in 1938-1951, decreasing to generally between 100 and 1,200 m^2/yr (0.3-3.9 m/yr) for segments 65-70 in 1951-1961 and increasing to 900-3,200 m^2/yr (3.0-10.5 m/yr) for segments 61-64.

SHORELINE CHANGES: TOM NEVERS HEAD TO SMITH POINT

Segments 70-137 extend across the south shore of Nantucket Island (Figure 3). The shoreline is bordered by cliffs eroded in glacial outwash sediments ranging from 6-10 m in the east near Tom Nevers Head to 3 m or less in the west. There is a foreland build out 250-260 m from the cliffs at Surfside. This foreland (segments 93-100) is bordered by vegetated dunes approximately 3 m in height. Segments 130-137 represent Smith Point which was breached in the vicinity of segments 130-132 during Hurricane Esther in September 1961, leaving Smith Point at the end of a sand spit extending 1.5 km west of shoreline segment 137 on the new Esther Island. The cliffs on Esther Island are in glacial outwash material except for segments 136 and 137 where the cliffs are eroded from dune material.

Shoreline Changes, Historical, 1846-1938

Marindin (1893) reported accretion for segments 65-75 amounting to approximately 4.0 m/yr. In contrast segments 76-92 were eroding between 2.5 and 3.5 m/yr with a maximum of 4.2 m/yr near segment 92 just east of Surfside. This group of segments lost approximately 668,000 m^2 of material in 44 years which was contributed to a series of accreting segments (94-100) at Surfside. In 1846 the shoreline at Surfside was concave but by 1890 it had become convex with these segments accreting as much as 336 m over 44 years. The remainder of the south shore (segments 101-137) was eroding at rates as high as 6.2 m/yr near the end of Smith Point, but generally between 2.5 and 4.0 m/yr. Gulliver (1903) measured a retreat of 5.4 m/yr near segments 128-129 for 1889-1903.

Smith Point underwent major changes from 1846-1890. In 1846 a long, narrow, sandy beach extended as a spit past Tuckernuck Island. There was a channel between the spit and Tuckernuck measuring 250 m (Marindin, 1893). In 1856 the point was situated 1.6 km east of its 1846 position and in 1887 the spit formerly connected to Nantucket Island had been breached and was welded to the south shore of Tuckernuck Island. This 1887 spit extended westward past Muskegat Island, but the point named Smith was located 5.6 km east of its 1846 position and attached to Nantucket Island proper.

The Cooperative Extension Service map (1966) indicated extensive cliff erosion along the south shore in 1908, 1915, 1924 and extremely widespread erosion in 1938 during the Great New England Hurricane.

Shoreline Changes, 1938-1970

The southern shoreline of Nantucket showed a trend toward considerable erosion during the 32 year study period (Figures 7, 8, 9). The only accretion measured occurred in the dune and high tide lines of the foreland at Surfside (segments 94-101). Most of the foreland did show erosion in 1951-1961 (Figure 8). Erosion measured for the cliff line west of the foreland to Smith Point was generally greater than erosion of the cliff line east of the foreland (Tom

FIGURE 7

Total Shoreline Changes:
Tom Nevers Head to Smith Point, 1938-1951

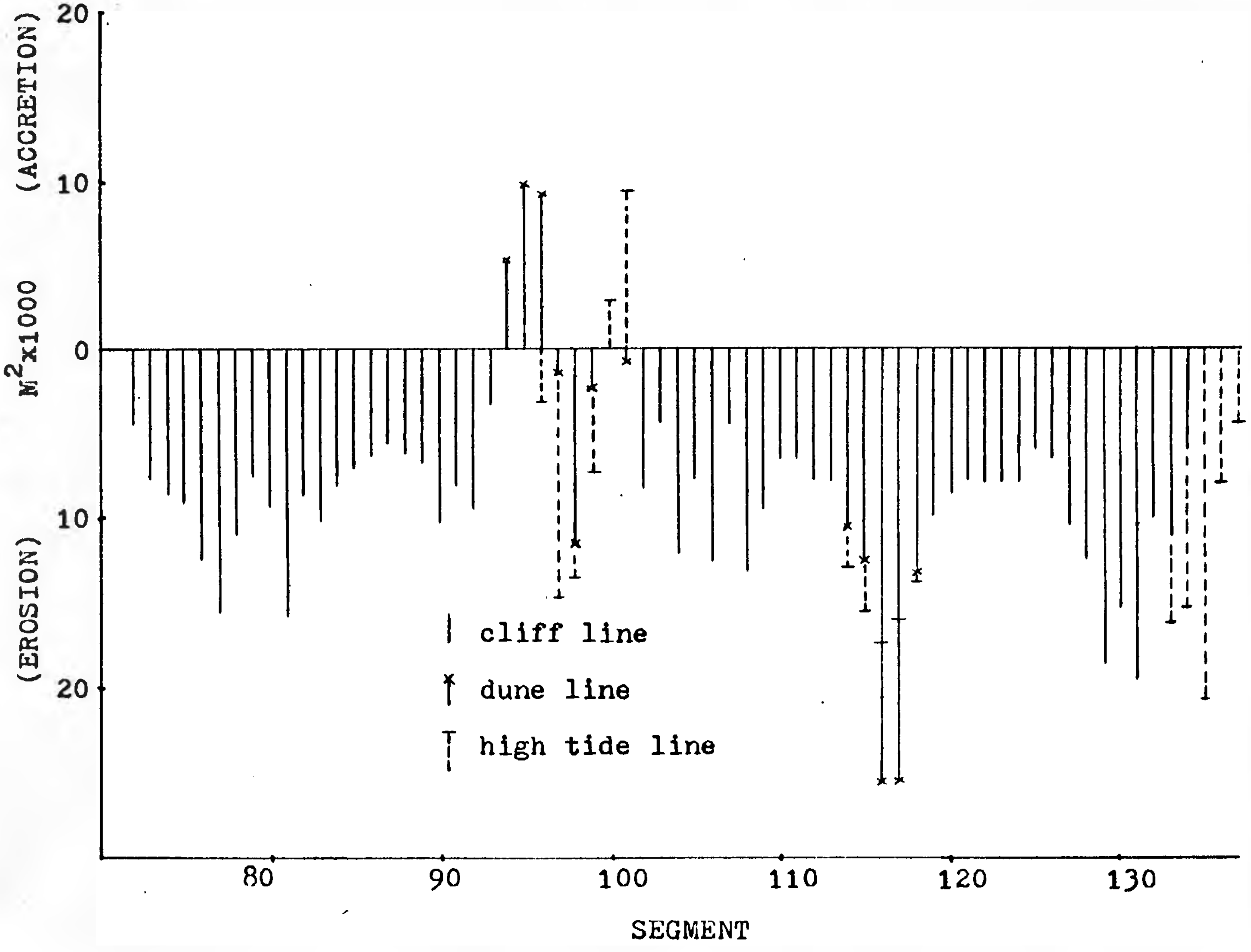

(ACCRETION)
(EROSION)
M²x1000
20
10
0
10
20
cliff line
dune line
high tide line
80
90
100
110
120
130
SEGMENT

FIGURE 8

Total Shoreline Changes:
Tom Nevers Head to Smith Point, 1951-1961

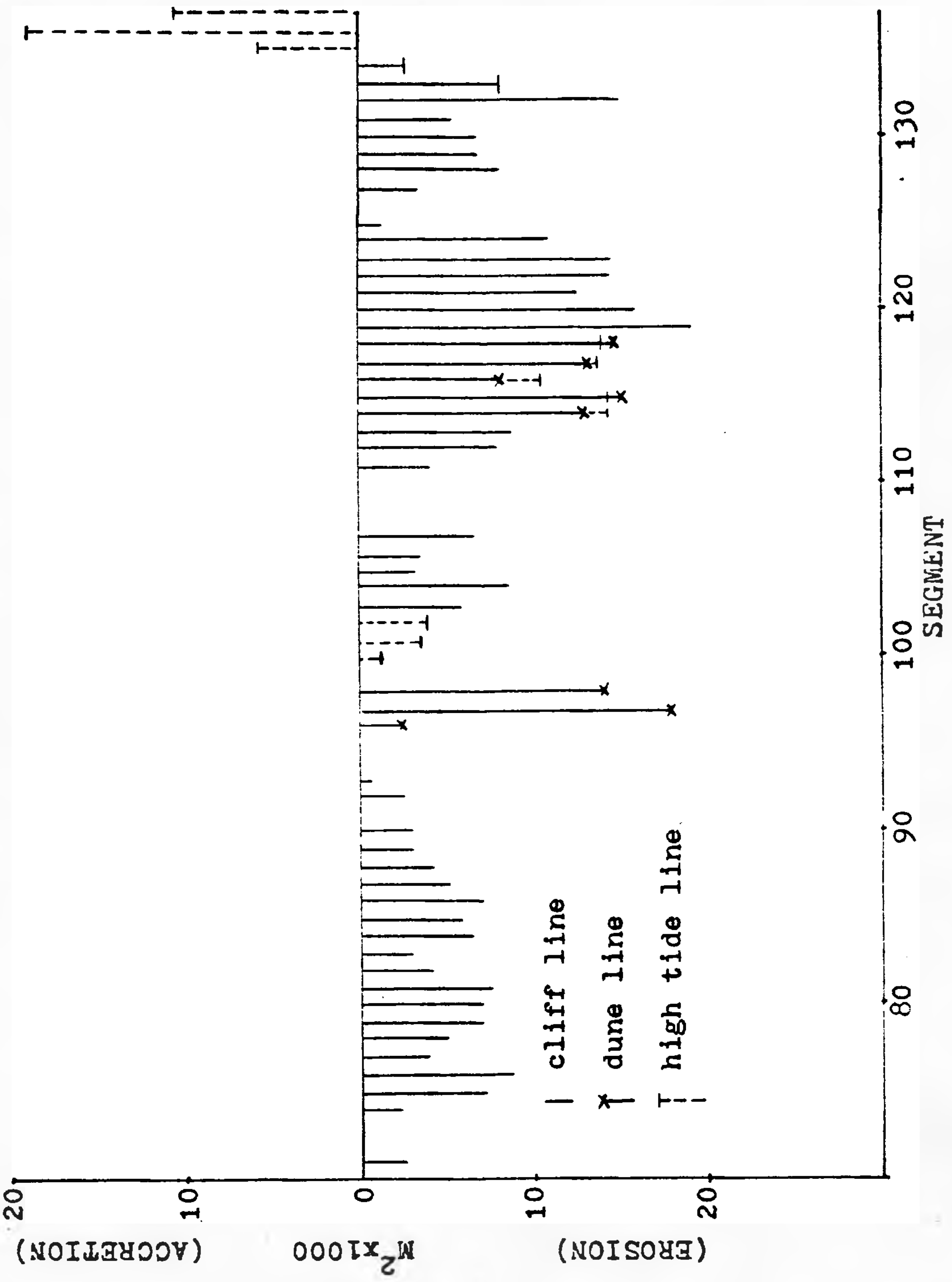
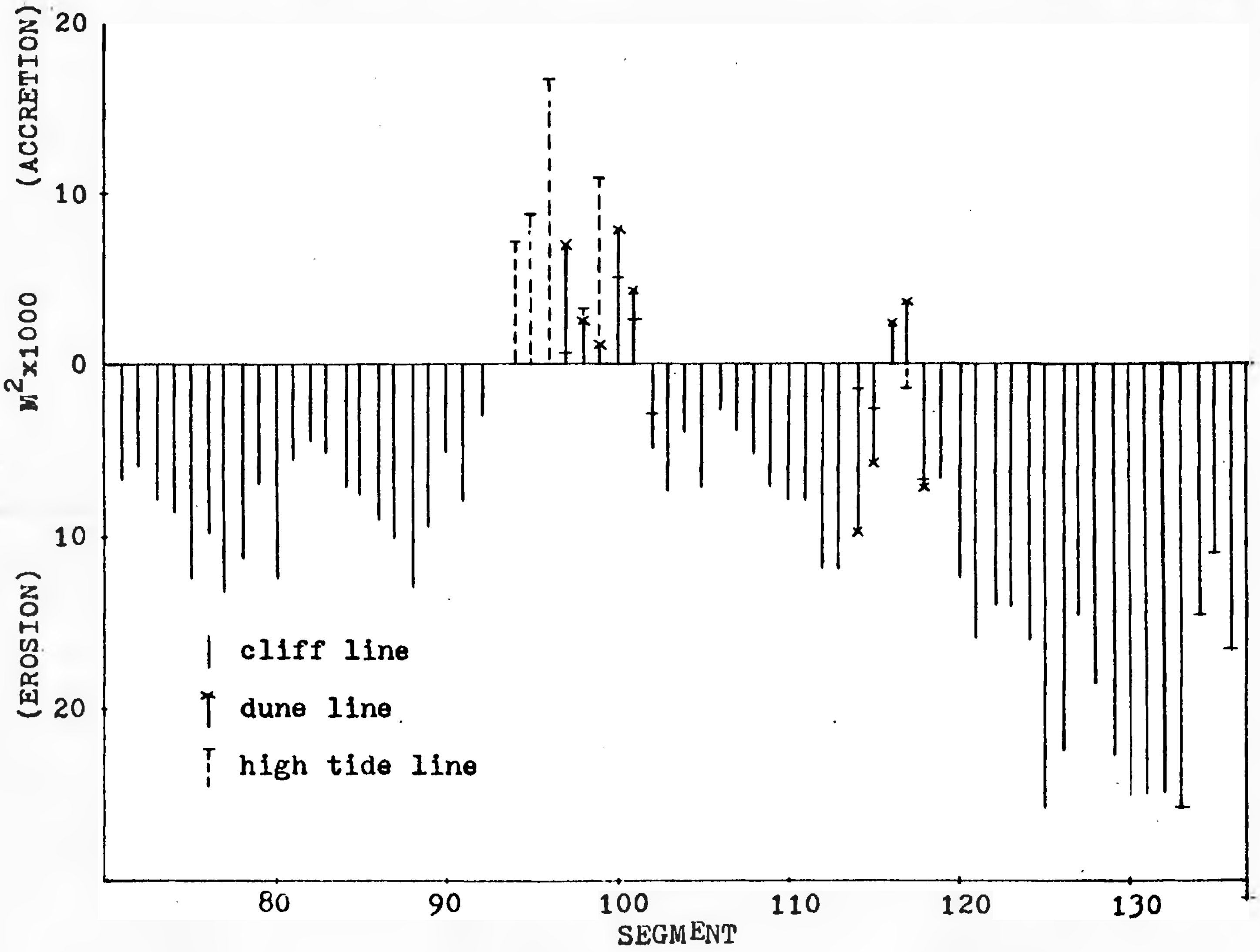

20
10
0
10
20
(ACCRETION)
M²x1000
(EROSION)
SEGMENT
80
90
100
110
120
130
cliff line
dune line
high tide line

FIGURE 9

Total Shoreline Changes:
Tom Nevers Head to Smith Point, 1961-1970


(ACCRETION)
M2x1000
(EROSION)
20
10
0
10
20
cliff line
dune line
high tide line
80
90
100
110
120
130
SEGMENT

Nevers Head to the foreland). The western section experienced its greatest erosion during 1961-1970 (Figure 9). As much as 50,000 m^2 (163.9 m) was lost from individual cliff segments, and in September, 1962 Smith Point was breached and permanently separated from the main island during Hurricane Esther (the resulting small island was named Esther Island).

