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AUG 82 P E SPEER, D G AUBREY, E RUDER
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20. ABSTRACT CONTINUED

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BEACH CHANGES AT NAUSET INLET, CAPE COD, MASSACHUSETTS
1670-1981

By

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July, 1982

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ABSTRACT

A historical study of barrier beach and inlet changes for the Nauset Inlet region, Cape Cod, Massachusetts, was performed to document patterns of beach and inlet change as a preliminary to designing and carrying out field studies of inlet sediment transport. 120 historical charts from 1670 and 125 sets of aerial photographs from 1938 formed the basis for this study. Specific aspects of barrier beach and inlet change addressed include onshore barrier beach movement, longshore tidal inlet migration, and longshore sand bypassing past the inlet. In an effort to correlate forcing events with barrier changes, an exhaustive study of the local storm climate was performed. Detailed treatment of the specific mechanisms responsible for Nauset Inlet migration episodes in a direction opposite the dominant littoral drift are treated in a companion paper by Aubrey, Speer, and Ruder (1982). Documentation of the data base available for the Nauset Area is presented herein as appendices.

INTRODUCTION

This document presents the results of an historical survey of barrier beach changes at Nauset Inlet, MA. Onshore barrier movement, tidal inlet migration, and bypassing events are all discussed in this document. Data on which this work was based are presented as several appendices.

Migration of tidal inlets and the associated changes in adjacent barrier beaches have profound implications on both the geological evolution of inlet/estuary systems and the short-term stability of these features. Past studies have documented many instances of inlets migrating in the direction of net littoral drift along sandy shores, but have uncovered few cases (e.g., Indian River, Delaware, and Thorsminde Inlet, Denmark) where inlets appear to migrate in directions opposed to the dominant longshore transport direction (Bruun, 1978). Migration of tidal inlets in a direction opposite to littoral drift increases the incidence of inlet-induced changes in the estuary (specifically filling in the estuary with littoral sands derived from updrift sources, as flood tide delta growth accompanies the migration of the inlet). The freedom to migrate in an updrift direction causes marsh development (colonization and plant emergence) to become more variable and less permanent.

Previous attempts to explain the reversal in direction of inlet migration suggest a change in direction of net littoral drift, causing a change in migration direction. This explanation is not realistic for some inlets where wave forcing and nearshore bathymetry have remained constant through time. This study presents three alternatives to explain the tendency of some inlets to migrate updrift, each supported by historical observations at a site with a large-volume, directionally-biased littoral drift.

STUDY AREA

The study site is located on the Atlantic coast of Cape Cod, Massachusetts (figure 1), exposed to open ocean waves from the east and a two-meter ocean tide. Offshore bathymetry and sediments are described elsewhere (Aubrey, Twichell and Pfirman, 1982). Nearshore sediments are described by Wright (1978) and Wright and Brenninkmeyer (1979). Longshore transport rates and directions were studied by Zeigler (1954, 1960), and net littoral drift has been estimated at 250,000 m^3 per year towards the south (U.S. Army Corps of Engineers, 1969). Sediment is derived from erosion of sea cliffs bordering Nauset Inlet to the north.

Overwash processes along Nauset barrier beaches are described in Zaremba and Leatherman (1982). Aubrey and Speer (1981, 1982) discuss tidal flows and velocity asymmetries in the bay. Other sedimentologic studies of the general area can be found in a summary volume by Leatherman (1981).

Sea level in this area is rising at an average rate of about 3 mm/year (based on tidal data at two nearby stations, Table 1). This rate is three times greater than the mean sea level rise of one mm/year over the past 2100 years established from measurements of salt marsh peat accumulation at Barnstable Harbor, Cape Cod (Redfield and Rubin, 1962). As discussed by Emery (1980) and others, even short-term mean sea level records show considerable oscillations about a mean trend; thus the present increased rate of sea level rise may represent just a short-term oscillation superimposed on the slower 2100 year trend. Sea level rise favors landward migration of developing barrier beaches.

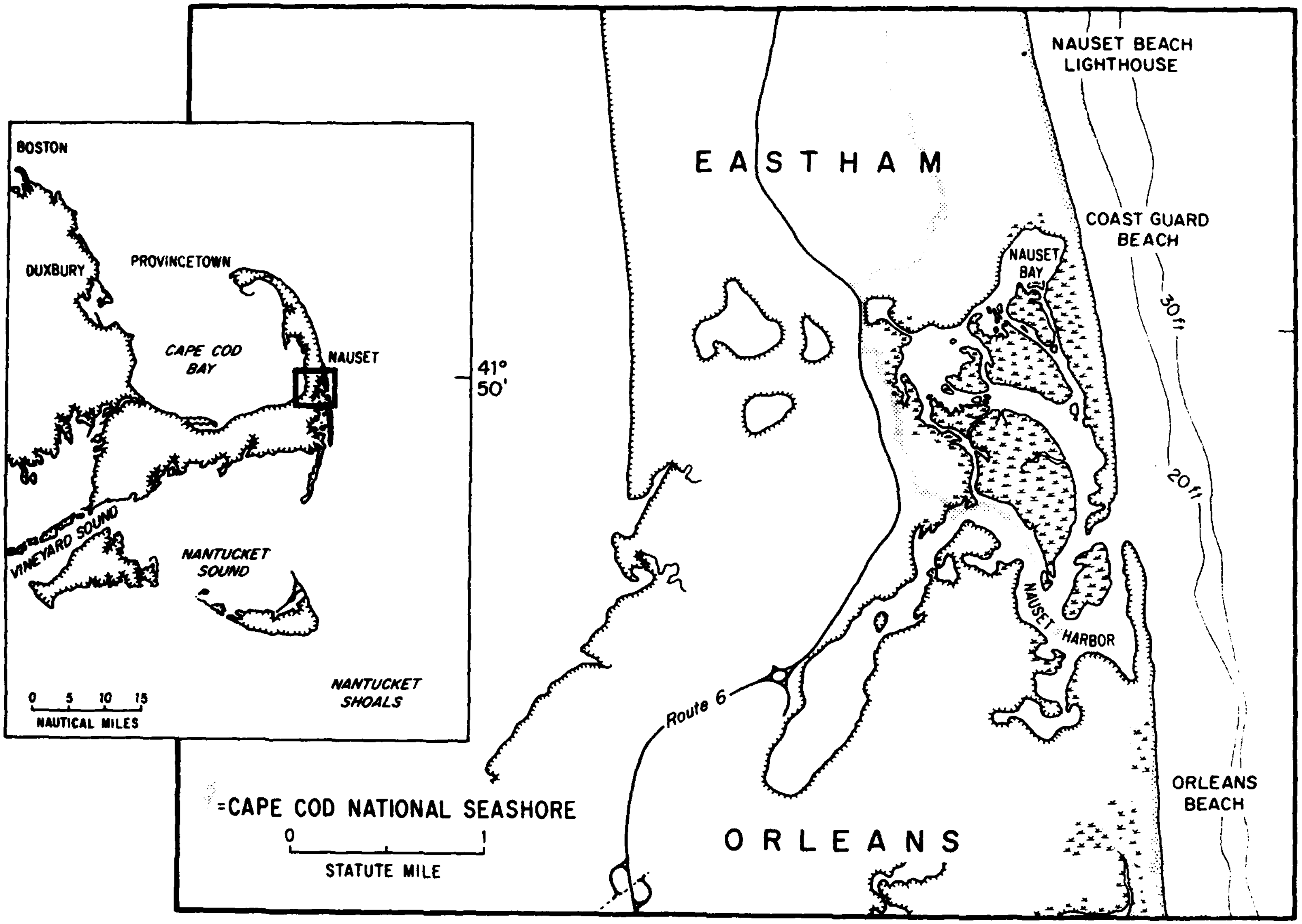


Figure 1. Location map for study area.

TABLE 1

REGRESSION ESTIMATES OF

SEA LEVEL RISE

Station	Length of Record	Mean Rate of Sea Level Rise	Coefficient · Determinati (R^2)
Woods Hole, MA	43 Years	3.3 mm/year	0.79
Boston, MA	54 Years	3.8 mm/year	0.76

METHODS

Historical charts and aerial photographs of the Nauset Inlet area dating from 1670 and 1938, respectively, were examined to define and (where possible) quantify changes in inlet and shoreline position and morphology. Historical data (figure 2) were obtained from a variety of sources including government agencies, the National Archives, the Library of Congress, the Woods Hole Oceanographic Institution, and private industry (Apendices 1 and 2). Chart coverage is dense from 1790 to present (coverage was sparse before 1790), and good aerial photographic coverage exists from 1951 to present (only one aerial photo sequence was available prior to 1951, taken in 1938).

Small scale and uncertain mapping techniques used in pre-1846 historical charts make it difficult to quantify changes in inlet morphology during this period, but these charts are valuable in depicting general trends in inlet morphology. Care was required in interpreting the charts because several of the charts from the 1800's did not specify survey dates, and are merely reproductions of earlier and perhaps outdated surveys. Also, in the case of U.S. Coast and Geodetic Survey (USCaGS) charts, only limited shoreline segments were updated between editions.