Smith Point was located approximately 670 m west of cliff segment 137 at the end of a long narrow spit in 1938. This spit extended approximately 800 m in 1951 and had migrated 155 m north. Total areal accretion between 1938-1951 was 44,100 m^2. Photographic coverage did not allow complete measurements for 1951-1961 but there appeared to have been a northward migration of the spit. By 1970 the spit was 1,260 m in length and had gained 46,770 m^2 since 1951 in spite of the 1962 breaching. The spit migrated 260 m north of its 1951 position.

Mean Annual Shoreline Changes: Tom Nevers Head to Smith Point

Mean annual rates of changes for each shoreline segment on the south shore are presented in Table II of the appendix. Generally the south shore had erosion rates decreasing from 1938-1951 to 1951-1961 and then increasing again in 1961-1971. Glacial cliff segments 71-93 from west of Tom Nevers Head to the Surfside foreland generally had higher erosion rates in 1938-1951 and 1951-1961 with a slight decrease in erosion rates for 1961-1970. Erosion rates in 1938-1951 were between 350 and 1,200 m^2/yr (1.2-3.9 m/yr), decreasing to between 250 and 900 m^2 (0.8-2.8 m/yr) before increasing to rates of between 600 and 1,400 m^2/yr (1.9-4.6 m/yr).

The foreland at Surfside showed varying rates of erosion and accretion of the dune line between the successive time periods. The eastern portion (dune line segments 94-96) was accreting at the rate of 500-10,000 m^2/yr (1.6-32.8 m/yr) but was stable in 1951-1961 and 1961-1970. In contrast erosion rates for dune line segments 97-100 on the western portion of the foreland were between 100 and 900 m^2/yr (0.3-3.0 m/yr) in 1938-1951, increasing to over 1,400 m^2 (4.6 m/yr) in 1951-1961 before reversing to show accretion rates ranging from 140-900 m^2/yr (0.4-3.0 m/yr) in 1961-1970. The foreland's high tide line showed a tendency toward erosion and narrowing of the beach in 1938-1951, followed by stability in 1951-1961 and finally accretion in 1961-1970. Erosion rates for high tide segments 95-101 were generally between 250 and 1,150 m^2/yr (018-3.8 m/yr) in 1938-1951, stabilizing in 1951-1961 with final accretion rates of 100 to 1,900 m^2/yr (0.3-6.0 m/yr).

The shoreline from Surfside west to Smith Point (segments 102-137) generally had erosion rates of 100-2,000 m^2/yr (0.3-6.6 m/yr) in 1938-1951 with dune line segments 114-118 having the highest rates, decreasing to between zero and 1,600 m^2/yr (0.52 m/yr) during 1951-1961 and finally increasing to as much as 3,500 m^2/yr (11.5 m/yr) in 1961-1970 with highest erosion rates in the westernmost segments (130-137) and accretion rates of over 2,600 m^2/yr (8.5 m) for dune line segments 116 and 117. The high tide line west of the foreland generally eroded at the same rate as the cliff and dune lines with two exceptions. The high tide line for segments 114-118 had the same erosion rates as the dune line in 1938-1951 and 1951-1961 but showed a significant decrease in erosion rates in 1961-1970 while the dune line was accreting. The high tide line along segments 135-137 had a reversal of erosion rates of 350-1,600 m^2/yr (1.1-5.2 m/yr) to accretion rates of over 10,000 m^2/yr (32.8 m/yr) in 1951-1961 before returning to an erosion rate matching the rate at the cliff line in these segments.

SHORELINE CHANGES; SMITH POINT TO GREAT POINT

The northern shoreline of Nantucket from Smith Point east to Great Point is represented by shoreline segments 138-216 (Figure 3). Segments 138-144 are on the north shore of Esther Island and consist of cliffs in the glacial outwash with almost no beaches present at high tide. Segments 145-172 extend from Eel Point east to the western jetty protecting the entrance to Nantucket Harbor. Cliffs in the glacial till of the Nantucket moraine extend along these shoreline segments with the exception of segments 147-150, which are on an accreting foreland bordered by dunes of 3-4 m, and an ancient foreland built out from the base of the 16 m cliffs along segments 170-172 just west of the jetty. Glacial cliffs along segments 150-172 range in height from 5-10 m in the west to over 15 m in the east.

Shoreline segments 173-216 stretch from the eastern jetty across Coatue Beach (a barrier spit) and finally northward along the west side of Coskata and Great Point. All of these segments are backed by vegetated dunes approximately 3 m in height except for segments 206-216 which are located on low-lying sand spits. The sand spit on the west side of Great Point (segments 210-216) has some scattered dunes but is not extensively backed by dunes.

Historical Shoreline Changes, Early 1700's-1938

There has not been an extensive study of the northern shoreline of Nantucket. Marindin (1893) thought this section of shoreline was eroding although at a lower rate than the remainder of the island. Woodworth and Wigglesworth

(1934) reported on accounts from the early 1700's which indicated Capaum Pond (south of segment 163) being open to the sea until closed by a great storm in the early 1700's. Gulliver (1903) discussed some changes in beach width at the western jetty. From 1881-1897 sand piled up on the west side of this jetty adding 76 m to the beach. 1897-1902 saw an additional 46 m added to the beach width. Rosen (1975) included a map comparing the position of Coatue Beach from 1781 with the present configuration (1971) and it indicated a remarkable stability. The major change along Coatue Beach was a smoothing of the overall northern profile with major accretion at the western end of the beach against the eastern jetty.

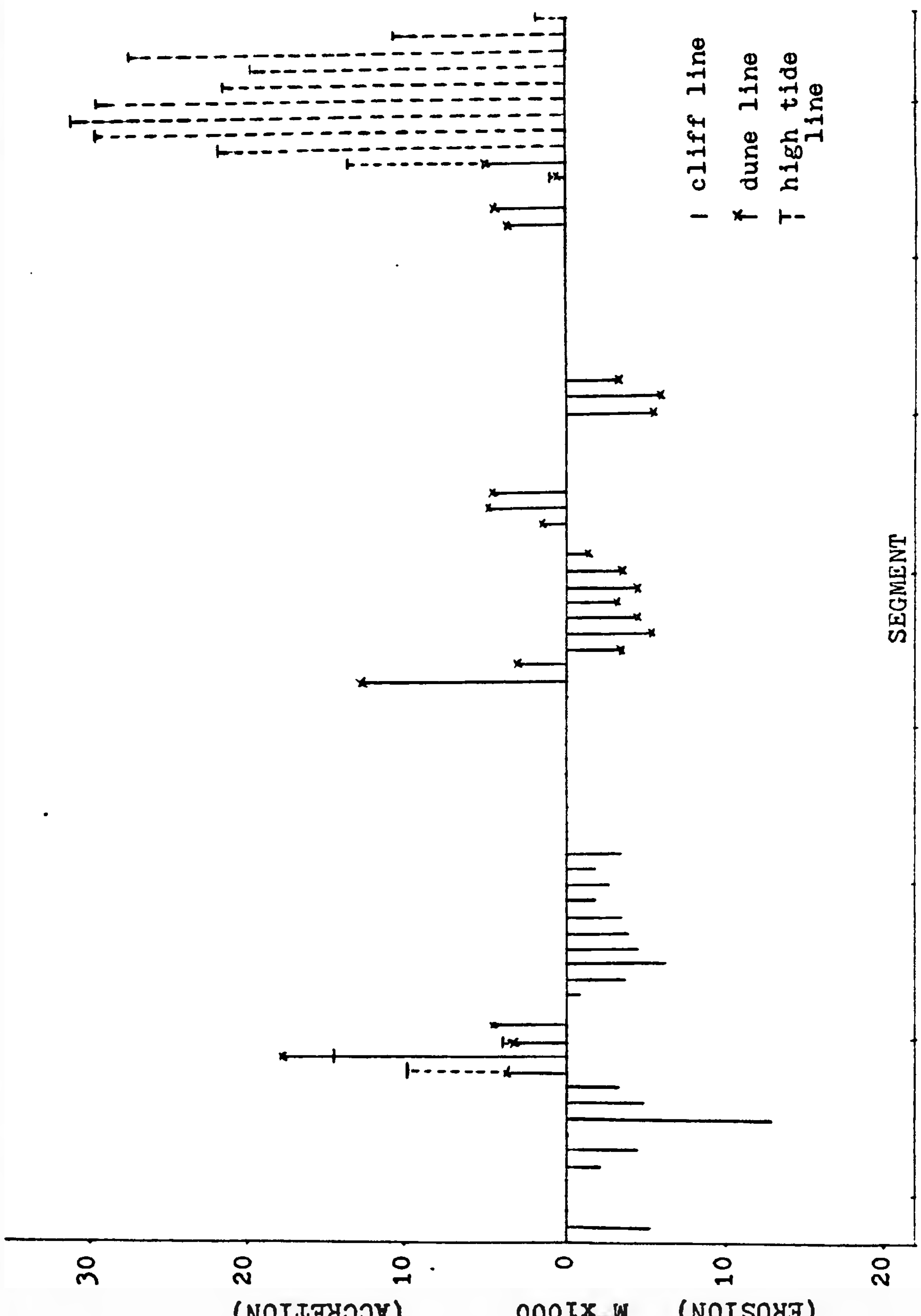
Shoreline Changes, 1938-1970

Erosion of generally less than 10,000 m^2 (32.7) per segment was measured for the island's northern shoreline extending from segment 138 on Smith Point east along the cliff line to segment 162 at Dionis (Figures 10, 11, 12). An accreting foreland just east of Eel Point (dune and beach line segments 149-151) probably derived most of its sediments from the eroding cliffs and beaches to the east and west. Some accretion was also measured against the western jetty protecting the entrance to the harbor during 1951-1961 (Figure 11). Cliff line segments 162-170 were stable throughout the entire study period.

Coatue Beach (dune and high tide line segments 173-198) showed a general erosional trend during 1938-1951 with some

FIGURE 10

Total Shoreline Changes:
Smith Point to Great Point, 1938-1951



cliff line
dune line
high tide line
SEGMENT
140
150
160
170
180
190
200
210
30
20
10
0
10
20
(ACCRETION)
M²x1000
(EROSION)