Aerial photographs provide more detailed information than the charts because they are generally larger in scale (allowing resolution of shoreline features such as bars and marshes). They also provide more comprehensive temporal coverage for a limited period (1951 to 1981) than do the charts, and the dates of coverage are unambiguous. Fifty vertical sets of the 125 photographs available were measured to quantify inlet and spit migration at Nauset. The remaining photographs were not measured because they were taken

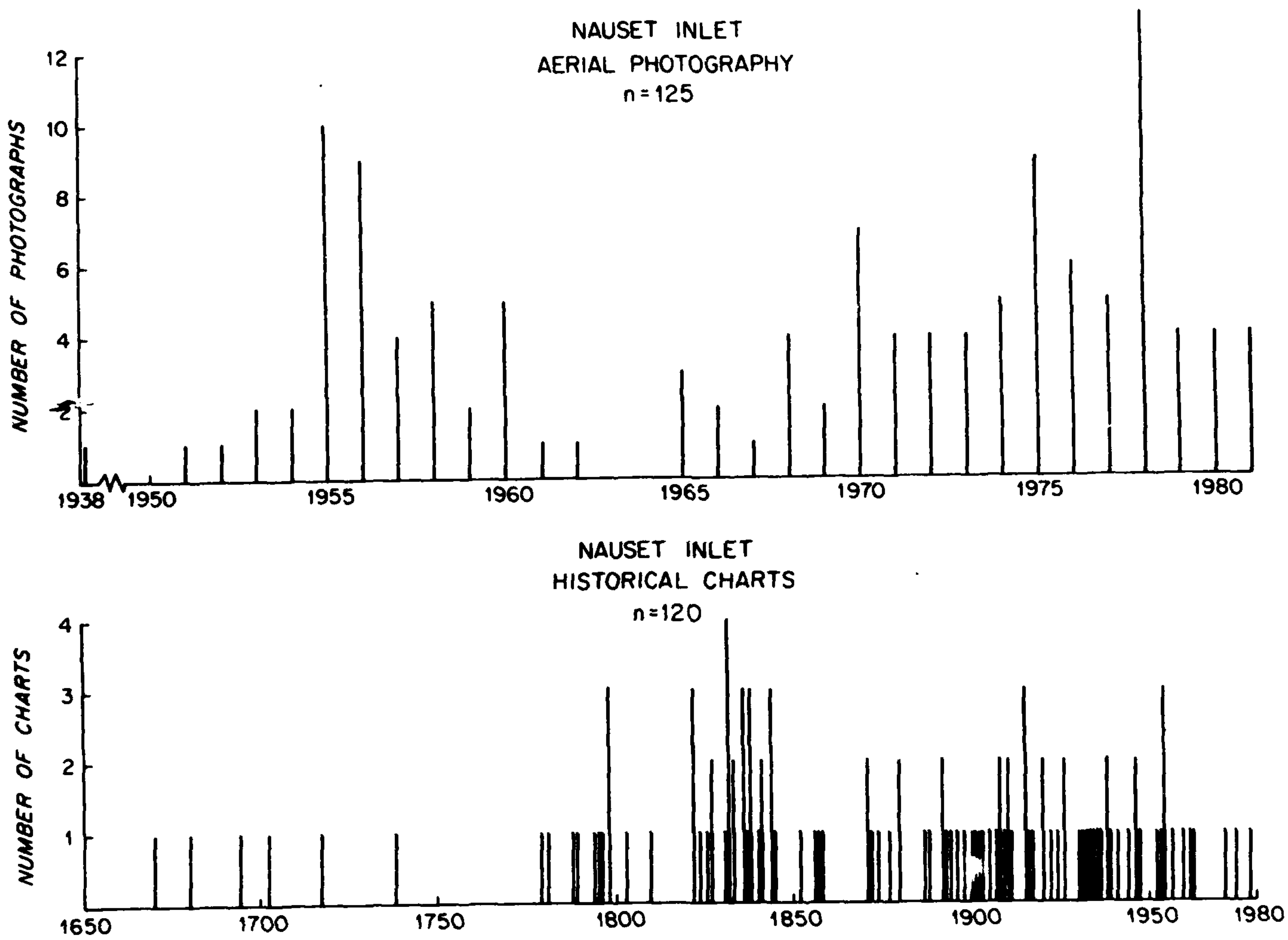


Figure 2. Summary of Nauset Inlet aerial photography (125 sets since 1938) and historical charts (120 sets since 1670).

at oblique angles, were poorly fitted mosaic series, or lacked sufficient ground control to assure measurement accuracy. They were, however, instrumental in providing a continuous record of relative changes in inlet and spit locations during the past 30 years.

Measurements of shoreline, spit and inlet location are relative to a baseline, sub-parallel to the shoreline, established between well-defined, permanent features identified on each set of aerial photographs (Figure 3). The known length of this baseline provided a consistent determination of scale for all photos. Shoreline was measured at each of ten evenly-spaced stations between the reference points. Shoreline location was defined as the perpendicular distance from the baseline station to the waterline. Measurement to the high tide line would be preferred, but variations in photo resolution, due to differing degrees of exposure, environmental conditions and photographic equipment, make accurate and consistent location of the high tide line impossible. Estimates of tidal stage for each photo (based on observations of exposure of marshes, offshore bars and tidal deltas) were incorporated into the measurements of shoreline and inlet location. The majority of photographs were taken at or near low water, presumably to allow for better resolution of intertidal features.

Additional uncertainty in some measurements results when one of the two primary reference points is absent from the particular photo mosaic. In these cases, secondary landmarks are used along with geometrical relations to define the baseline from the one available endpoint. As a result of such variations in the photographs, overall accuracy of measurements is estimated to be ± 15 m, despite a measurement resolution of 5 m.

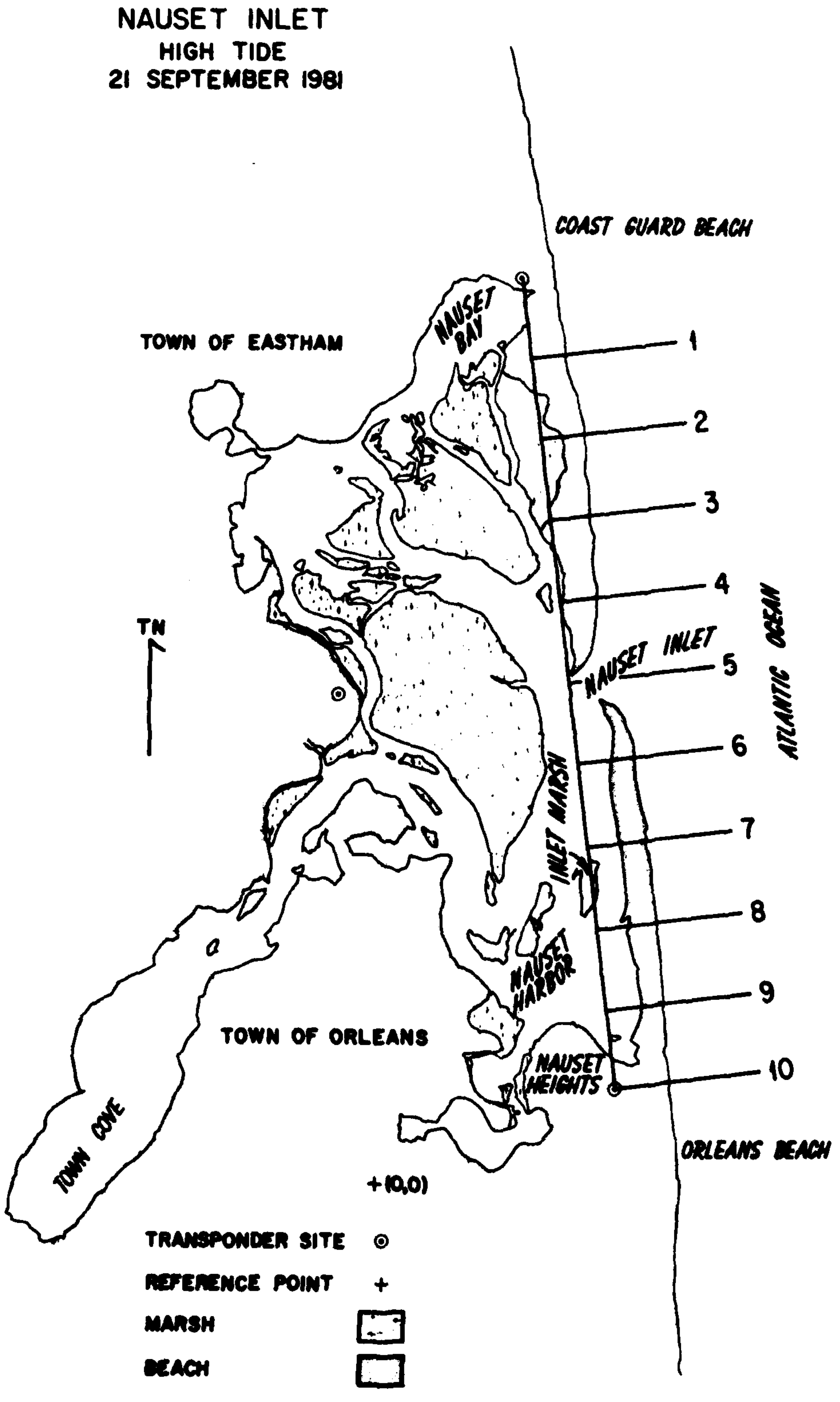


Figure 3. Station locations and baseline reference points for the Nauset Inlet study area.

No allowances or corrections were made for seasonal variations in beach profiles and sea level, which can alias a high-frequency variation into lower-frequency trends. Measurements of seasonal mean sea level (MSL) intercept migrations along this beach show an average winter shoreward displacement of about 30 m compared to the summer position (Miller and Aubrey, 1982). This is partly balanced by an estimated 30 cm steric sea level drop in the winter (Emery and Uchupi, 1972). Neglecting profile readjustment, a 30 cm vertical change translates to a 7 m horizontal seasonal change in MSL-intercept, with a seaward motion in the winter.

RESULTS

Analysis of historical charts and photographs reveals patterns of inlet migration and barrier beach elongation/shortening at Nauset. Two specific problems were addressed in the historical analysis: inlet migration with accompanying barrier beach changes and onshore/offshore barrier beach migration. The analysis has also provided insight into patterns for bypassing longshore sediment transport past a tidal inlet. Finally, the storm climate at Cape Cod was compiled for correlation with major inlet migration episodes.

LONGSHORE INLET/BARRIER BEACH MIGRATION

Historical charts (dating from 1779) and aerial photography (dating from 1938) show the preferred inlet location to have been just north of Nauset Heights, at the southern (downdrift) extremity of the bay drainage system. Subject to limitations imposed by sparse historical coverage (figure 2), the charts indicate that prior to the 1950's Nauset Inlet consistently has been immediately north of Nauset Heights (figure 4). No charts examined to 1946 reveal a significant south spit. Previous episodes of inlet migration may be undersampled by aperiodic historical coverage. The persistence of the southern location, however, suggests this is an historically stable inlet configuration.

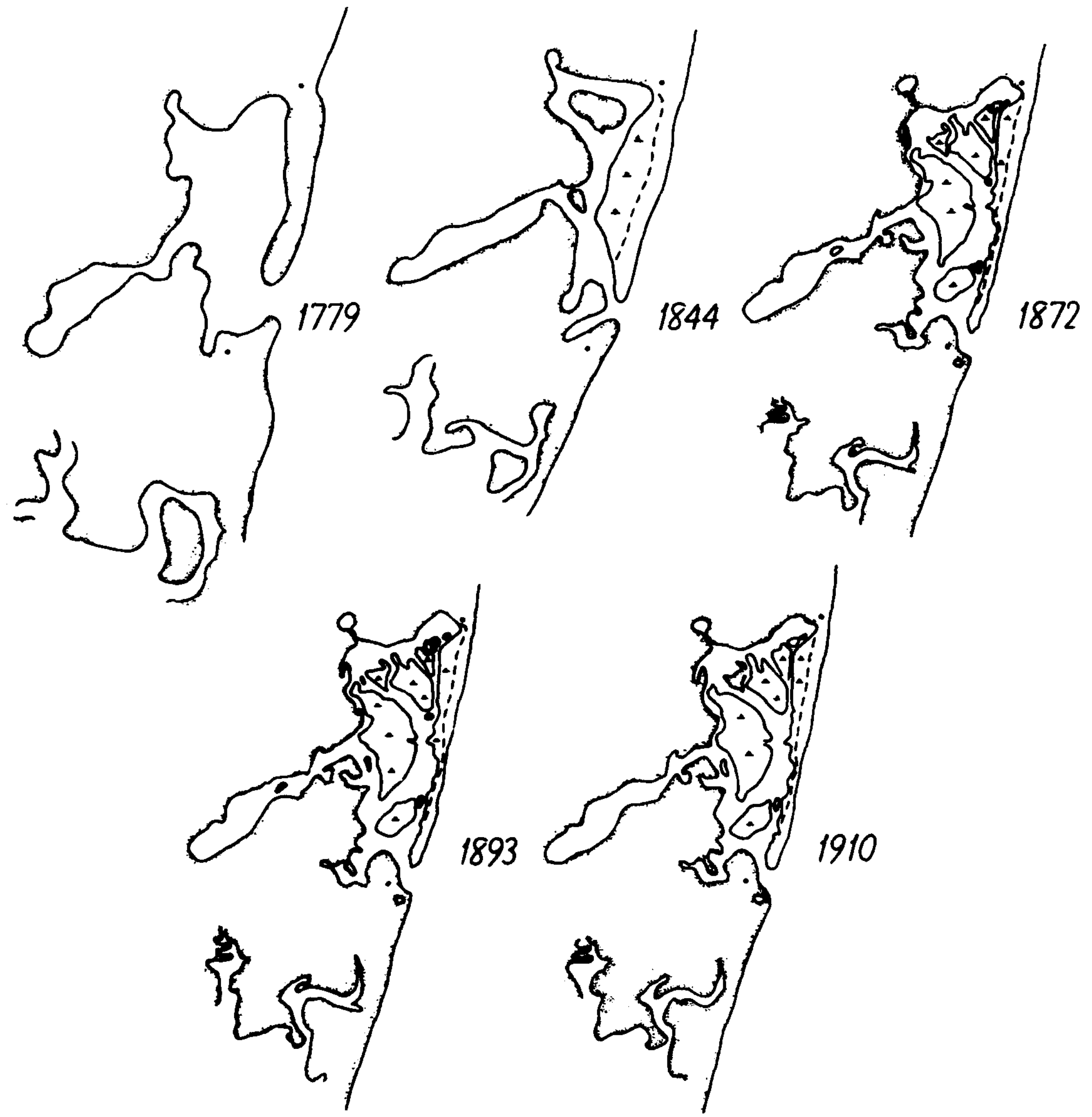


Figure 4. Five representative historical charts depicting variability of Nauset Inlet from 1779-1910.

Two peculiar features depicted in the earliest charts are missing in later charts: a channel connecting Pleasant Bay to Nauset Harbor, and multiple inlets in the north barrier beach. Pleasant Bay is a bay to the south of Nauset which drains into Nantucket Sound and the Atlantic Ocean. The 1779 Des Barres chart is the first showing the Pleasant Bay channel. Charts from 1781, 1795, 1798 and 1810 (Appendix 4) also show this channel. It apparently filled in between 1810 and 1832. Vestiges exist today as a marshy region and a small pond west of Orleans Beach below Nauset Heights. If deep enough, the connection to the large drainage system of Pleasant Bay may have had significant impact on inlet stability. Three charts (1779, 1781, 1795) show three openings in the north barrier beach. It is not clear whether these openings were semi-permanent inlets or simply large overwashes through the dune line. Aside from temporary and very shallow storm breaches, no other instances of multiple inlets have been noted.

A 1938 aerial photograph places the inlet just north of Nauset Heights, with no south barrier apparent (figures 5, 6a). No photographs exist for the 1940's; however, a 1946 U.S.G.S. chart shows the inlet still in this location (figure 6b). From the 1950's into the early 1980's, the inlet has been very active, with several cycles of migration culminating in a recent steady, northward movement.

Between 1946 and October 1951, the southern spit lengthened 800 m north from the headlands at Nauset Heights. This growth was most likely the result of a storm breaching the north spit (figure 6c). The northern spit eroded 690 m over this same period. In 1952, a breach developed on the north spit, shortening it by approximately 420 m. A marshy island (Inlet Marsh; figures 3, 6a), formerly located behind the north spit, was exposed to the ocean (figure 6d). During this period, the south spit remained in the same

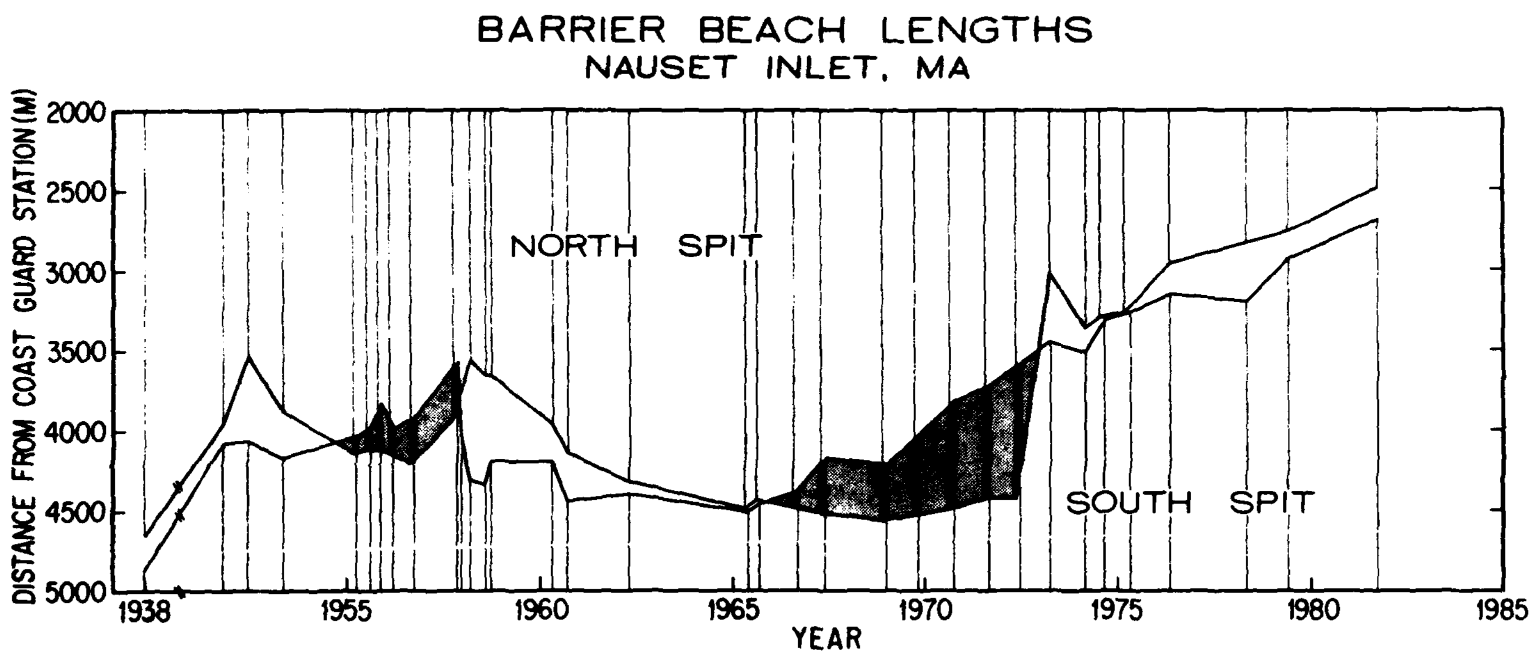


Figure 5. Barrier beach lengths, Nauset Inlet, MA.