FIGURE 11

Total Shoreline Changes:
Smith Point to Great Point, 1951-1961

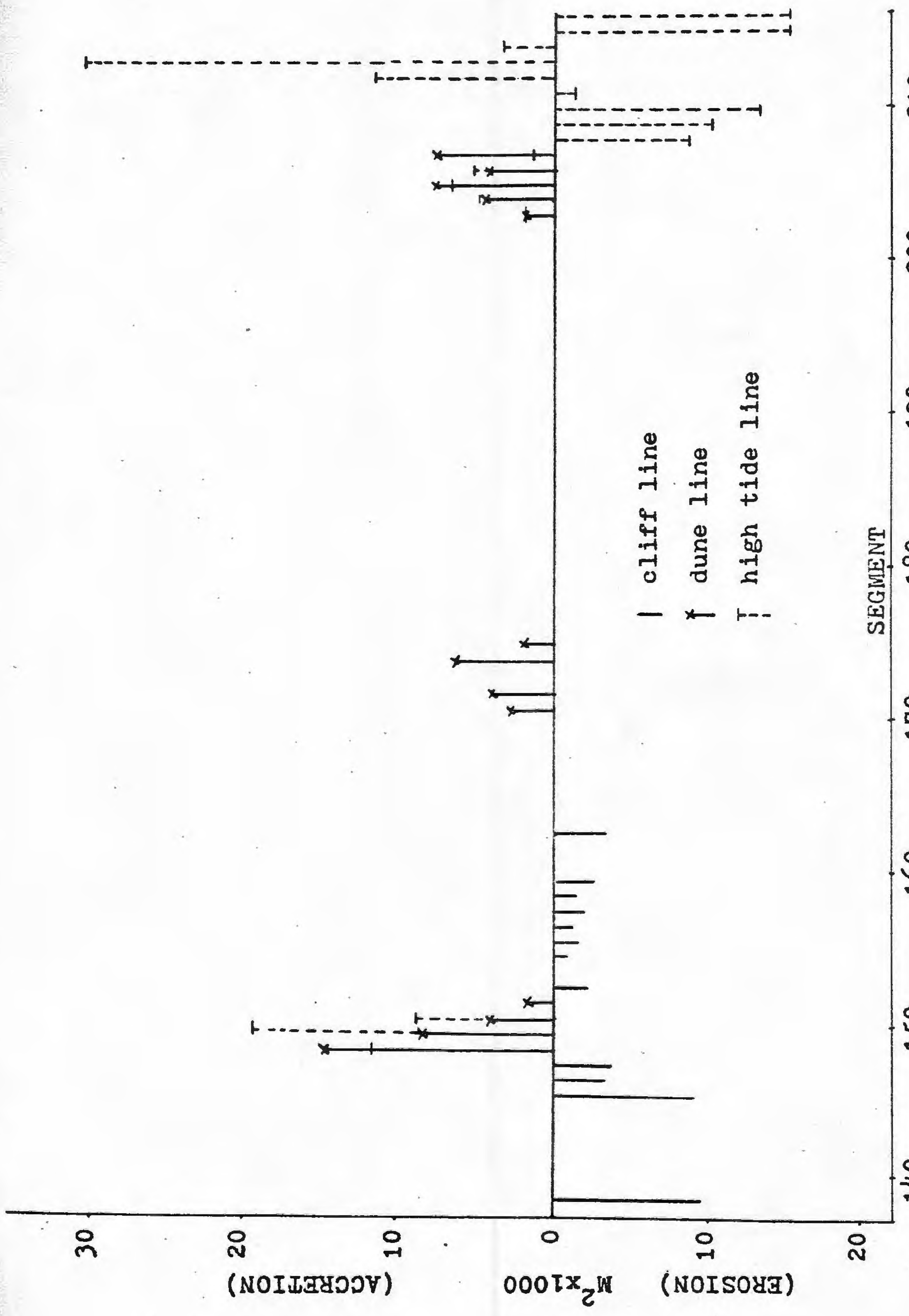
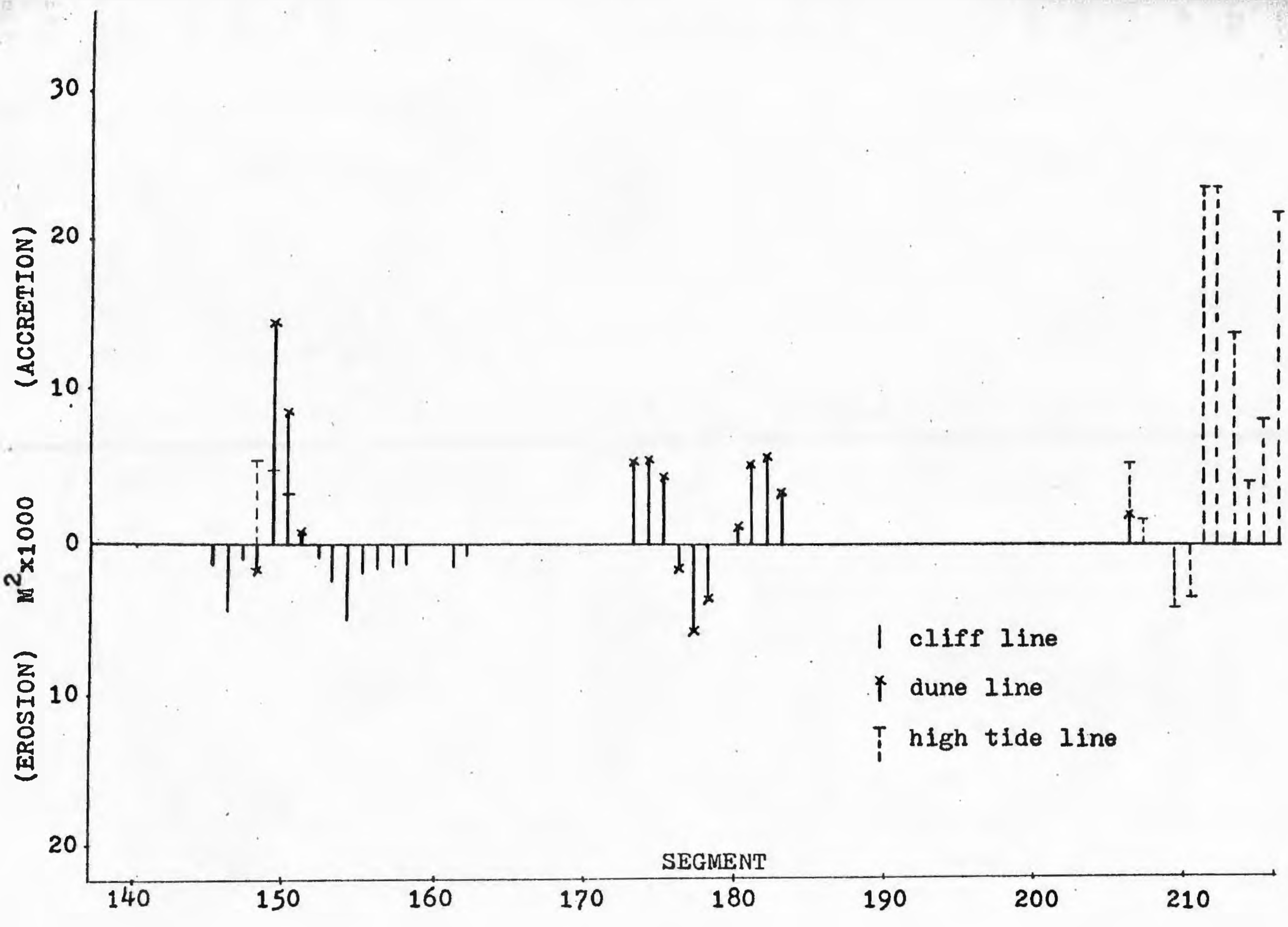

30
20
10
0
10
20
(ACCRETION)
M²x1000
(EROSION)
140
150
160
170
180
190
200
210
SEGMENT
cliff line
dune line
high tide line

FIGURE 12

Total Shoreline Changes:
Smith Point to Great Point, 1961-1970


30
20
10
0
10
20
(ACCRETION)
M^2x1000
(EROSION)
140
150
160
170
180
190
200
210
SEGMENT
cliff line
dune line
high tide line

accretion measured against the eastern jetty (Figure 10). In contrast, 1951 to 1961 and 1961 to 1970 had either an accretional or stable shoreline (Figures 11, 12).

The dune line on the west shoreline of Coskata (segments 199-206) and the spit connecting Great Point to the main island gained large amounts of sediments during 1938-1951 (Figure 10) with overwashing of the spit of particular importance. This accretion corresponds to large amounts of erosion on the east side of the spit during 1938-1951 (Figure 4). Large vegetated dunes visible on the spit in 1938 photographs were absent in 1951 suggesting this overwashing process. Accretion continued to be the dominant process during 1951-1961 and 1961-1970 (Figures 11, 12).

The small barrier spit enclosing the lagoon on the west side of Great Point (segments 212-216) accreted nearly 60,000 m^2 from 1938 to 1951 with the entrance to the lagoon migrating 400 m south. During 1951-1961 the spit had a net gain of only 15,900 m^2 with the northern portion undergoing some erosion and the entrance to the lagoon moving westward 180 m. By 1970 the spit had extended south into high tide segment 211 (220 m south of 1961 position) with a net areal gain of 94,750 m^2.

<u>Mean Annual Shoreline Changes, Smith Point to Great Point</u>

The general trend of mean annual shoreline changes (Table 2, Appendix) was a decrease in erosion and accretion rates from 1938-1951 to 1951-1970. The cliff line on Eel Point had erosion rates that decreased in each successive time period. For example, cliff line segment 145 had an erosion rate that decreased from 1,000 m^2/yr (3.3 m/yr) in 1938-1951 to 950 m^2/yr (3.0 m/yr) in 1951-1961 and finally to 130 m^2/yr (0.4 m/yr) in 1961-1970. In contrast, accretion rates of the dune line on the foreland increased slightly from an average 490 m^2/yr for segments 148-151 during 1938-1951 to 550 m^2/yr (1.8 m/yr) in 1951-1961, decreasing again to 500 m^2/yr in 1961-1970. Cliff line segments 152-162 had a trend toward decreasing erosion rates from 1938-1951 to 1951-1961 with no significant change in 1961-1970. Erosion rates for these cliff lines were on the order of 200-400 m^2/yr (0.6-1.3 m/yr) during 1938-1951 decreasing to between 100 and 300 m^2/yr (0.3-1.0 m/yr) in 1951-1961 and 1961-1970.

Generally shoreline segments on Coatue (173-198) were stable in 1951-1961 with erosion and accretion rates showing little difference between 1938-1951 and 1961-1970. Dune line accretion rates were between 300 and 1,000 m^2/yr (1.0-3.3 m/yr) in 1938-1051 and between 200 and 600 m^2/yr (0.6-2.0 m/yr) in 1961-1970. Erosion rates for the dune line were generally on the order of 400 m^2/yr (1.3 m/yr) during 1938-1951 and 1961-1970. However, there were more eroding dune line segments in 1938-1951 than in 1961-1970.

The dune line on Coskata (segments 202-206) had accretion rates increase from between 300 and 400 m^2/yr (1.0-1.3 m/yr) in 1938-1951 to between 400 and 800 m^2/yr (1.3-2.6 m/yr) in 1951-1961 before becoming generally stable during 1961-1970. The spit connecting Great Point (high tide line segments 211-216) had a combined accretion rate of 4,600 m^2/yr in 1938-1951 decreasing to 1,600 m^2/yr in 1951-1961 but increasing to 10,500 m^2/yr in 1961-1970.

Erosion and accretion rates in the high tide line along the north shore did not show a significant difference from those of the corresponding dune and cliff lines except on the Eel Point foreland and to some extent on Coskata. On the Eel Point foreland, high tide line segments 148-150 had accretion rates increase from between 100 and 1,000 m^2/yr (0.3-3.3 m/yr) in 1938-1951 to as much as 1,900 m^2/yr (6.2 m/yr) during 1951-1961 before decreasing to between 300 and 600 (1-2 m/yr) in 1961-1970. On Coskata, a stable high tide line in 1938-1951 began to show accretion rates of between 100 and 650 m^2/yr (013-2.1 m/yr) in 1951-1961, becoming stable again in 1961-1970.

SHORELINE CHANGES: TUCKERNUCK AND MUSKEGAT ISLANDS

Changes were considerable along the south and southwest shoreline of Tuckernuck Island over the 32-year study period (Figure 13). A steady retreat of the glacial cliffs from 1938-1951 and 1951-1970 resulted in a loss of approximately 444,000 m^2 with only 19,500 m^2 accreted at the east and west extremities. The glacial cliffs along the northern shoreline eroded slightly on the order of 25,000 m^2 (25 m) during 1938-1951 but were stable from 1951-1970. The two barrier spits (with 3 m vegetated dunes) on the east and west sides of the northern shoreline accreted slightly at the distal ends of these spits. The western barrier spit lengthened by approximately 150 m from 1938-1970 while the eastern spit did not lengthen but became slightly wider (approximately 30 m) at the tip. Accretion on Tuckernuck Island only accounts for about 6 percent of the total erosion of 480,000 m^2 on the island during the 1938-1970 period with the rest of the eroded material (more than 400,000 m^2) being contributed to the shoals to the north and west of the island as well as offshore to the south. A strong tidal flow between Tuckernuck and Smith Point may also carry some sediments north to the Eel Point region of Nantucket Island.

Shoreline changes on the island of Muskegat (Figure 14) show this island eroding extensively from 1938-1970 together with the formation of a small cuspate foreland it its eastern point. The shoreline to the north and west retreated steadily with the western shoreline cut back over 200 m and