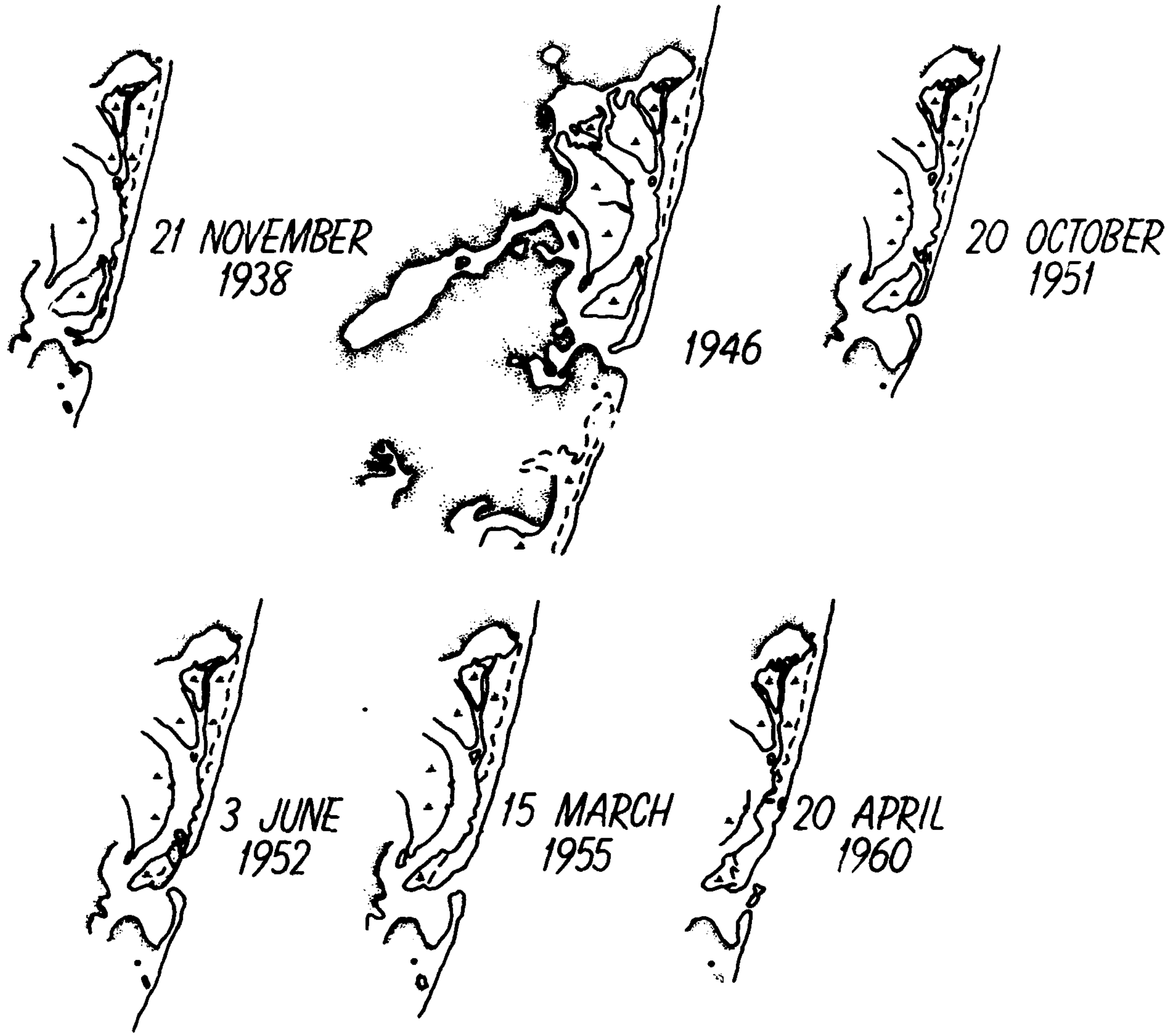


Figure 6. Tracings of vertical aerial photographs of Nauset Inlet between 1938 and 1960.

location, as did the main inlet channel. From 1952 to 1957, the north spit grew southward and attached itself to the bay island (Inlet Marsh), as longshore transport closed a shallow channel which had separated the barrier and the northern part of the island (figures 5, 6e). The resultant beach (known as Eastham Beach) lengthened approximately 700 m. Simultaneously, the south spit resumed a pattern of northward migration, lengthening by 500 m. A pattern of overlapping spits emerged (figure 5). In December 1957, major inlet migration occurred when the south spit was breached approximately on-third of the way from its northern tip. Over the next year, the main inlet channel stabilized at this breach, while the northern remnant of the south spit disappeared (probably moving onshore to the bay island and alongshore to the south), shortening the barrier by 780 m (figure 5). The north spit also was shortened by 300 m during this period as a shallow channel separated Inlet Marsh from the north barrier.

Between 1958 and 1960, the south spit grew north, and the north spit reattached itself to Inlet Marsh, lengthening by 500 m (figure 5). In early spring 1960, the south spit was breached again while the north spit remained intact (figure 6f). The detached remnant of the spit disappeared, leaving the south spit approximately 300 m shorter (figure 5).

From September 1960 to 1965, little change took place in the south spit, although this lack of variability may be due to poor temporal coverage. The north spit lengthened 300 m during this period (figures 5, 7a). By April 1965, the inlet/barrier beach configuration was similar to that in 1938. The major difference is landward migration of the north spit due to repeated overwashes (Zaremba and Leatherman, 1982), which caused attachment of the north spit to the marsh island (Inlet Marsh), originally separated by a narrow channel. From

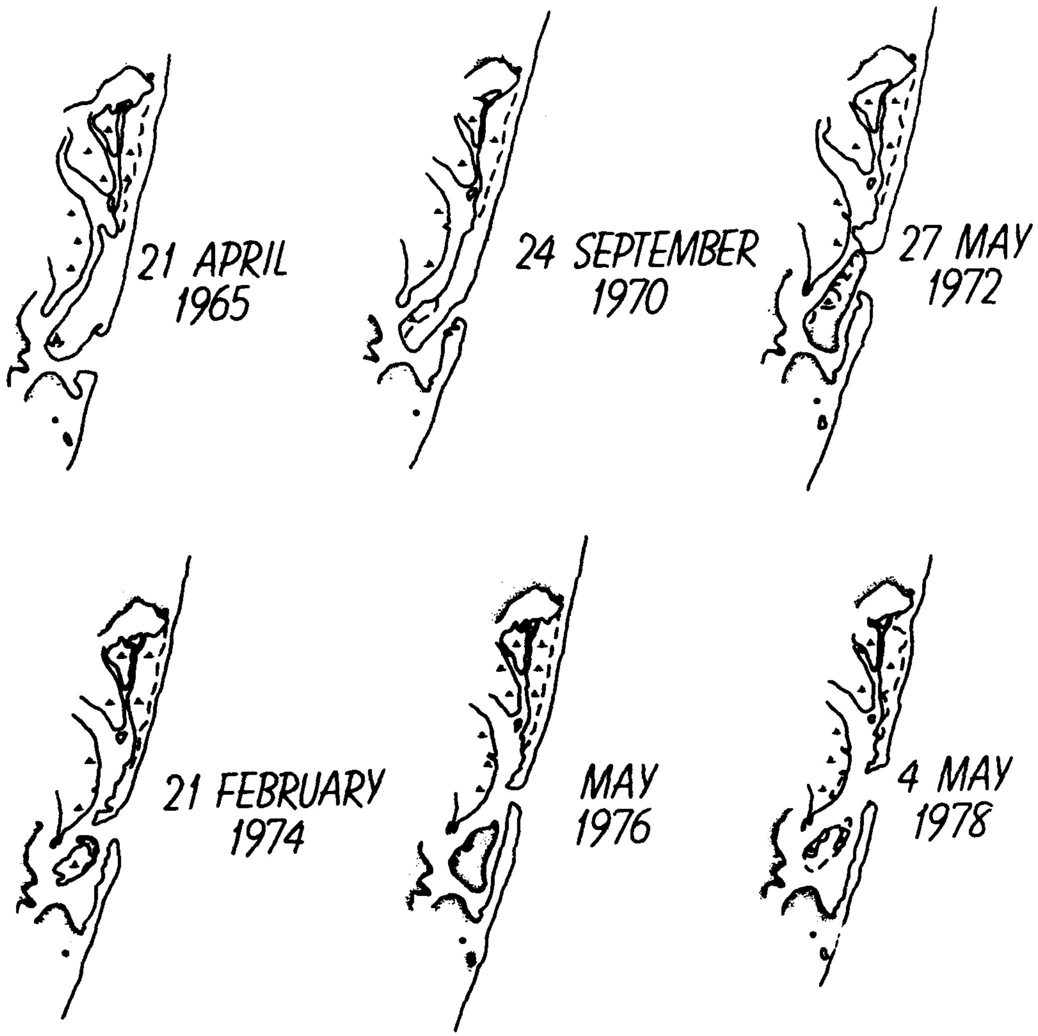


Figure 7. Tracings of vertical aerial photographs of Nauset Inlet between 1965 and 1978.