FIGURE 13

Shoreline Changes:
Tuckernuck Island, 1938-1970

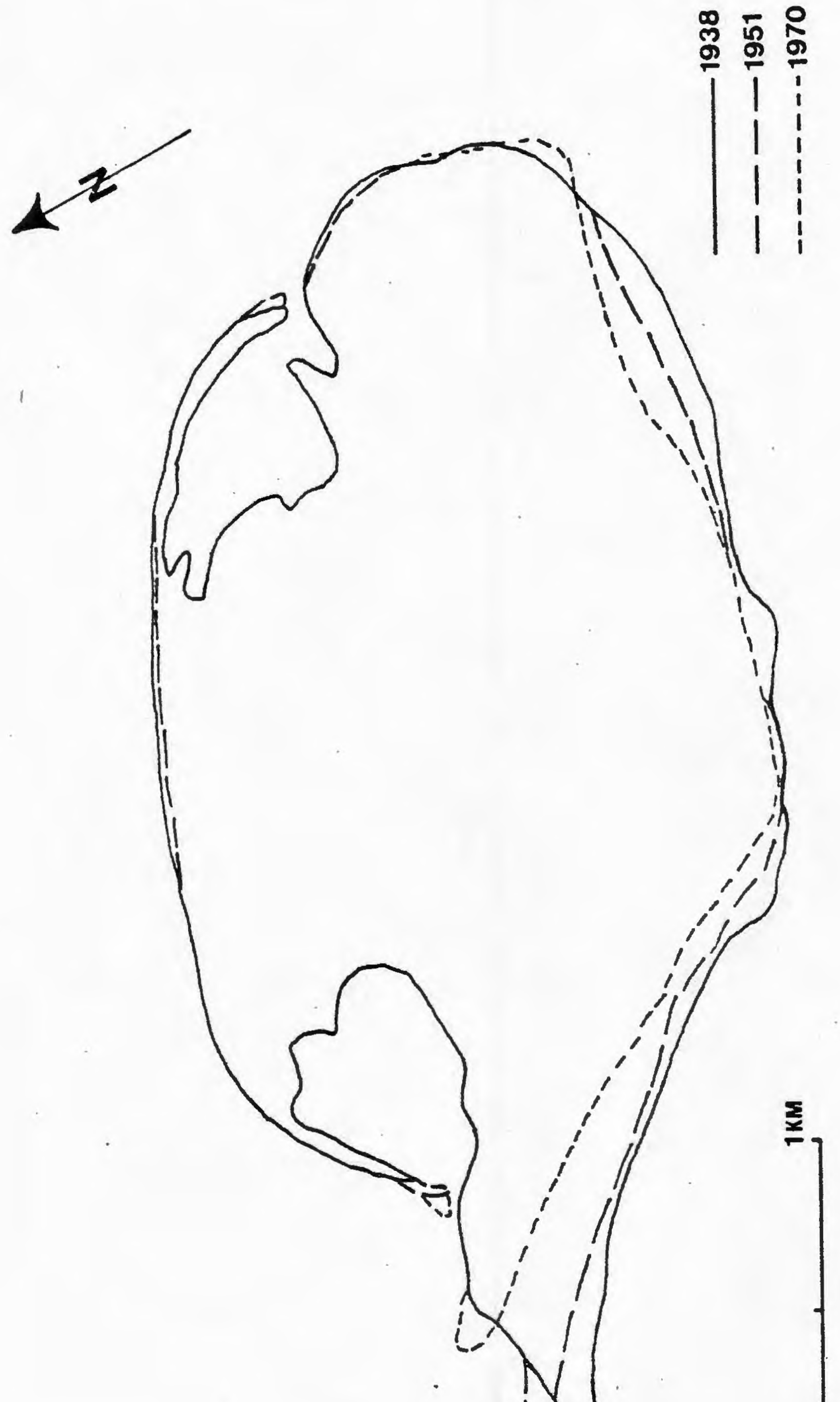
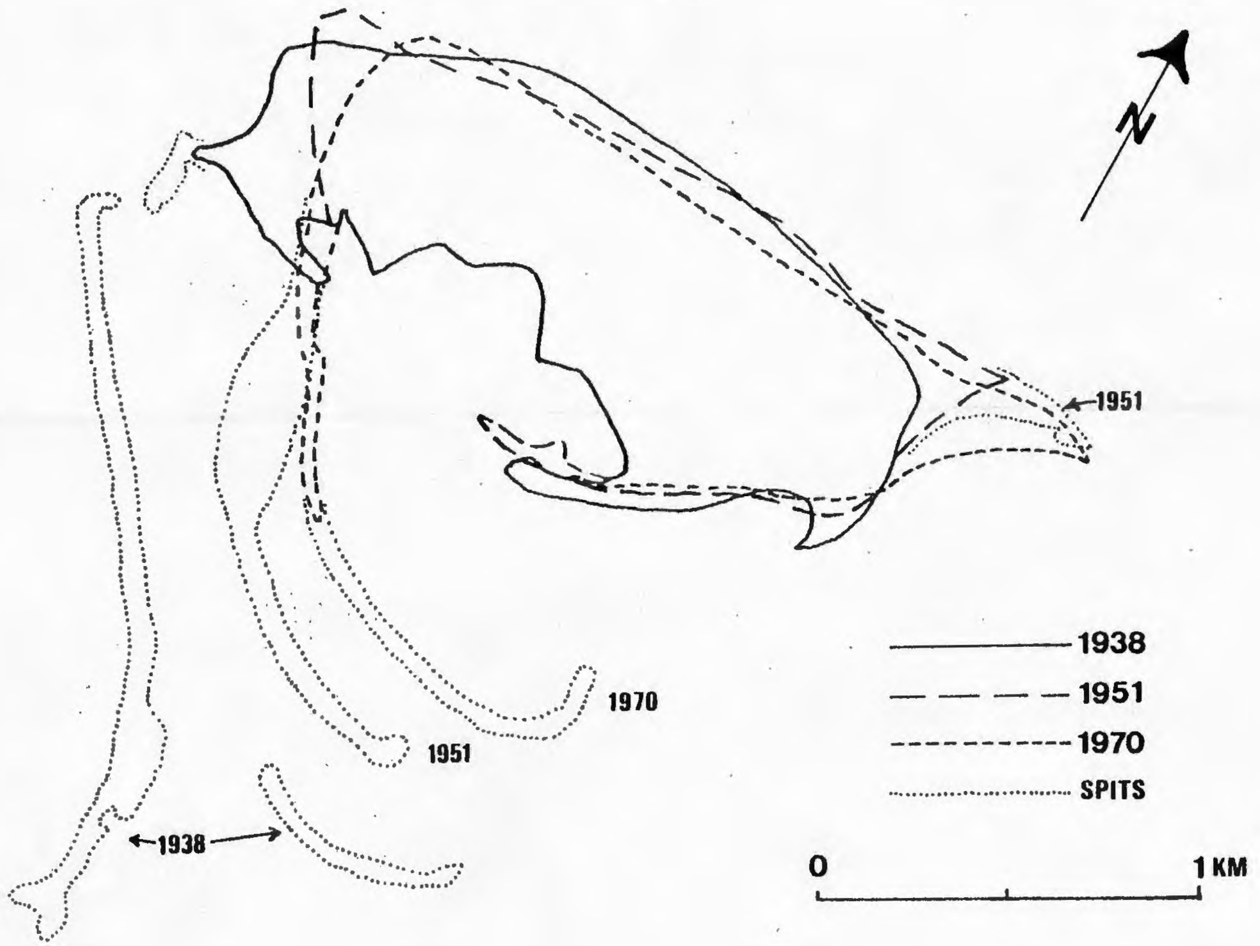

N
1938
1951
1970
0
1KM

FIGURE 14

Shoreline Changes:
Muskegat Island, 1938-1970


N
1951
1938
1951
1970
SPITS
1970
1951
1938
0
1 KM

the northern shoreline losing 75-85 m between 1938 and 1970. The eastern point of Muskegat lengthened by almost 500 m in the 32 years to form a cuspate foreland. The southern shoreline of Muskegat eroded back 60-70 m from 1938-1970. A low-lying spit extending southeast from the western end of Muskegat migrated approximately 500 m to the northeast between 1938 and 1970. Total areal erosion on Muskegat between 1938 and 1970 was 226,500 m^2 while accretion totaled 119,000 m^2 (mostly on the cuspate foreland) resulting in a net areal loss to the offshore and surrounding shoals of approximately 107,500 m^2. Apparently most of this eroded material is transported to the northeast from the cuspate foreland and deposited between Tuckernuck and Muskegat on tidal flats and shoals.

SHORELINE CHANGES: NANTUCKET ISLAND, 1974-1978

The Landsat satellite imagery for 1974 and 1976 was not useful for making direct measurements of shoreline changes. Resolution of Landsat imagery is generally only 200 feet (Fisher, 1977) so that changes occurring on the island of less than 200 feet would not be detectable. The satellite imagery, however, was employed to make some qualitative comparisons of some shoreline features (mainly sand spits) that had changed in shape or orientation. The 1974 Landsat imagery showed an apparent reduction in size of the spit at the end of Smith Point. The length of the spit had significantly decreased from that observed on the 1970 aerial photograph. There appears to have been a large build-up of sand on the south shore of Tuckernuck possible related to this truncation of the Smith Point spit. There was a northward migration of the Muskegat Island spit so that its 1974 trend was nearly east-west. There may also have been an increase in shoaling across the ocean side of the breach separating Esther Island from the main island. The 1976 Landsat imagery showed a spit approximately 600 m long built out to the east from the bend in the south shore of Tuckernuck. The Muskegat spit continued to migrate north and may eventually weld itself across the south shore of Muskegat and enclose a small lagoon. Clearly visible on the satellite imagery from 1974 and 1976 are the areas of shoals associated with Miacomet Rip (Surfside), Point Rip (Great Point) and Old Man Shoal (Siasconset). These shoals did not appear to have significantly changed in trend or dimension between the 1974 and 1976 imagery.

The spit connecting Coskata and Great Point was partially breached during the blizzard of February 1978 just below Great Point. A stretch of the beach 200 m long had water washing across at high tide (Nantucket Inquirer and Mirror, February 16, 1978). Photographs in the Nantucket Inquirer and Mirror of February 16, 1978 clearly show this near breach and also damage and overwash of the young vegetated dunes on the spit.

GEOMORPHIC ANALYSIS OF COMPOSITE SHORELINE CHANGES

Composite annual shoreline changes differ from mean annual changes in that they represent the net value of long-term changes (in this case 32 years) rather than short-term variations in change. Composite shoreline also reveal patterns of erosion and accretion along the shore and allow a comparison of these changes. It would be difficult to make direct comparisons of areal changes because the volume of sediments from a unit area of a cliff or dune of a given height is different than the volume from the same area of a beach. There appear to be no estimations of volume-per-unit-area of a dune or cliff, so it will be assumed in this study that a cliff or dune of a given height would have a greater volume of sediments in proportion to that height than a beach of the same area. For example, a 10 m high cliff or dune would have approximately 10 times as much volume as an equivalent area of beach.

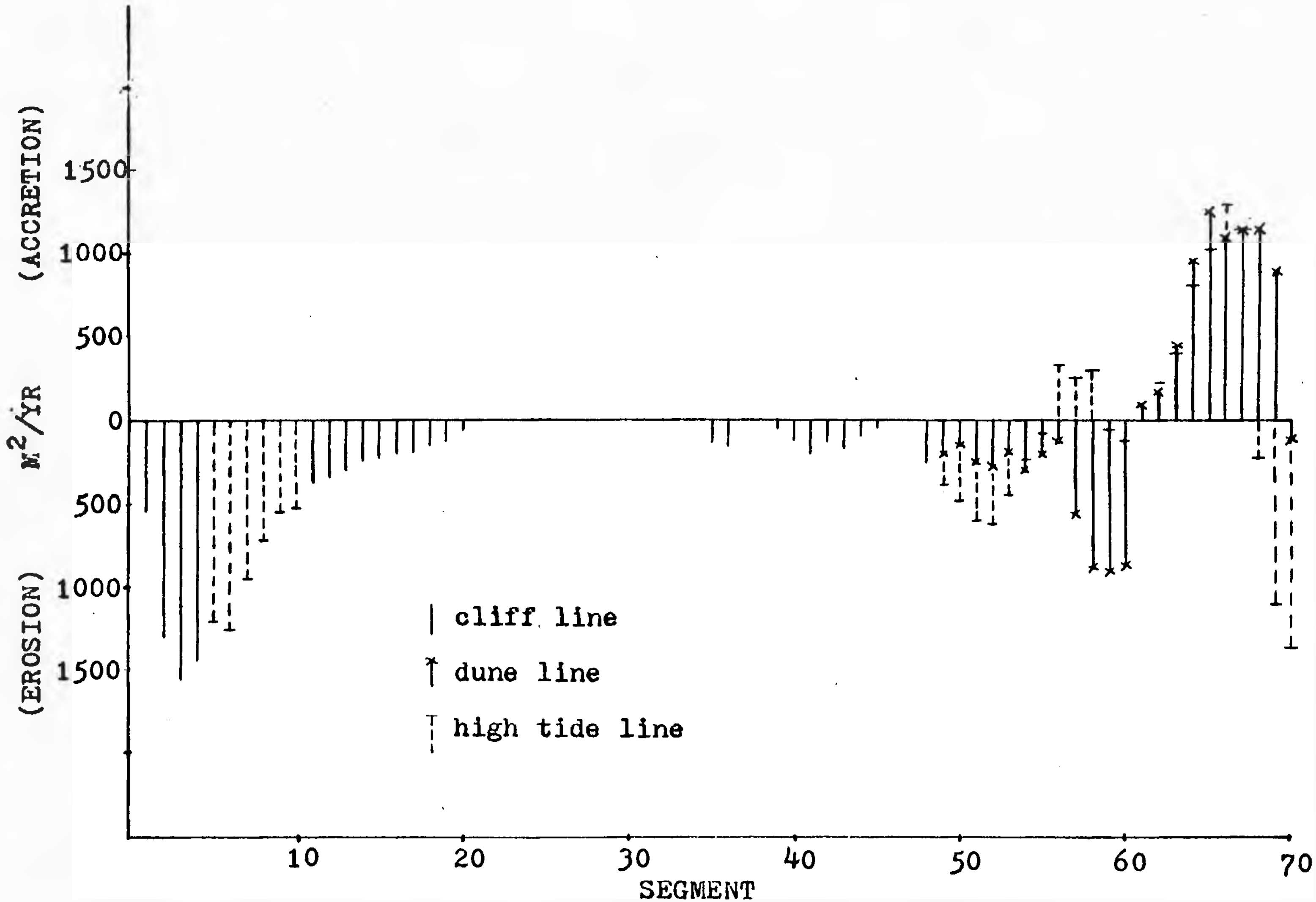
GREAT POINT TO TOM NEVERS HEAD

The general trend of the composite annual shoreline changes (Figure 15) was towards decreased erosion south from Great Point with accretion becoming prevalent along the dune and high tide lines along segments 65-70. Erosion rates were highest for the cliffs in the dune material on Great Point (segments 1-4) with a maximum of 1,550 m^2/yr (5.0 m/yr). Erosion rates were lower on the spit connecting Great Point and generally decreased to the south with high tide line segment 5 losing 1,250 m^2/yr (4.1 m/yr) and high tide line segment 10 losing 500 m^2/yr (1.6 m/ur). Cliffs in dune material along segments 11-20 on Coskata showed erosion rates ranging from 400 m^2/yr (1.3 m/y) down to only 50 m^2/yr for segment 20. The cliffs in dune and glacial material along shoreline segments 21-34 across Haulover Beach and into Quidnet were stable throughout the 32 year study period.

A portion of the sediments eroded from the cliffs in dune material and high tide line along segments 1-20 were being deposited on the west side of Great Point and Coskata totaled 296,000 m^2 in contrast to areal erosion on the east side of over 392,800 m^2. Over 225,000 m^2 of this erosion was from cliffs averaging 6 m in height which would yield a total eroded volume of approximately 1,500,000 m^3 compared to the accreted volume of 296,000 m^3 on the west side of Great Point for the high tide line. Accretion therefore would account for approximately 20 percent of the total erosion with the remainder of the material being transported

FIGURE 15

Composite Annual Changes:
Great Point to Tom Nevers Head, 1938-1970


(ACCRETION)
(EROSION)
M²/YR
1500
1000
500
0
500
1000
1500
10
20
30
40
50
60
70
SEGMENT
cliff line
dune line
high tide line