1965 to 1972, the pattern of barrier overlap observed in the 1950's again repeated. The south spit grew nearly 900 m during this period, while the north spit remained approximately the same length (figures 5, 7b). The main inlet channel, while maintaining its base at the 1965 position, consequently lengthened 900 m to the north.

In the spring of 1972, a significant change occurred in the inlet/barrier beach configuration. An overwash developed in the north spit at a location where temporary breaches previously had occurred (just north of Inlet Marsh, figure 7c). In this instance, the south spit remained intact. A new inlet location stabilized by March 1973 at the overwash, causing a 1.4 km shortening of the north spit. Inlet Marsh, which had been attached to the tip of the north spit, broke up, and parts of it rapidly disappeared. By this point, the inlet/barrier beach system had stabilized to the general configuration it has today. Between 1973 and February 1974, the north spit temporarily lengthened by attachment to a remnant of the beach separated by the 1972 overwash event (figures 5, 7d). Since this time, the inlet has migrated north at a rate of approximately 100 m/yr, with elongation of the south spit and shortening of the north (figures 5, 7e, f). No major breaches affecting the stability of the south have developed in the period 1973-1980, so northward inlet migration has continued. A large overwash occurred at the northernmost part of the north spit during the 6 February 1978 blizzard. Since the overwash emptied into a shallow (< 1 m deep) bay (Nauset Bay), it did not evolve into a permanent breach. Such an overwash occurring on the south spit would probably result in a new inlet location.

ONSHORE BARRIER BEACH MIGRATION

Changes in shoreline position at ten stations spaced at equal intervals of 535 m along the photographic baseline (figure 3) were documented by analysis of vertical photographs. The analysis shows onshore spit migration to be highly variable in both location and time (figure 8). For the purposes of discussion, the stations are divided into three groups: station 1-5, all on the north spit; stations 6-8, in areas of inlet migration; and stations 9 and 10, south of the inlet.

Stations 1-4 show a coherent picture of shoreline changes over time. All four show a seaward movement of the barrier during the period 1951-1953, followed by a relatively stable position up to 1956. The magnitude of the growth from 1951 to 1953 ranged from 50 m at station 1 to approximately 100 m at station 4. At station 4, a further 50 m seaward migration occurred through December 1957. A similar seaward growth at stations 1-3 is suspected though there were problems making accurate measurements for these stations. This pattern of migration may be partly explained by seasonal differences in mean water level. A landward migration of the shoreline took place at the four stations from 1958 to 1962. The retreat was approximately 100 m at station 4 and as much as 190 m at station 1. The period 1962 to 1972 showed little net change in shoreline position. Since 1972, shoreline position has retreated landwards from 40 m to 80 m at these stations, especially noticable at stations 1, 3, and 4 (Table 2). Excursions of the shoreline both seaward and landward on the order of 40-50 m occur during this period and, in the case of station 2, obscure any trend in the 1970's. For most of this time period, station 5 shows similar trends to stations 1-4. Seaward migration from 1951 to 1953 of 75 m was followed by a stable period until March 1955. The shoreline then retreated landward (with oscillations) 130 m up to March 1962. From

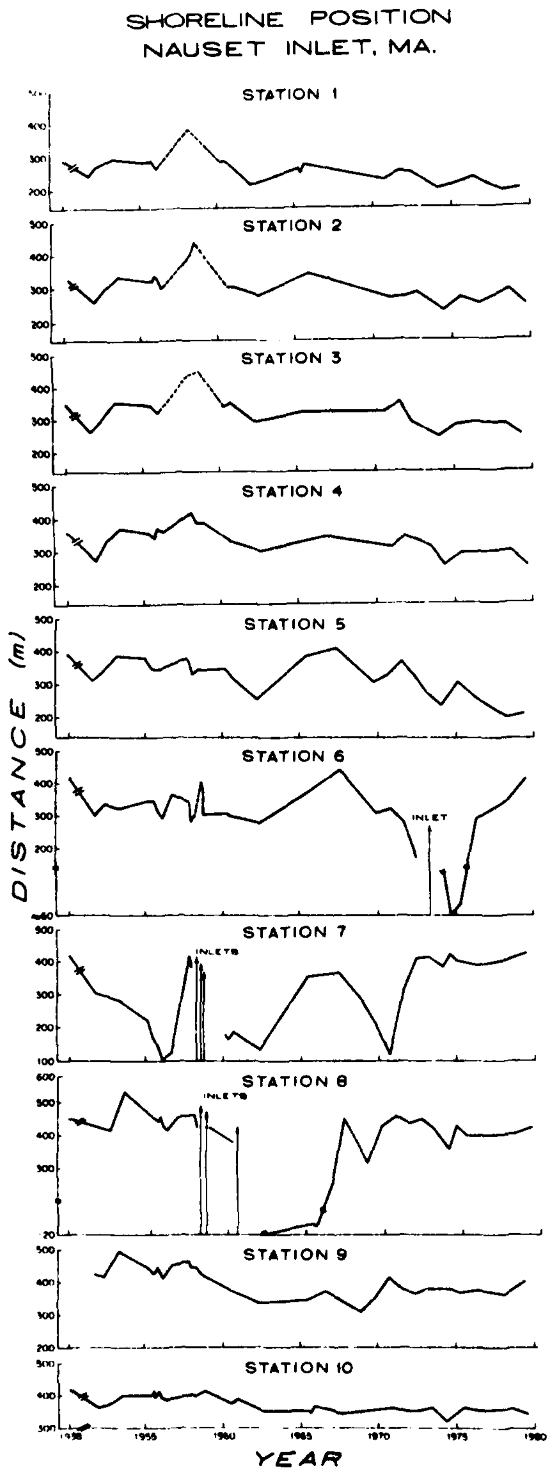


Figure 8. Shoreline position, Nauset Inlet, MA.

TABLE 2

REGRESSION ESTIMATES OF SHORELINE POSITION

STATION	SLOPE (m/year)	INTERCEPT (m)	R^2
1	-2.5	412	0.61
2	-1.7	405	0.25
3	-1.7	416	0.28
4	-2.3	480	0.35
5	-3.6	553	0.42
6	-5.3	624	0.18
7	-4.7	457	0.15
8	-2.0	504	0.02
9	-3.3	605	0.42
10	-2.0	502	0.57

1962 to 1967, the shoreline moved seaward 160 m. The period 1967 to May 1979 has seen a shoreline retreat of approximately 240 m--a rate of nearly 20 m/yr. Again, large excursions of the shoreline (~75 m) over shorter time scales are superimposed on this general trend.

Stations 6-8 (especially 7 and 8) show a complicated picture of onshore/offshore spit migration since they are in the region of active inlet movement. This is particularly true until the period following 1972. Stations 7 and 8 have been on the south spit in the period 1973-1982 and shoreline position has been stable. Station 6 has displayed a trend of seaward migration in shoreline since 1975, amounting to approximately 400 m. The large changes in shoreline position for all these stations may be attributed to rapid beach erosion or accretion of sand bars during periods of inlet migration.

Stations 9 and 10 are the southernmost lines measured. In 1938 station 9 was located in the inlet, but it has been part of the south spit since the early 1950's. Station 10 is located south along Nauset Heights and has not been directly affected by episodes of inlet migration. A general onshore migration of the south spit occurred at station 9 from 1953 to 1968, with a net shoreline displacement of 190 m, followed by a seaward migration of approximately 105 m from 1968 to 1971. Since 1972, no real trend in onshore/offshore migration has been observed at this station. Little net change in shoreline position occurred at station 10 during this study. In the 1950's, the shoreline was essentially stable. From 1958 to 1962, it retreated landward approximately 50 m. Since 1962, it has shown no strong tendency for either onshore or offshore migration.

STORM ANALYSIS

The Atlantic shore of Cape Cod is frequently buffeted by storms which have the potential to cause dramatic changes in shoreline configuration. A U.S. Army Corps of Engineers report (1979) cites 160 gales with wind speeds greater than 32 mph between 1870-1975. Half of these were northeasters. Both tropical and extra-tropical (including northeasters) cyclones produce dramatic changes at Nauset Inlet because of the geographical orientation of the outer Cape.

Three types of storm data were collected for comparison with large-scale morphologic changes at Nauset (documented by aerial photos):

a) Hayden and Smith (1982) compiled a monthly list of cyclone occurrences off the east coast between 1885 and 1982, using as a data base the "Tracks of the Centers of Cyclones at Sea Level" published by Monthly Weather Review and in recent years by Mariners Weather Log. Cyclone statistics (both tropical and extra-tropical) are available on 2.5° latitude by 5° longitude grid cells. The four grid cells bordering the Cape Cod region to the east and southeast (total area covered is 60°W to 70°W, 37 1/2°N to 42 1/2°N) are used as the region of storm influence for the study area. For generation of year-by-year and monthly mean statistics, storm values for the four grid cells are summed. Although this yields an overestimate of the number of storms (the same storm may pass more than one grid cell), it will still provide a qualitative indication of storm duration and persistence, since on the average a storm tracking through two grid cells generates waves in the study area for a longer period of time than one passing a single grid cell.

Cyclone statistics resulting from the averaging serve as a crude indicator of wave activity. Large cyclone counts suggest high wave activity; a small cyclone count represents low wave activity. Persistence and frequency of storms are our criteria for wave intensity. Clearly storm intensity or magnitude would be a useful weighting factor for linking waves and storms; unfortunately, this information is not available.

Monthly mean storm frequency over the 96 year period (Figure 9) shows the expected result that storm incidence is highest in the winter (Jan., Feb. and March) and lowest in the late spring and summer (June through September). These data can also be combined to yield annual number of storms since 1885 (Figure 10). The period from 1885 through 1949 experienced a relatively low incidence of storm activity. Within this low background level, the periods from 1885-1893, 1921-1924, and 1930-1941 have local maxima in cyclone frequency. The last thirty years of the record show consistently higher cyclone frequency, with local maxima at 1950-1954, 1961-1962, 1972 and 1974. Although the absolute number of storms may be sensitive to the quality and quantity of weather observation stations, local trends (minima and maxima) are valid indicators of relative storm occurrence.

b) Another source of storm incidence data was the U.S. Army Waterways Experiment Station (WES) wave hindcast program (data provided by W. Birkemeier). This program computes nearshore wave height statistics based on weather observations and local bathymetry. The study identified the 157 largest storm events from 1956 to 1976 (inclusive). These storms were assigned recurrence intervals according to their rankings, allowing for weighting of storms by severity. The WES compilation (Figures 11 and 12) correlates well with cyclone data. Relative seasonal values are similar, but the difference between summer and winter storm activity is much greater in the W.E.S. modeling than in the cyclone

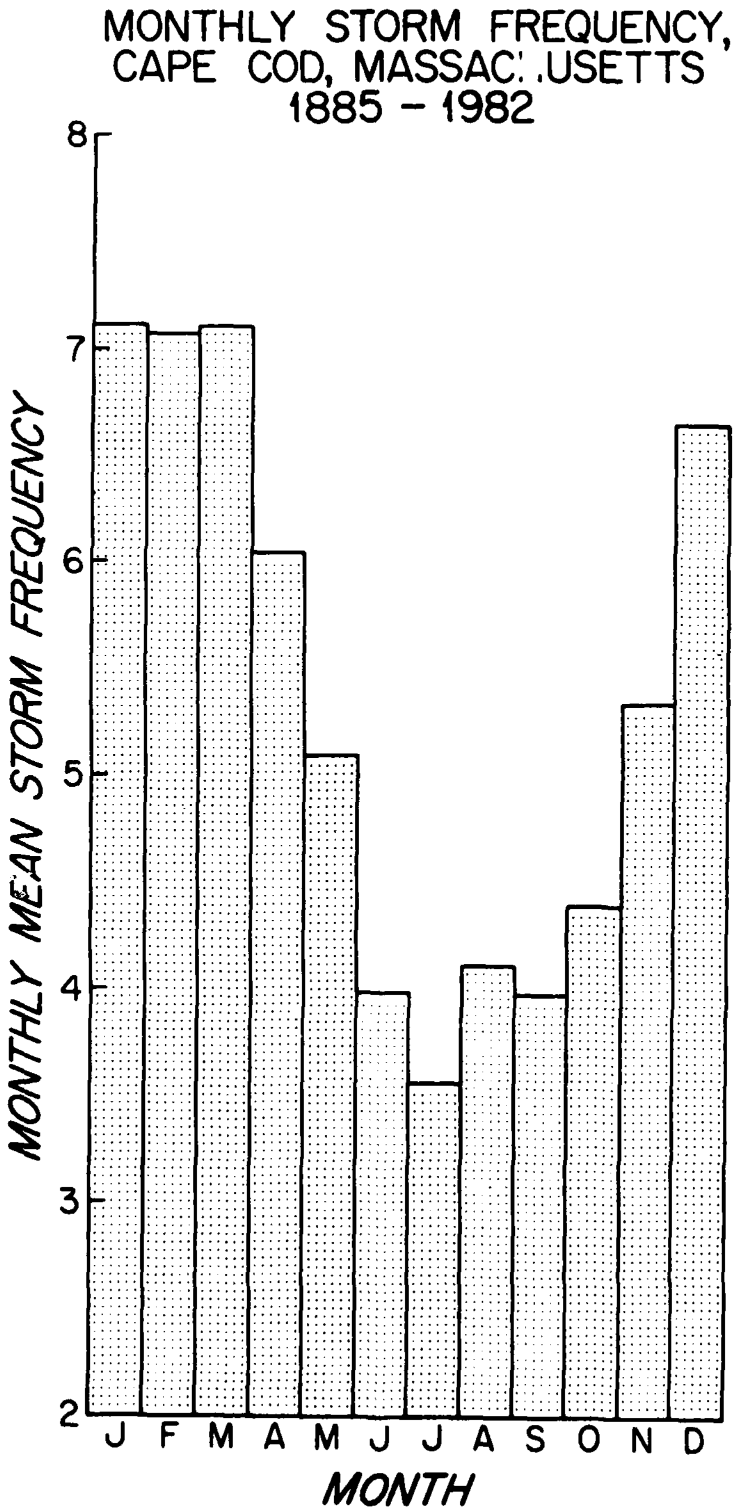


Figure 9. Mean monthly cyclone frequency off Cape Cod, Massachusetts (including area 60°W to 70°W, 37½°N to 42½°N), from Hayden and Smith (1982).

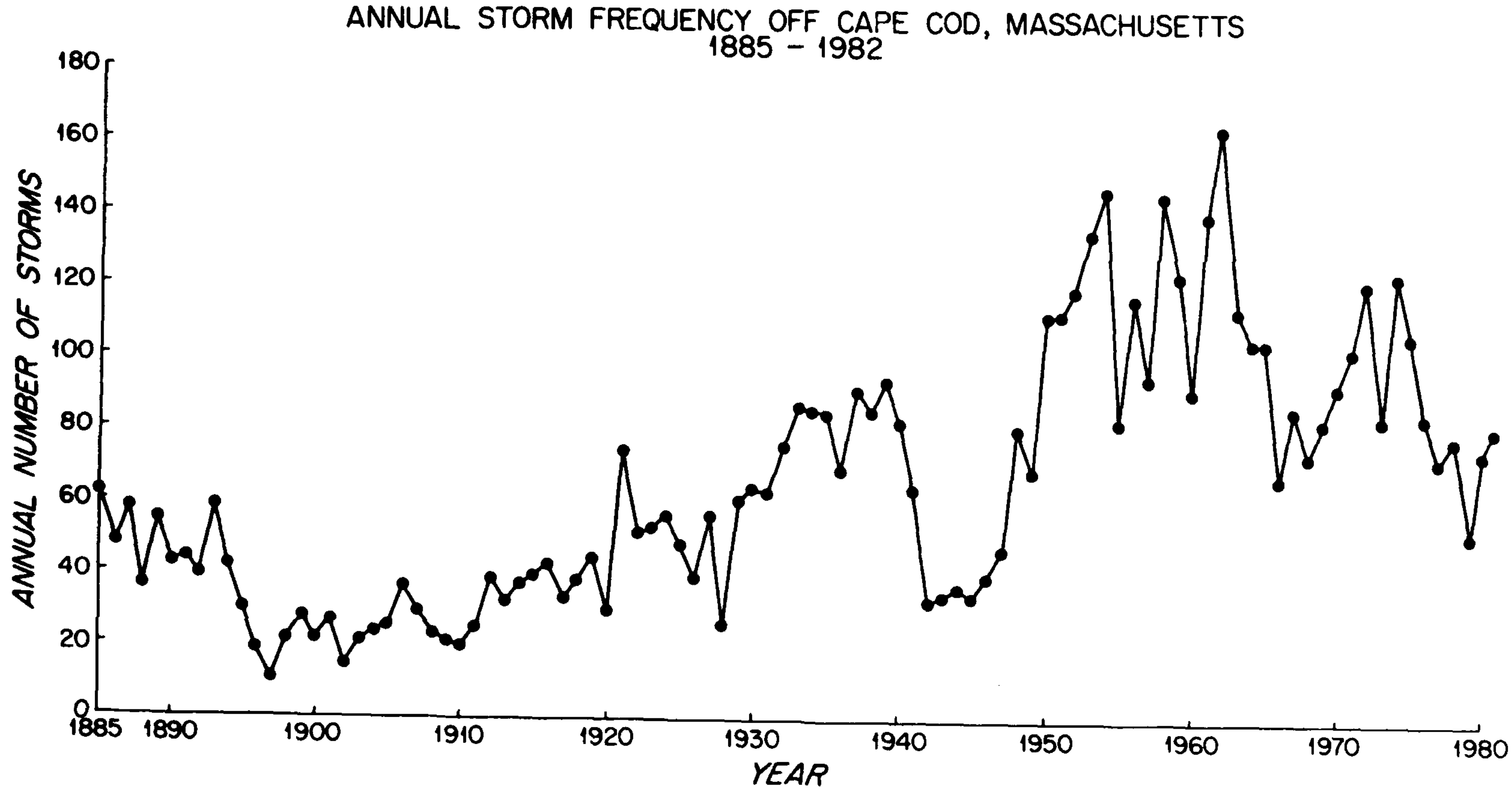


Figure 10. Number of cyclones affecting Cape Cod, Massachusetts (including area 60°W to 70°W, 37½°N to 42½°N) from 1885 to 1981. Storm count is indicative of storm duration, and not individual cyclone events. Data derived from Hayden and Smith (1982).