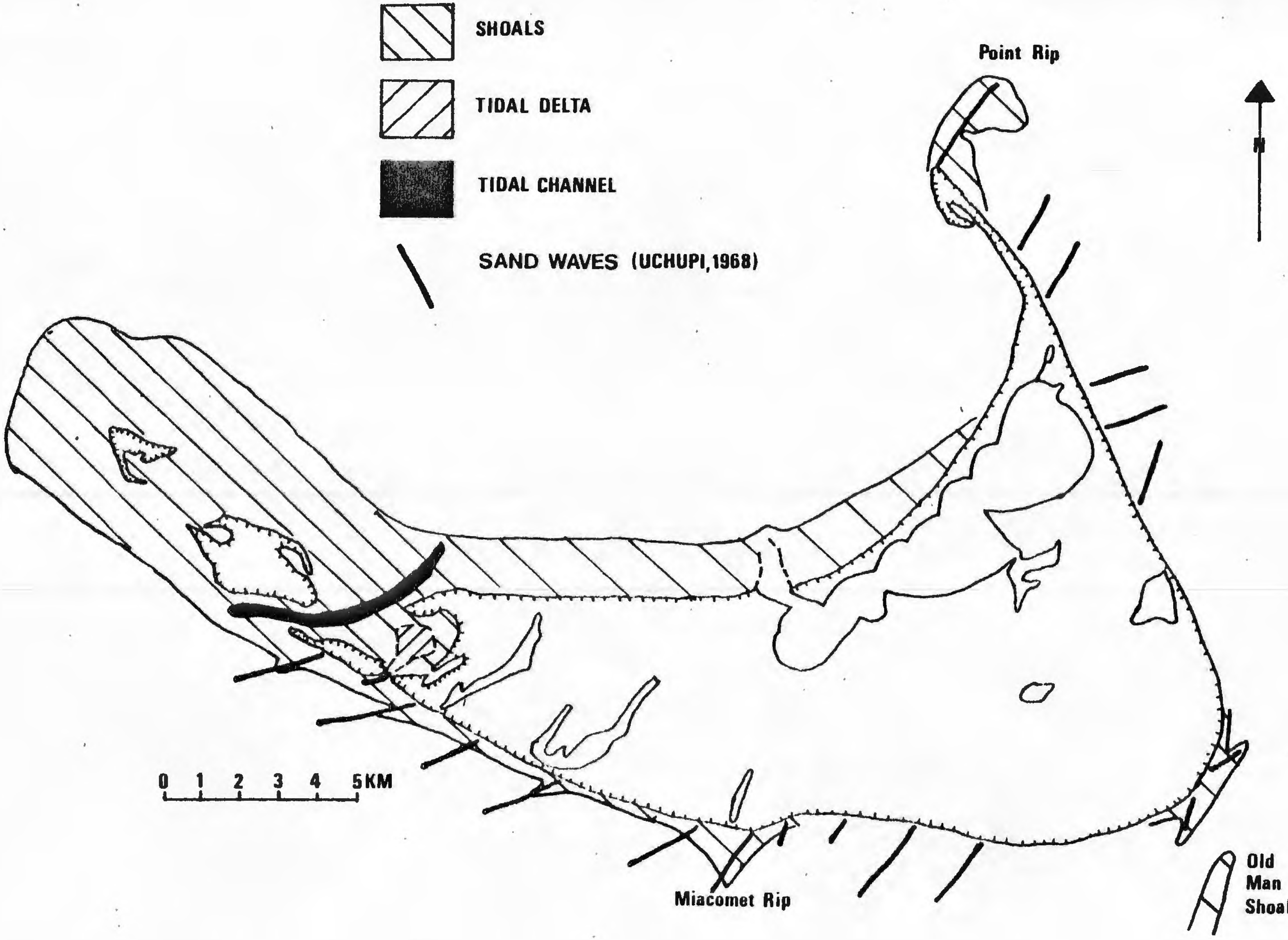
offshore to the northeast of Great Point and deposited in part on a shoal known as Point Rip (Figure 16). Of the sediment transported around Great Point, that portion not deposited on the shoreline may be contributed to a series of parallel sand bars along Coatue Beach. Overwash of the spit connecting Great Point was an important source of eroded sediment transport during 1938-1951. Large amounts of erosion were measured along the east side of the spit and considerable accretion was also measured on the west side while vegetated dunes visible on the spit were no longer present in 1951.

Glacial cliff segments 35 and 36 had erosion rates of 150 m^2/yr (0.5 m/yr) increasing to 200 m^2yr (0.7 m/yr) for glacial cliff segments 41 and further increasing to 250 m^2/yr (0.8 m/yr) for cliff segment 48 on Sankaty Head, resulting in a general tendency toward increased erosion to the south. The dune line along segments 48-56 was eroding 100-300 m^2/yr (0.3-1.0 m/yr) with erosion rates increasing to the south and west to 850-900 m^2/yr (2.8-3.0 m/yr) for dune line segments 58-90. In contrast to these high erosion rates, the dune line along segments 61-70 had accretion rates as high as 1,450 m^2/yr (4.8 m/yr).

Erosion rates in high tide line segments 49-52 of 400-600 m^2/yr (1.3-2.0 m/yr) decreased to only 100 m^2/yr (0.3 m/yr) for high tide line segment 55. Accretion rates for high tide line segments 60-66 generally increased to as high as 1,300 m^2/yr (4.3 m/yr) before decreasing to 900 m^2/yr for

FIGURE 16

General Location of Shoals Surrounding Nantucket
(source: U.S.C.G.S. Navigational Chart 265,
Nantucket Island, 1968)


SHOALS
TIDAL DELTA
TIDAL CHANNEL
SAND WAVES (UCHUPI,1968)
Point Rip
N
0 1 2 3 4 5KM
Miacomet Rip
Old
Man
Shoal

segment 67 and reversing to erosion rates of 200-1,300 m^2/yr (0.7-4.3 m/yr) for high tide line segments 68-70.

The erosion of the cliff line along segments 35-48 and the dune line along segments 49-60 contributed sediments to the accreting dune line in segments 61-70. Considering that erosion of the approximately 10 m high cliff line produces three times the volume of sediments than does erosion of the 3 m high dunes, a greater amount of sediments eroded from this entire section of shoreline (segments 49-70) than was deposited as new dunes. The high tide line along segments 49-70 had a net accretion of 42,000 m^2, accounting for some of the excess erosion from the dune and cliff lines. The remainder of the eroded sediments were transported offshore to the northeast and southwest depending on the predominant wave approach.

A net areal loss of 383,641 m^2 was measured for the eastern shoreline from 1938-1970. This amounts to an annual erosion rate of 0.56 m/yr. Marindin (1893) reported an annual erosion rate of 0.19 m/yr. for 1846-1891 representing an increase in the erosion rates for 1938-1970 of approximately 200 percent.

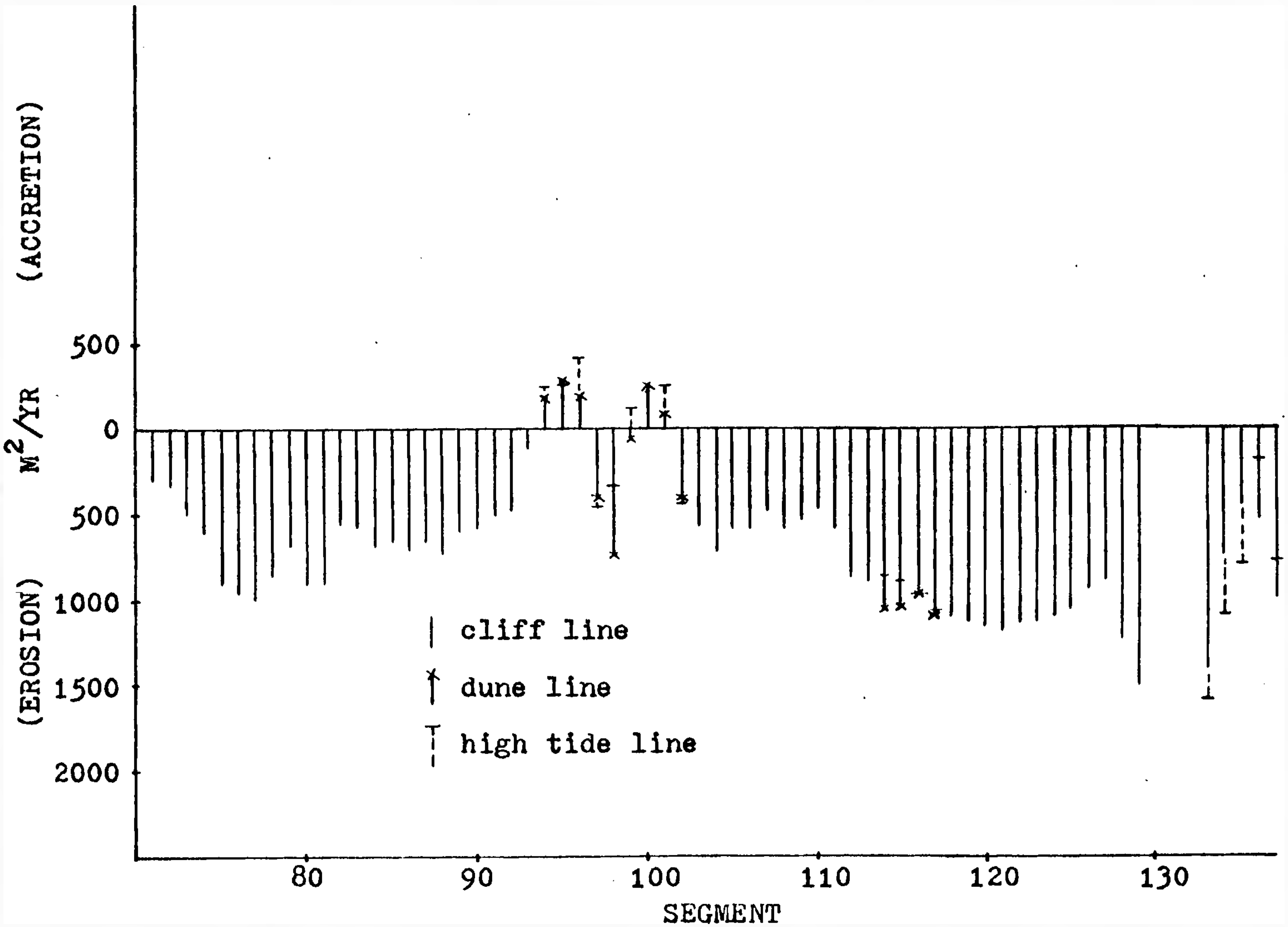
TOM NEVERS HEAD TO SMITH POINT

The southern shoreline of Nantucket showed a general trend toward overall erosion with the exception of some accretion of the foreland at Surfside (Figure 17). Glacial cliff segments 71-93 showed erosion rates increasing from 300 m^2/yr ((1.0 m/yr) for segment 71 to approximately 900-1,000 m^2/yr (3.0-3.3 m/yr) for the glacial cliffs along segments 75-81. These erosion rates decreased slightly to approximately 700 m^2/yr (2.3 m/yr) for the glacial cliffs between segment 81 and the foreland at Surfside (segment 93). Approximately 461,500 m^2 was eroded from the glacial cliffs between segment 71 and the foreland. Some of this material was probably transported east to the dune fields built out from the cliffs in the vicinity of Tom Nevers Head. Most of the transport appeared to be west where the material was deposited on the foreland at Surfside and transported offshore at Miacomet Rip extending southwest from the foreland.

The dune line on the Surfside foreland (segments 94-101) had accretion rates of generally 100-300 m^2/yr (0.3-1.0 m/yr) for segments 94-96 and 100-101 in contrast to erosion rates as high as 700 m^2/yr (2.3 m/yr) in the dune line of the central portion of the foreland (segments 97-99). The corresponding high tide line on the foreland generally had accretion rates that matched those of the dune line while erosion rates were generally lower and limited to segments 97 and 98. The high tide line on the foreland had a net gain of 24,700 m^2 while the dune line lost approximately 2,300 m^2.

FIGURE 17

Composite Annual Changes:
Tom Nevers Head to Smith Point, 1938-1970


(ACCRETION)
M²/YR
(EROSION)
500
0
500
1000
1500
2000
80
90
100
110
120
130
SEGMENT
cliff line
dune line
high tide line

Erosion of the dune line alone could not account for all the accretion of the high tide line even considering the extra volume derived from 3 m high dunes. Sediments for high tide line accretion were derived from erosion of the glacial cliffs to the east and west of the foreland. Sediments are transported offshore to the south from segments 95096. Coast and Geodetic Survey Navigational Chart 265 of Nantucket indicates a shoal called Miacomet Rip in the vicinity where some of this sediment may be deposited (Figure 16). It appears that most of the material eroded from the glacial cliffs east of the foreland was transported offshore with probably much less than 5 percent being redeposited on the southern shoreline (erosion of 461,500 m^2 from 6 m cliffs versus accretion of 25,000 m^2 for the foreland high tide line).

The glacial cliff and dune line segments west of the Surfside foreland had erosion rates that generally increased to the west and were higher than erosion rates measures in the glacial cliffs east of the foreland. Glacial cliff segments 102-111 had an erosion rate of approximately 500 m^2/yr (1.6 m.yr) increasing to between 1,000 and 1,200 m^2/yr for glacial cliff segments 119-121. This was followed by a slight decrease in erosion for segments 122-127 to approximately 900 m^2/yr (3.0 m/yr). Erosion of the glacial cliffs along segments 128-129 increased to as much as 1,500 m^2/yr (5.0 m/yr) and subsequently dropped to 350 m^2/yr just west of the 1961 breach on Esther Island before increasing again to 1,000 m^2/yr (3.3 m/yr) along the cliffs in the dune material in segments 136-137. High tide line segments 133-137 on Esther Island showed a similar trend in erosion patterns, with erosion decreasing from 1,550 m^2yr (5.1 m/yr) for segment 133 to 200 m^2/yr (0.6 m/yr) for high tide line segment 135 and finally increasing to 700 m^2/yr (2.3 m/yr) for high tide line segment 137.

An areal loss of 917,000 m^2 was measured for the glacial cliffs and dunes west of the Surfside foreland from 1938-1951. Accretion of spits at the end of Esther Island and on both sides of the Esther Island breach totaled approximately 240,000 m^2. Considering an average cliff height of 3 m along this section of the south shore, accretion of the spits accounts for less than 10 percent of the material eroded.

Bathymetry for the near shore of Nantucket (particularly along the east and south shoreline) show a series of narrow shoals trending perpendicular to the shoreline. Uchupi (1968, Figure 11) suggests that these features represent the crests of sandwaves, and illustrates the location of a number of these sandwaves along the east and south shoreline of Nantucket. The approximate positions of these "sand waves" are shown in Figure 16. It has been suggested by Swift (1975) that material from shoreface erosion tends to be stored as shoreface connected and tide maintained ridges. These ridges mark the retreat paths of depocenters associated with littoral drift convergence. It can therefore be assumed that these shoals or "sand waves" connected to the Nantucket shorelines are the storage area for a portion of the material eroded from the south and west shoreline that is not reposited downdrift on the beaches, and provide mechanism for the introduction of shoreface eroded materials to the inner shelf.

Following the breach of Smith Point in 1961, a tidal delta formed in Madaket Harbor where some of the sediments apparently eroded from the glacial cliffs west of Surfside were being deposited. A portion of the eroded sediments from the south shore were transported west past the spit on Smith Point and deposited in the shoals around Muskegat and Tuckernuck Island where these sediments were distributed by tidal currents (Figure 16).

Some of the material eroded from dune line segments and high tide line segments 114-117 may have been deposited as overwash into Hummock Pond. The beach at this location is 90 m wide and in 1938, 1951 and 1961 photography showed very low (less than 1 m) non-vegetated dunes. Overwash may have been less significant in 1961-1970 as the dune line accreted and became vegetated. The Cooperative Extension Service shoreline damage map showed the existence of a breach into Hummock Pond in 1954. There was no indication of how long this breach remained open but it was not visible in the 1961 photographs. Aerial photographs from 1961 and 1970 show a channel which may allow sea water to enter Hummock Pond in segment 117 during extremely high tides.

Total net erosion of 1,380,800 m^2 was measured for the south shore for an annual erosion rate of 2.11 m/yr. Marindin (1893) reported an annual erosion rate of 1.42 m/yr for

1846-1891, representing an increase in erosion of 48 percent for 1938-1970.

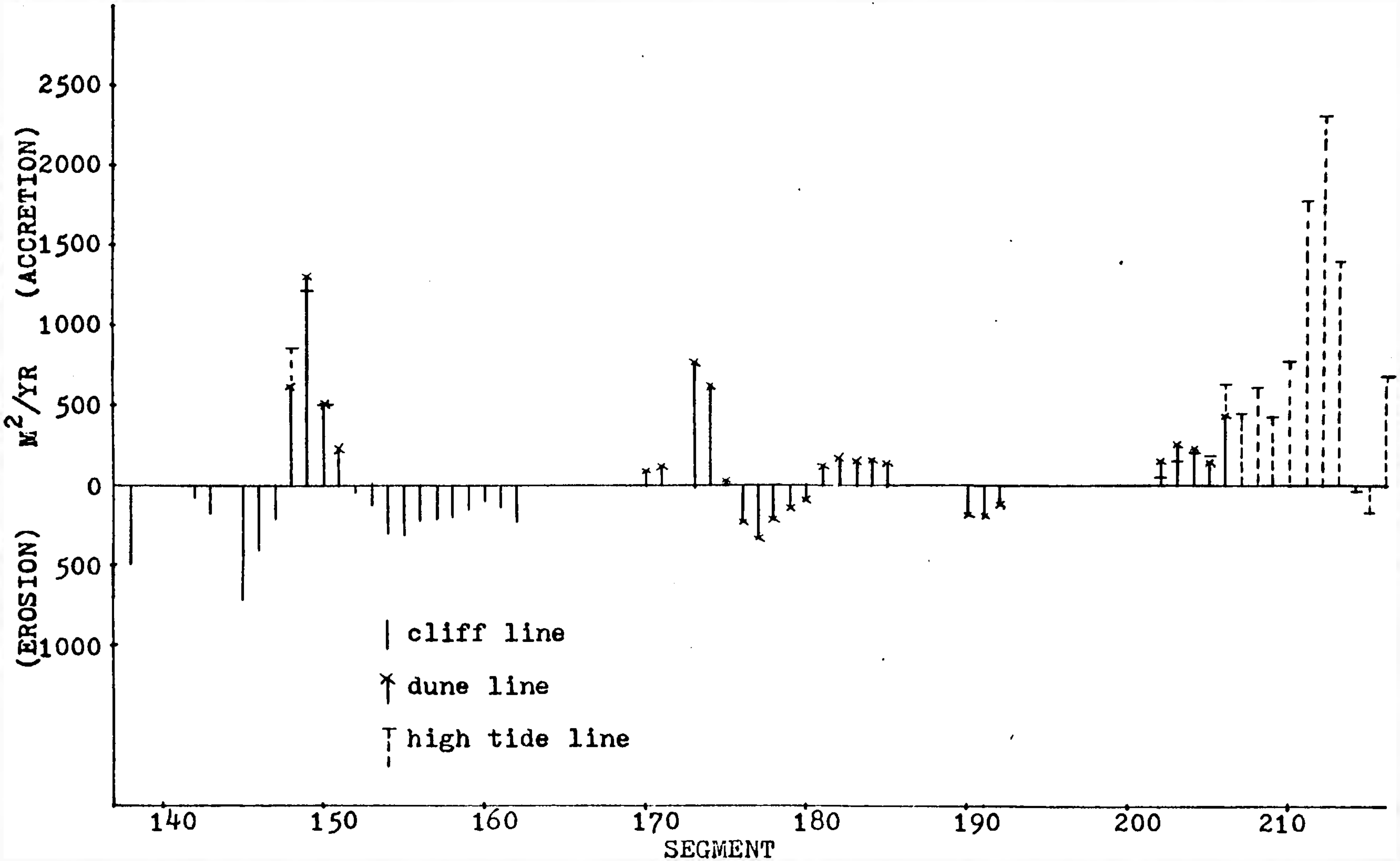
SMITH POINT TO THE WEST JETTY

The north shore of Nantucket tended to have fairly low net erosion rates overall with several sections of the shoreline (the Eel Point foreland, west end of Coatue, and Coskata to Great Point) showing significant rates of accretion (Figure 18). The glacial cliff segments on the north side of Smith Point generally had higher rates of erosion at the west end with 500 m^2/yr (1.6 m/yr) being eroded from cliff line segment 138 while less than 150 m^2/yr (0.5 m/yr) eroded from cliff segments 142-143 farther to the west. The breach of Smith Point in 1961 appears to have had no effect on the north shore of Smith Point with most of the sediments that moved through the breach being deposited on the tidal delta in Madaket Harbor. Erosion of the west end of Smith Point may be due in part to strong tidal currents moving between Tuckernuck Island and Smith Point and finally past Eel Point to the north and east. These strong tidal currents may also influence erosion on the south shore of Tuckernuck Island and supply some sediments for deposition on the Eel Point foreland.

Erosion rates in the cliffs in dune material along Eel Point (segments 145-147) decreased from 700 m^2/yr (21. m/yr) for segment 145 to 200 m^2/yr (0.6 m/yr) for segment 147 adjacent to the foreland. Accretion rates for the Eel Point foreland (dune lines segments 148-151) were generally highest in the center of the foreland with rates on the order of 1,200-1,250 m^2/yr (4.0-4.1 m/yr) for both the dune lines

FIGURE 18

Composite Annual Changes:
Smith Point to Great Point, 1938-1970


M²/YR (ACCRETION)
(EROSION)
2500
2000
1500
1000
500
0
500
1000
cliff line
dune line
high tide line
140
150
160
170
180
190
200
210
SEGMENT

and high tide line. The glacial cliffs east of the foreland (segments 152-162) had erosion rates generally on the order of 100-300 m^2/yr (0.3-1.0 m/yr) decreasing slightly to the east. Accretion of the dune line along segments 170-172 resulted in rates of approximately 100 m^2/yr. Accretion on the north shore between Eel Point and the west jetty totaled approximately 90,000 m^2 including between 6,000 and 10,000 m^2 at the west jetty and 84,000 m^2 on the foreland at Eel Point. Erosion of 125,000 m^2 was measured for the 3-10 m dune and glacial cliffs along the north shore. The amount of material deposited on the north shore from Eel Point to the west jetty accounts for 30-40 percent of the total erosion (125,000 m^2 eroded from 6 m high cliffs versus accretion of 90,000 m^2 for 3 m high dunes) with the excess eroded sediment deposited offshore.

EAST JETTY TO GREAT POINT

Accretion rates as high as 750 m^2/yr (2.5 m/yr) for dune line segment 173 against the eastern jetty on Coatue decreased and reversed to an erosion rate of 350 m^2/yr for dune line segment 177. This was followed by a decrease and reversal of erosion rates to show accretion rates of approximately 150 m^2 (0.5 m/yr) for dune line segments 181-185 in the center of the Coatue shoreline. Due to a slight trend toward erosion in 1938-1951, dune line segments 190-192 showed erosion rates of approximately 200 m^2/yr, but generally the remainder of Coatue Beach (dune line segments 186-198) was stable throughout the 32 years. Dune line segments 202-206 on Coskata had a trend toward increasing accretion rates northward towards Great Point ranging from 150 m^2/yr (0.5 m/yr) up to 450 m^2/yr (1.5 m/yr).

Despite erosion in both 1951-1961 and 1961-1970 the net trend of the spit connecting Great Point (high tide line segments 207-210) was toward accretion rates of between 400 and 800 m^2/yr (1.3-2.6 m/yr) with most of this accretion being due to high accretion rates in 1938-1951. The spit on the west side of Great Point (high tide line segments 211-216) had the highest accretion rate (2,300 m^2/yr), decreasing northward to only 700 m^2/yr for high tide line segment 216.

The section of high tide shoreline from Great Point south and west along Coatue Beach has a very smooth slightly concave-seaward outline. This would suggest steady longshore currents moving from Great Point towards Coatue. A series of longshore bars trend parallel to Coatue Beach. These bars extend directly from the beach in segment 194 and gradually become more distant from the beach to the west towards the jetty (Figure 16). These bars result from sediments being carried offshore by the longshore current moving south from Great Point. North of dune line segment 194 there has been extensive accretion, but to the south and west of this segment on Coatue Beach some erosion has occurred. This would generally support the idea that most material available for accretion on Coatue Beach from the north is moving offshore near segment 194. There was a net accretion of 13,500 m^2 on Coatue Beach suggesting that some extra material is being provided from the north.

A net areal erosion of 34,600 m^2 was measured for Smith Point east to the west jetty protecting the harbor, resulting in a net erosion rate of 0.1 m/yr. Net accretion from the west jetty on Coatue to Great Point totaled 310,500 m^2 mostly on the west side of Great Point and on the shoreline of Coskata, resulting in a net accretion rate of 0.72 m/yr. There are no previous surveys of the north shore that give a net erosion of accretion rate for a period of time prior to 1938-1970 for comparison purposes. The net erosion rate of 0.1 m/yr for the north shore from Eel Point to the west jetty for 1938-1970 is considerably lower than the 0.65 m/yr for the east shore and the 2.11 m/yr rate of the south shore. The large amount of accretion from the east jetty to Great Point in combination with this low erosion rate suggest a general low energy state along the entire north shore of Nantucket.

SUMMARY AND CONCLUSIONS

The eastern exposure of Nantucket Island, stretching from Great Point south to Tom Nevers Head, had a net erosion from 1938-1970 of approximately 384,000 m^2 resulting in a net erosion rate of 0.56 m/yr. Much of the eroded sediments have been deposited offshore, however some sediments have been transported around Great Point and deposited on its west side on an accreting spit. The spit connecting Great Point to Coskata is subject to overwash during strong extra-tropical cyclones (Nor'easters) that pass through the area. These storms, with their strong northeast winds, probably have the greatest impact on the eastern exposure of the island and are important in transporting sediments southeast along Coskata and Coatue Beach from Great Point. The strong northeast winds and the predominant southwest winds help transport sediments to the Sconset area from the north and the west resulting in the variable accretion/erosion between Sankaty Head and Tom Nevers Head.

The southern exposure of Nantucket extends from Tom Nevers Head to the end of a spit on Smith Point (now Esther Island). Total erosion over the 32 year study period was approximately 1,380,800 m^2 for an annual erosion rate of 2.11 m/yr. The only accretion measured on the south shoreline was at the Surfside foreland and the spit at the western end of Smith Point. This accretion accounted for less than

10 percent of the total south shore erosion. There has been some overwash of the beach and deposition of sand in Hummock Pond and the formation of a flood tidal delta in Madaket Harbor as a result of the breaching of Smith Point by Hurricane Esther in 1961. Sediments also appear to be stored in numerous shore-connected "sand waves" or ridges. Longshore drift patterns are variable along the south shore but probably predominant in the easterly direction as a result of the southwest and westerly winds that predominate. Extremely high winds and a strong westerly drift pattern would be set up by the southeasterly storm winds resulting from hurricanes. The lengthening and general areal accretion of the Smith Point spit suggests a westerly longshore drift pattern predominating in this area.

The northern exposure of Nantucket experienced a net accretion of nearly 276,000 m^2 or an annual rate of 0.36 m/yr. Generally the northern shoreline from the west jetty protecting the harbor to Smith Point experienced an erosion amounting to 0.1 m/yr while the shoreline stretching from the eastern jetty along Coatue and Coskata to Great Point had an annual accretion rate of 0.72 m/yr. The short fetch of the protective Nantucket Sound accounts for the lower erosion rates on the north shore and the large amount of sediments introduced from around Great Point and by overwash of the spit connecting Coskata and Great Point result in the overall accretion of the northern exposure from the eastern jetty to Great Point. Longshore drift patterns vary along the north shore depending primarily on the predominant westerlies and the strong northeast storm winds.

The outer islands of Tuckernuck and Muskegat (both to the west of Nantucket) eroded considerably from 1938-1951. Tuckernuck lost over 400,000 m^2 of sediments primarily from the south shore while accreting only 30,000 m^2. Muskegat Island lost 226,000 m^2 during the same period however, nearly 120,000 m^2 of accretion was measured in the formation of a small cuspate foreland at the eastern-most point of Muskegat. Sediments lost from Tuckernuck and Muskegat Island are deposited in numerous tidal flats and shoals surrounding the small islands.