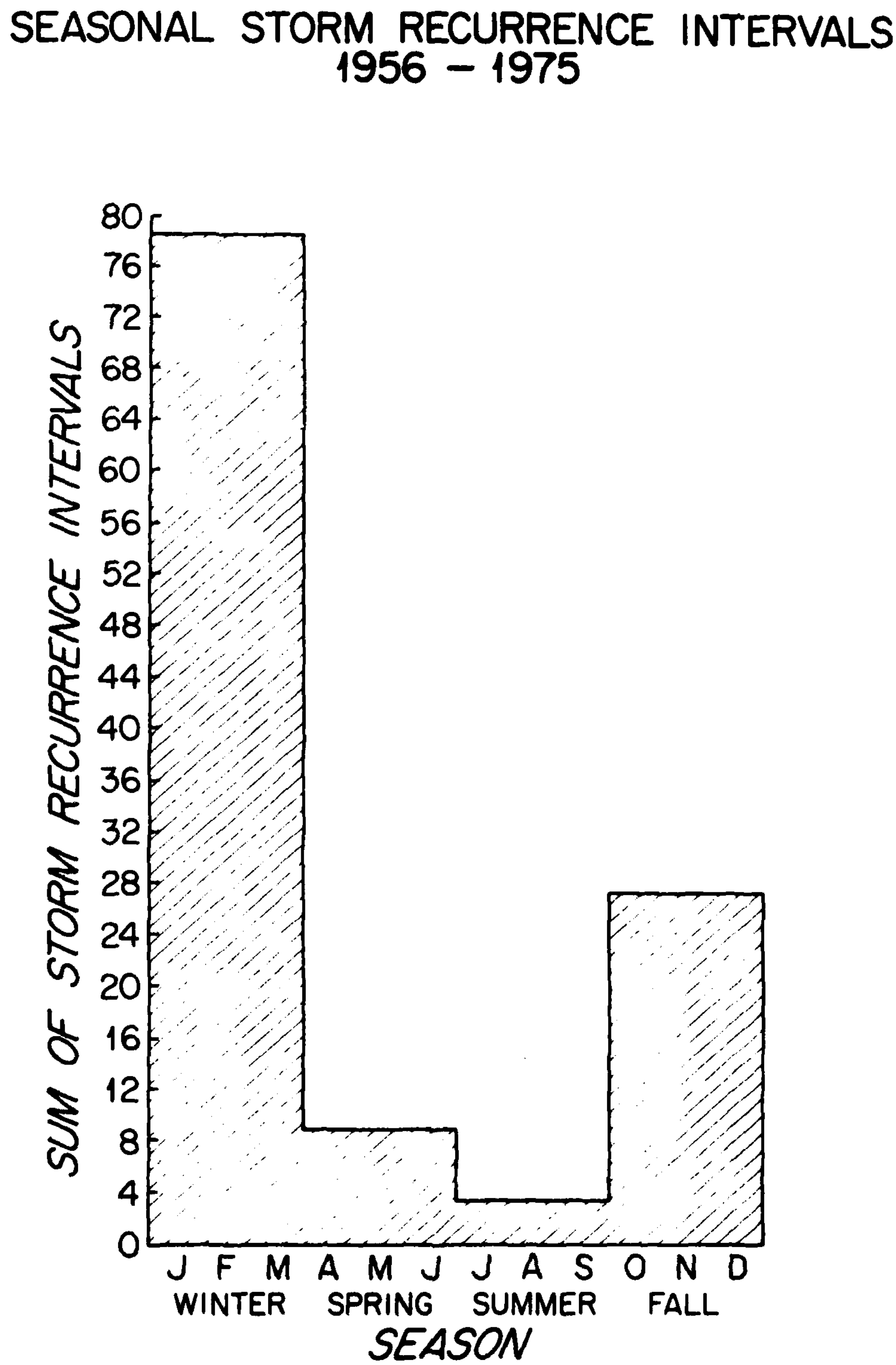


Figure 11. Seasonal storm activity as indicated by storm recurrence intervals for period 1956-1975. Data from W.E.S. compilation.

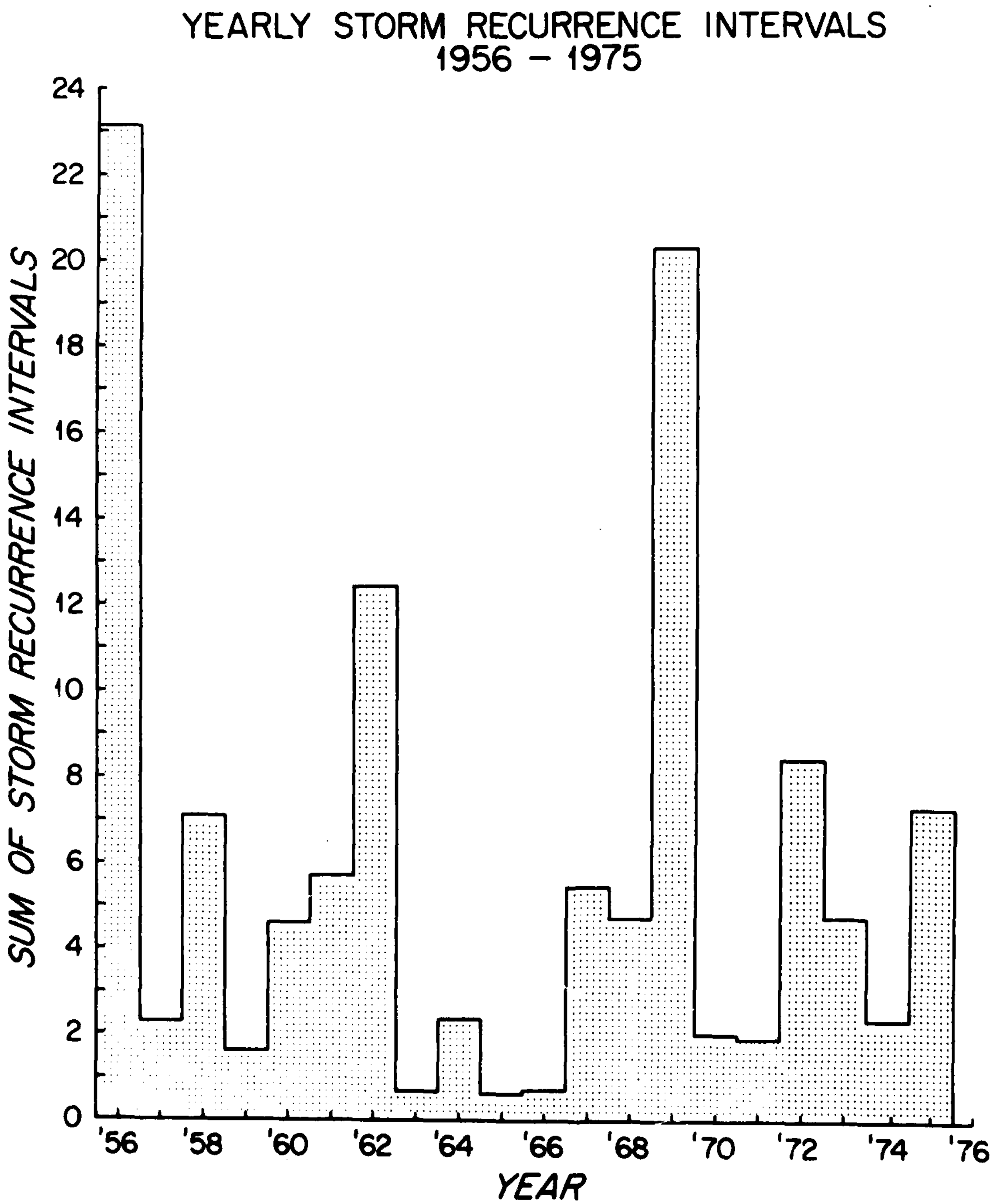


Figure 12. Yearly storm activity from 1956-1976 off Cape Cod, Massachusetts, determined by W.E.S. hindcast.

statistics. W.E.S. data show high storm activity in 1956, 1962, and 1972; however, it also indicates a high level of storm activity in 1969 which does not appear in cyclone data. Differences between the two data sets are the result both of weighting procedures and different representations of the data base.

c) Finally, a list of major storms affecting the outer Cape was compiled from newspapers, historical descriptions, and published tropical storm tracks (Figure 13). This list is incomplete since prior to 1948 it only includes hurricanes and storms of historical significance. It is possible to identify specific storms which are likely to cause changes at Nauset Inlet, although irregular sampling afforded by aerial photography (figure 2) makes direct correlation difficult. Through this method, ten significant storms were found that were not hindcast in the WES study.

The importance of storm activity to major changes in inlet/barrier beach configuration is illustrated by comparison of inlet migration with storm frequency. Historical data (figures 10, 12, 13) show three periods of high storm activity since 1933, preceded by a 48 year period of relative quiescence. The first period of intense activity lasted from 1933 until 1939. Unfortunately, inadequate chart or photo coverage prevents documentation of the response to this stormy period. The second period of high storm activity couvered the years 1950 to 1962. Large scale inlet migration, together with overwash and breaching of the barrier beaches, occurred during this time. Breaches developed through the north barrier during May 1953 and January 1956, and through the south barrier during December 1957 and early spring 1960. Storm-induced changes in barrier beach length of as much as 780 m have been noted. A third period of intense storm activity existed in the early 1970's. One of the peak years, 1972, coincides with a breach in the north spit, which initiated the current phase of steady northward inlet migration.