APPENDIX

Table I

Total Shoreline Changes (m^2)

Cliff Line Segments

	1938-1951	1951-1961	1961-1970
1	-5,334	-6,304	-6,142
2	-8,082	-18,795	-15,149
3	-18,750	-16,532	-14,502
4	-24,569	-10,077	-11,421
11	-11,961	-	-
12	-9,536	-	-1,212
13	-9,536	-	-242
14	-5,334	-	-2,748
15	-4,526	-	-2,829
16	-3,879	-	-2,748
17	-3,879	-	-2,748
18	-2,586	-	-2,263
19	-1,616	-	-2,586
20	-808	-	-485
21-34	-	-	-
35	-4,178	-	-
36	-4,499	-	-
37	-	-	-
38	-	-	-
39	-	-1,285	-
40	-2,250	-	-1,285
41	-3,615	-	-2,732
42	-1,687	-	-2,169
43	-2,290	-	-3,875
44	-	-	-3,096
45	-	-	-1,141
46	-	-	-
47	-	-	-
48	-	-	-7,740
71	-	-2,597	-6,493
72	-4,545	-	-5,713
73	-7,791	-	-7,791
74	-8,648	-2,597	-8,440
75	-9,090	-7,272	-12,336
76	-12,466	-8,648	-9,739
77	-15,582	-3,896	-12,985
78	-11,037	-5,194	-11,245
79	-7,684	-7,044	-6,813
80	-9,375	-7,044	-12,551
81	-15,880	-7,684	-5,533
82	-8,734	-4,253	-4,482

Total Shoreline Changes (m^2)

Cliff Line Segments

	1938-1951	1951-1961	1961-1970
83	-10,245	-2,818	-5,123
84	-8,094	-6,403	-7,172
85	-7,172	-5,891	-7,684
86	-6,403	-7,172	-8,965
87	-5,763	-5,123	-9,989
88	-6,376	-4,081	-12,753
89	-6,810	-2,806	-9,360
90	-10,202	-3,061	-5,101
91	-8,161	-	-7,907
92	-9,565	-2,551	-2,806
93	-3,392	-510	-
102	-8,346	-	-4,819
103	-4,491	-5,782	-7,324
104	-12,046	-8,481	-1,927
105	-7,833	-3,264	-7,180
106	-12,402	-3,473	-2,611
107	-4,569	-6,527	-3,916
108	-13,054	-	-5,222
109	-9,582	-	-6,971
110	-6,527	-	-7,833
111	-6,527	-3,915	-7,833
112	-7,833	-7,833	-11,749
113	-7,833	-8,695	-11,749
119	-9,955	-19,247	-6,424
120	-8,495	-15,928	-12,398
121	-7,752	-12,398	-17,707
122	-7,964	-14,389	-13,937
123	-7,964	-14,389	-13,937
124	-7,964	-10,884	-15,928
125	-5,973	-1,327	-25,671
126	-6,637	-	-22,565
127	-10,353	-3,318	-14,601
128	-12,471	-8,012	-18,694
129	-18,694	-6,676	-22,699
130	-15,355	-6,676	-25,000*
131	-19,575	-5,341	-25,000*
132	-10,014	-14,688	-25,000*
133	-11,083	-8,012	-25,824
134	-6,009	-2,671	-14,688
135	-	-	-11,083
136	-	-	-16,691
137	-	-	-31,378
138	-5,345	-9,621	-
139	-	-	-

*estimates for breached segments

Total Shoreline Changes (m^2)

Cliff Line Segments

	1938-1951	1951-1961	1961-1970
140	-	-	-
141	-	-	-
142	-2,138	-	-
143	-4,677	-	-
144	-	-	-
145	-13,013	-9,063	-1,162
146	-4,954	-3,253	-4,331
147	-3,253	-2,789	-930
152	-	-2,091	-613
153	-930	-	-2,324
154	-3,718	-697	-4,880
155	-6,234	-1,394	-1,704
156	-4,415	-1,162	-1,627
157	-3,718	-1,859	-1,552
158	-3,510	-1,320	-1,320
159	-1,768	-2,639	-
160	-2,639	-	-
161	-1,768	-	-1,320
162	-3,299	-3,299	-660
163-169	-	-	-

Dune Line Segments

	1938-1951	1951-1961	1961-1970
49	1,935	-	-8,591
50	3,870	-1,290	-7,740
51	4,902	-3,870	-9,030
52	3,870	-3,870	-9,030
53	2,580	-1,290	-7,740
54	-	-4,515	-4,515
55	-	-1,935	-3,870
56	-1,290	-	-2,580
57	-9,468	-	-8,591
58	-19,478	-6,492	-
59	-20,776	-7,791	-
60	-27,268	-7,142	7,142
61	-7,791	2,597	8,310
62	-1,298	519	6,493
63	13,842	-	649
64	29,865	-	649
65	51,940	-4,311	-7,791
66	56,485	-22,075	649
67	47,395	-16,881	6,493
68	40,903	-	-4,155

Total Shoreline Changes (m^2)

Dune Line Segments

	1938-1951	1951-1961	1961-1970
69	19,478	5,194	4,545
70	1,299	-5,194	-
94	6,264	-	-
95	9.965	-	-
96	9,155	-2,563	-
97	-1,600	-17,983	7,228
98	-11,564	-14,128	2,563
99	-2,409	-	1,291
100	-	-	8,095
101	-964	-	4,337
114	-10,444	-13,055	-9,582
115	-12,402	-14,804	-5,875
116	-25,457	-7,833	2,611
117	-25,457	-13,055	3,916
118	-13,055	-14,360	-6,971
148	3,950	14,872	-1,627
149	18,125	8,366	14,640
150	3,484	3,950	8,598
151	4,648	1,673	613
170	-	2,593	-
171	-	3,890	-
172	-	-	-
173	13,040	6,259	5,216
174	2,999	1,956	5,216
175	-3,469	-	4,355
176	-5,477	-	-1,565
177	-4,564	-	-5,607
178	-3,130	-	-3,469
179	-4,355	-	-
180	-3,651	-	1,043
181	-1,304	-	5,216
182	-	-	5,607
183	1,565	-	3,260
184	4,825	-	-
185	4,572	-	-
186-189	-	-	-
190	-5,617	-	-
191	-6,009	-	-
192	-3,475	-	-
192-201	-	-	-
202	3,657	1,750	-
203	4,441	4,310	-
204	-	7,576	-
205	261	4,180	-
206	5,016	7,576	1,959

Total Shoreline Changes (m^2)

High Tide Line Segments

	1938-1951	1951-1961	1961-1970
5	-21,508	-10,973	-5,680
6	-19,365	-13,555	-7,230
7	-18,926	-10,328	-516
8	-18,590	-4,725	-
9	-17,428	-	-
10	-16,783	-	-
49	-4,128	-3,870	-4,309
50	-3,870	-4,515	-6,450
51	-4,515	-3,870	-10,320
52	-7,095	-258	-12,384
53	-2,580	-	-12,049
54	-	-	-7,740
55	-	-	-2,838
56	-	-	10,648
57	-	-10,388	18,179
58	-	-29,866	38,955
59	-16,881	-28,827	44,149
60	-12,336	-15,322	23,633
61	-1,948	30,515	-28,567
62	649	35,060	-28,567
63	11,037	23,373	-21,295
64	25,113	7,791	-7,791
65	43,500	-11,687	857
66	70,121	-33,761	7,272
67	38,436	-8,440	7,272
68	-14,543	-	7,142
69	-16,436	-649	-649
70	-13,556	-3,636	-3,795
94	-	-	7,749
95	-	-	8,834
96	-3,229	-	16,790
97	-14,852	-	852
98	-13,561	-	3,229
99	-7,361	-	10,977
100	2,970	-1,292	5,166
101	9,299	-3,435	2,583
114	-13,055	-14,360	-1,306
115	-15,666	-14,360	-2,611
116	-17,415	-10,444	-
117	-15,927	-13,708	-1,306
118	-13,708	-13,917	-6,528
133	-16,035	-8,018	-25,824
134	-15,367	-4,009	-14,688
135	-20,713	-5,880	-11,083

Total Shoreline Changes (m^2)

High Tide Line Segments

	1938-1951	1951-1961	1961-1970
136	-8,018	-18,708	-16,691
137	-4,543	-10,690	-31,378
148	10,001	11,761	5,334
149	14,669	19,202	4,667
150	4,000	8,881	3,067
151	-	-	-
202	-	1,829	-
203	-	4,833	-
204	-	6,631	-
205	784	5,225	-
206	13,716	1,306	5,225
207	21,997	-8,700	1,750
208	30,044	-10,241	-
209	31,350	-13,324	-3,419
210	29,600	-1,045	-3,475
211	21,762	11,756	23,513
212	19,803	30,697	23,513
213	27,693	3,475	13,716
214	10,711	-15,022	3,919
215	1,750	-15,022	8,099
216	-	-	21,977

Table II

Mean Annual Shoreline Changes (m^2/yr)

Cliff Line Segments

	1938-1951	1951-1961	1961-1970
1	-410.3	-663.6	-646.5
2	-621.6	-1,978.4	-1,594.6
3	-1,442.3	-1,740.2	-1,526.5
4	-1,889.9	-1,060.7	-1,202.2
11	-920.1	-	-
12	-733,5	-	-127.6
13	-733.5	-	-25.5
14	-410.3	-	-289.3
15	-348.2	-	-297.8
16	-298.4	-	-289.3
17	-298.4	-	-289.3
18	-198.9	-	-238.2
19	-124.3	-	-272.2
20	-62.2	-	-51.1
21-34	-	-	-
35	-321.4	-	-
36	-346.1	-	-
37	-	-	-
38	-	-	-
39	-	-135.3	-
40	-173.1	-	-135.3
41	-278.1	-	-287.6
42	-129.8	-	-228.3
43	-99.2	-	-407.9
44	-	-	-325.9
45	-	-	-120.1
46	-	-	-
47	-	-	-
48	-	-	-814.7
71	-	-273.4	-683.5
72	-349.6	-	-601.4
73	-599.3	-	-820.1
74	-665.2	-273.4	-888.4
75	-699.2	-765.5	-1,298.5
76	-958.9	-910.3	-1,025.2
77	-1,198.6	-410.1	-1,366.8
78	-849.0	-546.7	-1,183.7
79	-588.3	-741.5	-717.2
80	-721.1	-741.5	-1,321.2
81	-1,221.5	-808.8	-582.4
82	-671.9	-447.8	-471.8

Mean Annual Shoreline Changes (m^2/yr)

Cliff Line Segments

	1938-1951	1951-1961	1961-1970
83	-788.1	-296.6	-539.3
84	-622.6	-674.0	-754.9
85	-551.7	-620.1	-808.8
86	-492.5	-754.9	-943.7
87	-443.3	-539.3	-1,051.5
88	-490.5	-430.4	-1,342.4
89	-523.9	-295.4	-985.3
90	-784.8	-322.2	-536.9
91	-627.8	-	-832.3
92	-735.8	-268.5	-295.4
93	-260.0	-53.7	-
102	-642.0	-	-507.3
103	-345.5	-608.6	-770.9
104	-954.3	-892.7	-202.8
105	-602.5	-343.5	-755.8
106	-954.0	-365.6	-274.8
107	-351.5	-687.1	-412.2
108	-1,004.2	-	-549.7
109	-737.1	-	-733.8
110	-502.1	-	-824.5
111	-502.1	-412.1	-824.5
112	-602.5	-824.5	-1,236.7
113	-602.5	-915.3	-1,236.7
119	-765.8	-2,026.0	-676.2
120	-635.5	-1,676.6	-1,305.1
121	-596.3	-1,305.1	-1,863.9
122	-612.6	-1,514.6	-1,467.1
123	-612.6	-1,514.6	-1,467.1
124	-612.6	-1,145.7	-1,676.6
125	-459.5	-139.7	-2,702.2
126	-510.5	-	-2,375.3
127	-796.4	-349.3	-1,536.9
128	-959.3	-843.4	-1,967.8
129	-1,438.0	-702.7	-2,389.4
130	-1,181.6	-702.7	-2,631.6*
131	-1,505.8	-562.2	-2,631.6*
132	-770.3	-1,546.1	-2,631.6*
133	-825.5	-843.4	-2,718.3
134	-462.2	-281.2	-1,546.1
135	-	-	-1,166.6
136	-	-	-1,756.9
137	-	-	-3,302.9
138	-411.2	-1,012.7	-
139-141	-	-	-

*estimates for breached segments

Mean Annual Shoreline Changes (m^2/yr)

Cliff Line Segments

	1938-1951	1951-1961	1961-1970
142	-164.5	-	-
143	-359.8	-	-
144	-	-	-
145	-1,001.0	-954.0	-122.3
146	-381.1	-342.4	-455.9
147	-250.2	-294.5	-97.9
152	-	-220.1	-64.5
153	-71.5	-	-244.6
154	-296.0	-71.3	-513.7
155	-480.5	-146.7	-179.4
156	-339.6	-122.3	-171.3
157	-286.0	-195.7	-163.4
158	-270.0	-138.9	-138.9
159	-136.0	-277.8	-
160	-203.0	-	-
161	-136.0	-	-138.9
162	-253.8	-347.3	-69.5
163-169	-	-	-

Dune Line Segments

	1938-1951	1951-1961	1961-1970
49	148.9	-	-904.3
50	297.7	-135.8	-814.7
51	377.1	-407.4	-950.5
52	297.7	-407.4	-950.5
53	198.5	-135.8	-814.7
54	-	-475.3	-475.3
55	-	-203.7	-407.4
56	-99.2	-	-271.6
57	-728.4	-	-904.3
58	-1,623.1	-683.5	-
59	-1,731.3	-820.1	-
60	-2,272.4	-751.8	-751.8
61	-649.3	-273.2	-874.7
62	-99.9	-54.6	-683.5
63	1,064.8	-	-68.3
64	2,297.3	-	68.3
65	3,995.4	-45.4	-820.1
66	4,345.0	-2,323.7	68.3
67	3,645.8	-1,776.9	683.5
68	3,146.4	-	-437.4
69	1,498.3	546.7	478.4
70	99.9	-546.7	-
94	481.9	-	-
95	766.5	-	-
96	704.3	-269.8	-

Mean Annual Shoreline Changes (m^2/yr)

Dune Line Segments

	1938-1951	1951-1961	1961-1970
97	-123.1	-1,892.9	760.8
98	-889.6	-1,487.2	269.8
99	-185.3	-	135.9
100	-	-	852.1
101	-74.1	-	456.5
114	-803.4	-1,374.2	-1,008.6
115	-954.0	-1,558.3	-618.4
116	-1,958.2	-829.8	274.8
117	-1,958.2	-1,374.2	412.2
118	-1,004.2	-1,511.6	733.8
148	303.9	1,565.5	-171.3
149	1,394.2	880.6	1,541.1
150	268.0	415.8	905.1
151	357.5	176.1	64.5
170	-	272.9	-
171	-	409.5	-
172	-	-	-
173	1,003.1	658.8	549.1
174	230.7	205.9	549.1
175	-266.9	-	458.4
176	-421.3	-	-164.7
177	-351.1	-	-590.2
178	-240.8	-	-365.2
179	-355.0	-	-
180	-280.9	-	109.8
181	-100.3	-	549.1
182	-	-	590.2
183	120.4	-	343.2
184	371.2	-	-
185	351.7	-	-
186-189	-	-	-
190	-432.1	-	-
191	-462.2	-	-
192	-267.3	-	-
193-201	-	-	-
202	281.3	184.2	-
203	341.6	453.7	-
204	-	797.5	-
205	20.1	440.0	-
206	385.9	797.5	206.2

Mean Annual Shoreline Changes (m^2/yr)

High Tide Line Segments

	1938-1951	1951-1961	1961-1970
5	-1,654.5	-1.155.1	-597.9
6	-1,489.6	-1,462.8	-761.1
7	-1,455.8	-1,087.2	-54.3
8	-1,430.0	-497.4	-
9	-1,340.6	-	-
10	-1,291.0	-	-
49	-317.5	-407.4	453.6
50	-297.7	-475.3	678.9
51	-351.9	-407.4	1,086.3
52	-545 4	-27.2	1.303.6
53	-198.5	-	1,268.3
54	-	-	814.7
55	-	-	298.7
56	-	-	1,120.8
57	-	-1,093.5	1,913.6
58	-	-3,143.8	4,100.5
59	-1,298.5	-3,034.4	4,647.3
60	-948.9	-1,612.8	2,487.7
61	-149.9	3,212.1	-3,007.1
62	49.9	3,690.5	-3,007.1
63	849.0	2,460.3	-2,241.6
64	1,931.8	829.1	-820.1
65	3,346.2	-1,230.2	90.2
66	5,293.9	-3,553.8	765.5
67	2,956.6	-888.4	765.5
68	-1,118.7	-	751.8
69	-1,264.3	-68.3	-68.3
70	-1,042.8	-382.7	-399.5
94	-	-	815.7
95	-	-	929.2
96	-248.4	-	1,767.4
97	-1,142.5	-	89.7
98	-1,043.2	-	339.9
99	-566.2	-	1,155.5
100	228.5	-136.0	543.8
101	715.3	-361.6	271.9
114	-1,004.2	-1,511.6	-137.5
115	-1,205.1	-1.511.6	-274.8
116	-1,339.6	-1,099.4	-
117	-1,225.6	-1,442.9	-137.5
118	-1,054.5	-1,464.9	-687.2
133	-1,233.5	-844.0	-2,718.3
134	-1,182.1	-422.0	-1,546.1
135	-1,593.3	618.9	-1,166.6

Mean Annual Shoreline Changes (m^2/yr)

High Tide Line Segments

	1938-1951	1951-1961	1961-1970
136	-616.8	1,969.3	-1,756.9
137	-349.5	1,125.3	-3,302.9
148	769.3	1,238.0	561.5
149	1,128.4	2,021.3	491.3
150	307.7	934.8	322.8
151	-	-	-
202	-	192.5	-
203	-	508.7	-
204	-	687.5	-
205	60.3	550.0	-
206	1,055.1	137.5	550.0
207	1,692.1	-915.8	184.2
208	2,311.1	-1,078.0	-
209	2,411.5	-1,402.5	-359.9
210	2,276.9	-110.0	-365.8
211	1,674.0	1,237.5	2,475.5
212	1,523.3	3,231.3	2,475.5
213	2,130.2	36.6	1,443.8
214	823.9	-1,581.3	412.5
215	134.6	-1,581.3	852.5
216	-	-	2,315.5

Table III

Composite Annual Shoreline Changes (m^2/yr)

Cliff Line Segments

1	-555.6	71	-284.1	126	-912.6
2	-1,313.3	72	-320.6	127	-883.5
3	-1,555.8	73	-486.9	128	-1,224.3
4	-1,439.6	74	-615.2	129	-1,502.2
11	-373.9	75	-496.8	130	-1,562.5*
12	-335.9	76	-964.3	131	-1,562.5*
13	-305.6	77	-1,014.5	132	-1,562.5*
14	-252.6	78	-858.6	133	-1,403.7
15	-229.9	79	-673.2	134	-730.3
16	-207.1	80	-905.3	135	-346.3
17	-207.1	81	-909.3	136	-521.6
18	-151.5	82	-545.9	137	-980.6
19	-131.3	83	-568.3	138	-476.7
20	-40.4	84	-677.2	139	-
21	-	85	-648.3	140	-
22	-	86	-704.4	141	-
23	-	87	-652.3	142	-66.8
24	-	88	-725.3	143	-146.2
25	-	89	-593.0	144	-
26	-	90	-573.9	145	-726.2
27	-	91	-502.1	146	-391.8
28	-	92	-466.3	147	-217.8
29	-	93	-122.0	152	-40.9
30	-	102	-411.4	153	-101.7
31	-	103	-549.9	154	-290.5
32	-	104	-701.7	155	-292.9
33	-	105	-571.2	156	-225.1
34	-	106	-577.7	157	-222.8
35	-130.6	107	-469.1	158	-192.2
36	-140.6	108	-571.1	159	-137.7
37	-	109	-517.3	160	-82.5
38	-	110	-448.8	161	-96.5
39	-40.2	111	-571.1	162	-226.8
40	-110.5	112	-856.7	163	-
41	-198.3	113	-883.7	164	-
42	-120.5	119	-1,113.3	165	-
43	-161.4	120	-1,150.7	166	-
44	-96.8	121	-1,183.0	167	-
45	-35.7	122	-1,134.1	168	-
46	-	123	-1,134.1	169	-
47	-	124	-1,086.8		
48	-241.9	125	-1,030.3		

*estimate of composite annual change for breached segments

Composite Annual Shoreline Changes (m^2/yr)

Dune Line Segments

49	-280.0	98	-722.8	183	150.8
50	-161.3	99	-34.9	184	150.8
51	-249.9	100	252.9	185	142.9
52	-282.2	101	105.4	186	-
53	-201.6	114	-1,033.8	187	-
54	-282.2	115	-1,033.8	188	-
55	-181.4	116	-958.7	189	-
56	-120.9	117	-1,081.1	190	-175.5
57	-564.4	118	-1,074.6	191	-187.8
58	-811.5	148	639.0	192	-108.6
59	-892.7	149	1,285.3	193	-
60	-852.1	150	501.0	194	-
61	97.4	151	216.7	195	-
62	178.5	170	81.0	196	-
63	452.9	171	121.6	197	-
64	953.6	172	-	198	-
65	1,244.9	173	766.1	199	-
66	1,095.6	174	635.7	200	-
67	1,156.5	175	27.7	201	-
68	1,148.4	176	-220.1	202	169.0
69	913.0	177	-317.8	203	273.5
70	-121.7	178	-206.2	204	236.8
94	195.8	179	-136.1	205	138.8
95	311.4	180	-81.5	206	454.7
96	206.0	181	122.3		
97	-386.1	182	175.2		

High Tide Line Segments

5	-1,192.5	64	748.8	133	-1,558.7
6	-1,254.7	65	1,020.9	134	-1,064.5
7	-930.3	66	1,322.8	135	-809.9
8	-728.6	67	1,164.6	136	-187.5
9	-544.6	68	-231.3	137	-788.5
10	-524.5	69	-1,108.6	148	846.8
49	-384.6	70	-1,334.2	149	1,204.3
50	-463.6	94	242.2	150	498.4
51	-586.4	95	276.1	202	57.2
52	-616.8	96	423.8	203	151.0
53	-456.2	97	-437.5	204	204.1
54	-241.9	98	-322.9	205	187.8
55	-88.7	99	113.0	206	632.7
56	332.8	100	213.9	207	470.2
57	243.5	101	264.0	208	618.8
58	284.0	102	433.5	209	440.8
59	-48.7	114	-856.7	210	783.8
60	-125.8	115	-1,019.9	211	1,782.2
61	-	116	-870.6	212	2,312.9

Composite Annual Shoreline Changes (m^2/yr)

High Tide Line Segments

62	223.2	117	-966.9	213	1,402.6
63	409.8	118	-1,067.3	214	-12.3
				215	-161.7
				216	687.4

Table IV

Accuracy of Photogrammetric Technique

Objects		Field Measurements FT	Calculated Ground Area FT^2	Linear Photo Measurements IN	Scale (RF)	Measured Photo Area # SQ'S	Calculated Ground Area (#SQ'S) FT^2	Areal Variation
A	a	220	22,330	.224	1:11,933	2.33	22,789	2.06%
	b	205		.205	1:11,882			
B	a	150	54,000	.154	1:11,688	5.67	55,458	2.70%
	b	360		.367	1:11,771			
C	a	385	54,285	.387	1:11,937	5.50	53,795	0.90%
	b	141		.143	1:11,832			
D	a	187	59,560	.185	1:12,136	6.00	58,686	1.47%
	b	330		.333	1:11,891			
	c	198		.199	1:11,940			
	d	307		.306	1:12,039			
E	a	112	30,240	.115	1:11,686	3.25	31,788	5.12%
	b	270		.273	1:11,868			

Average scale: 1:11,867

REFERENCES CITED

Avery, T.E., 1977 Interpretation of aerial photographs (third edition), Minneapolis, Burgess Publishing Co.

Baker, Simon, 1977, A citizen's guide to North Carolina's shifting inlets: Sea Grant Publication UNC-SG-77-08.

Cooperative Extension Service, 1966, Selected resources of the Island of Nantucket: University of Massachusetts.

Dietz, R.S., 1947, Aerial photographs in the geological study of shore features and process: Photogram. Engineering, v. 13, n. 4, p. 537-545.

El Ashry, M.T., 1963, Effects of hurricanes on parts of the U.S. coastline as indicated by aerial photographs: unpublished M.S. thesis, Dept. of Geology, Univ. Illinois, Urbana, Illinois.

_____ 1966, Photo interpretation of shoreline changes in selected areas along the Atlantic and Gulf Coasts of the United States: unpublished Ph. D. thesis, Dept. of Geology, Univ. of Illinois, Urbana, Illinois, University Microfilms, Ann Arbor, Michigan.

_____ 1973, An example of coastal studies from space and aerial photographs: Jour. of Geological Education, March 1973, p. 75-78.

_____ and H.R. Wanless, 1965, Birth and growth of a tidal delta: Jour. of Geology, v. 73, n. 2, p. 404-406.

_____ and H.R. Wanless, 1968, Photo interpretation of shoreline changes between Capes Hatteras and Fear (North Carolina): Marine Geology, v. 6, n. 5, p. 347-379.

Fisher, J.J., 1977, Teaching geologic/earth science remote sensing at the collegiate and the secondary school level: Jour. Geological Education, v. 25, n. 1, p. 1-R.

Gato, L.W., 1975, Shoreline changes along the easterly shore of Cape Cod from Long Point to Monomoy Point: U.S. Army, Corps of Engineers, Cold Regions Research and Engineering Laboratory, 50 p.

Gulliver, F.P., 1903, Nantucket Shoreline, II: Bull. Geol. Soc. Am., v. 15, pp. 507-522.

Gulliver, F.P., 1909, Nantucket Shorelines IV, V: Bull. Geol. Soc. Am., v.17.

Kaye, C.A., 1973, Map showing changes in shoreline of Martha's Vineyard, Massachusetts, during the past 200 years: U.S. Geological Survey Misc. Field Studies, Map MF-534.

Langfelder, L.J., Stafford, D.B., and M. Amein, 1968, A reconnaissance of coastal erosion in North Carolina. A report prepared for the State of North Carolina: Coastal Research Program, Project ERD-238, Dept. Civil Engineering, North Carolina State University, 127 p.

Marindin, H.L., 1893, On changes in the ocean shorelines of Nantucket Island, Massachusetts, from a comparison of surveys made in the years 1846 to 1887 and in 1891: Ann. Rept. U.S. Coast and Geodetic Survey, app. 6, p. 243-252.

Nordstrom K.F. and Psuty N.P., 1977. Comments on study methods and regulatory policies presented at the National Conference on Coastal Erosion - draft discussion paper: in Proceedings of the National Conference on Coastal Erosion, Cape May N.J., July 6-8, 1977: Dept. of Housing and Urban Development, Federal Insurance Administration, p. 105-127.

Ogden, J.G., III, 1974, Shoreline changes along the southeastern coast of Martha's Vineyard, Massachusetts, for the past 200 years: Quarternary Research, v. 4, p. 496-508.

Regan, D.R., 1976, An aerial photogrammetric survey of long-term shoreline changes, southern Rhode Island coast: unpublished M.S. thesis, Univ. Rhode Island, 76 p.

Rosen, P.S., 1975, Origin and processes of cuspate spit shorelines: in Cronin, L.E. (ed.), Estuarine Research, v. 2, Academic Press, N.Y., p. 77-92.

Simpson, E.J., 1977, A photogrammetric survey of backbarrier accretion on the Rhode Island barrier beaches: unpublished M.S. thesis, Univ. Rhode Island, 123 p.

Stafford, D.B., 1968, Development and evolution of a procedure for using aerial photographs to conduct a survey of coastal erosion: unpublished Ph.D. thesis, Dept. of Civil Engineering, N.C. State University, Raleigh, N.C., University Microfilsm, Ann Arbor, Michigan.

Stafford, D.B., 1971, An aerial photgraphic technique for beach erosion surveys in North Carolina: U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Tech. Memo. No. 36, 115 p.

_____ and Langfelder, L.J., 1971, Air photo survey of coastal erosion: Photogram. Engr., v. 37, p. 565-575.

Stephen, M.F., Brown, P.J., FitzGerald, D.M., Hubbard, D.K., and Hayes, M.O., 1975, Beach erosion inventory of Charleston County, South Carolina: a preliminary report: Coastal Research Division, Tech. Rep. No. 4, Dept. Geology, Univ. South Carolina, 74 p.

Stirewalt, G.L., and Ingram, R.L., 1974, Aerial photographic study of shoreline erosion and deposition, Pamlico Sound, North Carolina: Univ. North Carolina Sea Grant Program Pub. No. UNC-SG-74-09, 66 p.

Swift, D.J.P., 1975, Tidal sand ridges and shoal retreat massifs: Marine Geology, v. 18, p. 105-133.

Tanner, W.F. (ed.), 1977, Standards for measuring shoreline changes: a study of precision obtainable and needed in making measurements of changes (erosion and accretion): sponsored by Coastal Plains Center for Marine Development Services, Wilmington, Delaware, 45 p.

Uchupi, E., 1968, Atlantic continental shelf and slope, physiography: U.S.G.S. Prof. Paper 529-C, 30 p.

Wahls, H.E., 1973, A survey of North Carolina beach erosion by air photo methods: the Center for Marine and Coastal Studies, N.C. State University, Report No. 73-1, 31 p.

Woodworth, J.B., and Wigglesworth, E., 1934, Geography and Geology of the region including Cape Cod, the Elizabeth Islands, Nantucket, Martha's Vineyard, and Block Island: Museum of Comparative Zoology, Harvard, Cambridge, Mass.

Zarillo, G., 1974, Task report: review of shoreline stability and inlet migration from aerial photographs: southern Long Beach Island, Little Beach Island, and Brigantine Island: Dames and Moore.