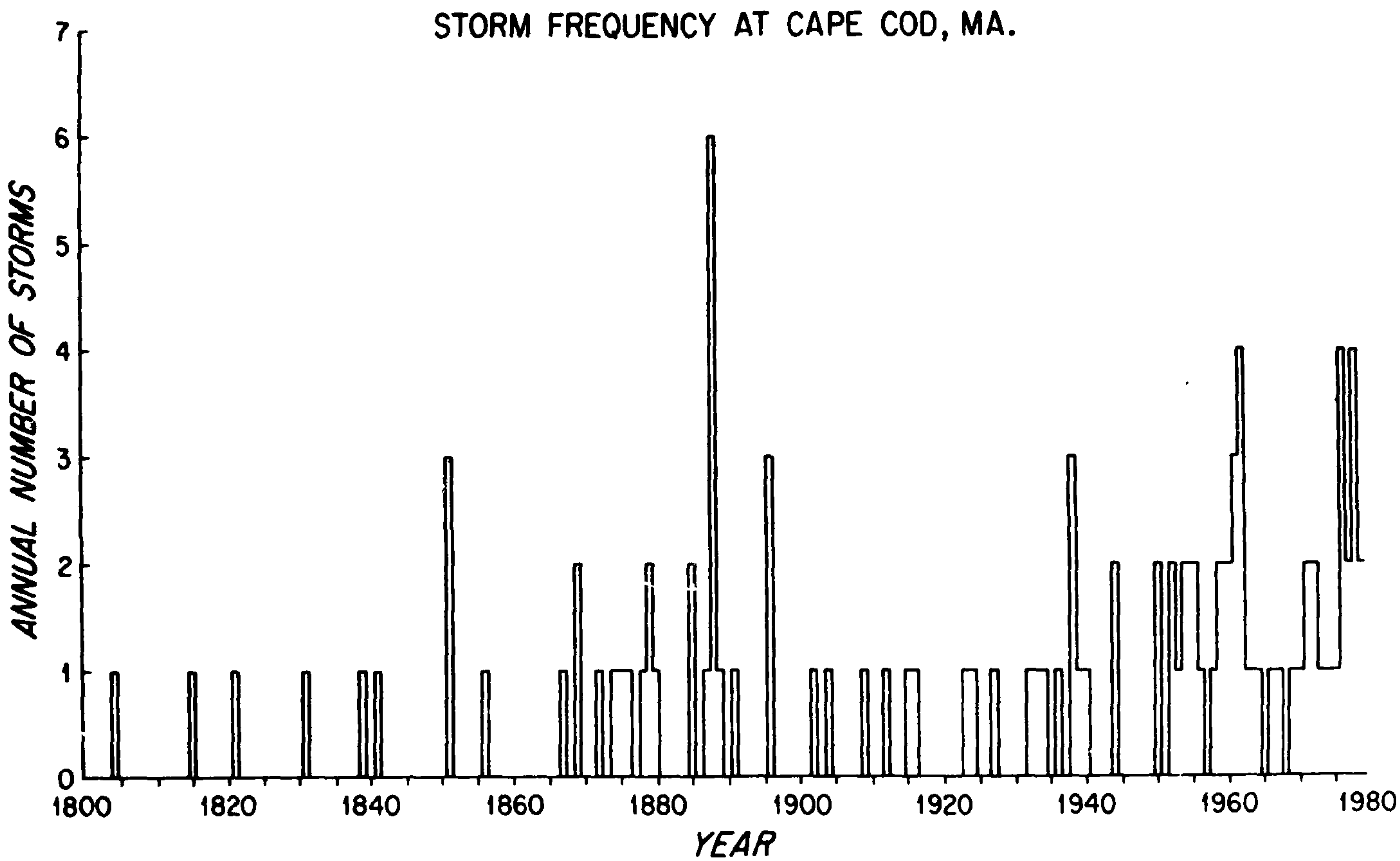


Figure 13. Compilation of storm events on an annual basis from 1800 through 1980. Sources are newspapers, historical descriptions, and published tropical storm tracks.

BAR BYPASSING OF LONGSHORE SEDIMENT TRANSPORT

A question of central importance to tidal inlet stability is the means by which longshore sediment transport bypasses the inlet. The volume rate of longshore transport and the tidal prism are two primary indicators of inlet stability (e.g., Brunn and Gerritsen, 1959; Brunn, 1978). Large net longshore transport rates, estimated to be about 250,000 m^3/yr to the south (U.S. Army Corps of Engineers, 1969), occur in this area. Consequently, shallow overwashes typically are filled quickly, and the tidal prism seems capable of supporting only a single stable inlet. The relative proportions of sediment trapped in the inlet/estuary and bypassed to the south are not known. Two mechanisms for sediment bypassing at inlets have been identified (Brunn, 1978):

a. Bar Bypassing - Sand moves alongshore on the ebb tide delta, from the updrift barrier to the downdrift barrier, driven by a combination of wave and current action.

b. Tidal Bypassing - Sand enters the estuary on the flood tide and exits on the ebb, with a net downdrift bias. Both mechanisms invoke some unknown mechanism for sediment to escape the refractive influence of the ebb tide delta.

Bar bypassing has been documented several times at Nauset Inlet, increasing the length of the southern (downdrift) barrier. Three series of photographs in the mid-1950's demonstrate the existence of a bar bypassing mechanism at Nauset. The photographs show the motion of distal ebb delta bars around the perimeter of the delta and in two cases, attachment of a bar to the south spit.

The first series consists of four photographs taken during summer 1955 on May 2, June 15, July 14 and August 20 (figure 14). The motion of two bars on the ebb delta was measured. One bar was north of the main inlet channel and the other was south of the channel. The northern bar moved 150 m southward and

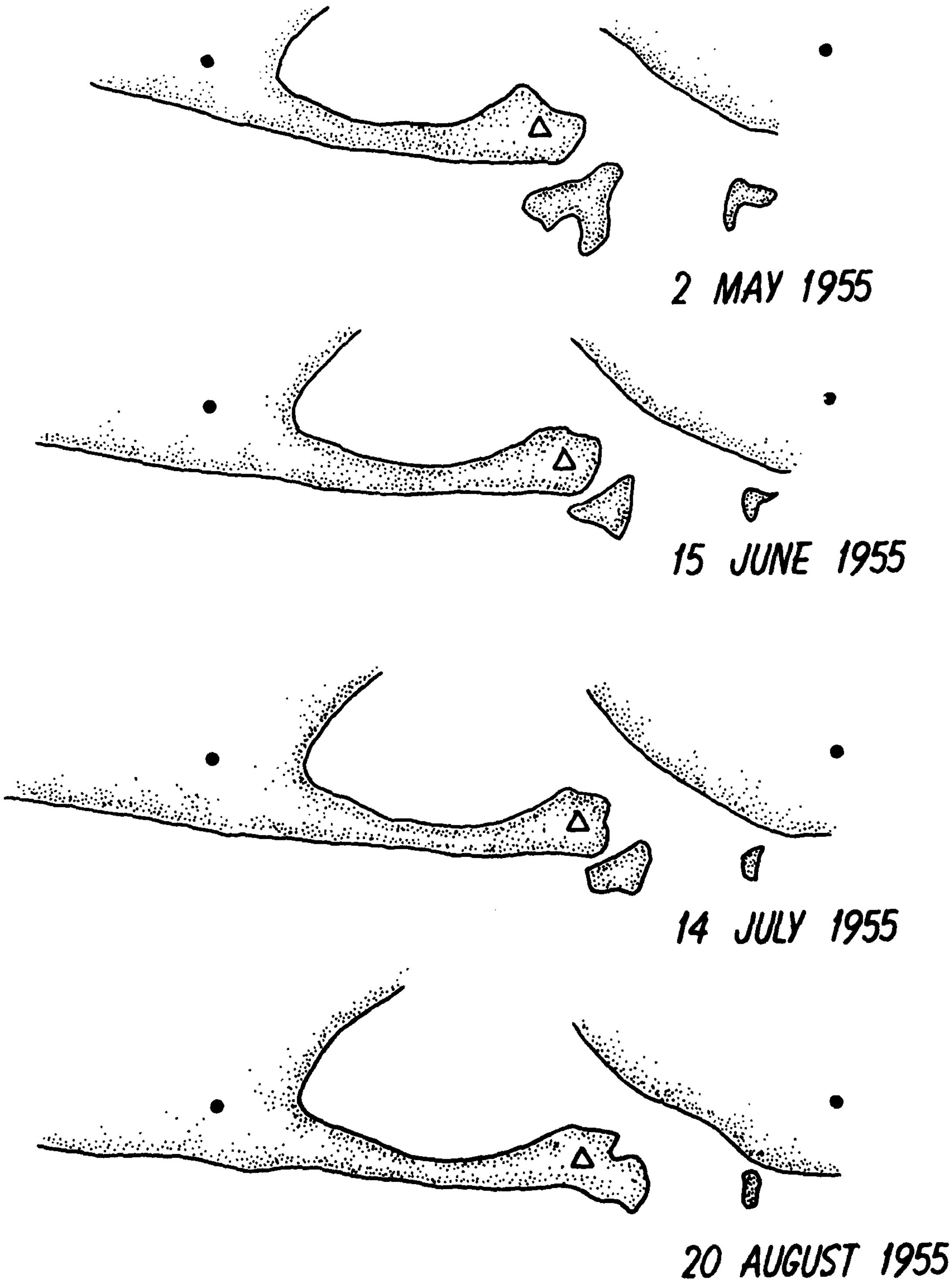


Figure 14. Four month bar-bypassing events observed at Nauset Inlet, Cape Cod, Massachusetts. Ebb tide distal bar migrated 300 meters shoreward, attaching itself to and lengthening the downdrift barrier spit.

380 m westward between May 25 and August 20, however, it did not cross the inlet channel axis. The southern bar displayed no net alongshore motion, moving first south and then north. It did migrate 270 m to the west over the summer and welded to the tip of the south spit by August 20.

The second series includes photographs taken February 9, February 21 and March 9, 1956. Additional observations were made on May 21 and on September 14, 1956. In this sequence, four bars were located on the ebb delta south of the inlet channel. One of the bars welded to the south spit between February 9 and 21. The other three migrated southward from 0 m to 100 m and westward from 40 m to 100 m. The bars followed a path along the edge of the ebb delta and, as they neared the tip of the south spit, elongated to the east.

The third series of photographs in which bar migration was measured dates from the winter of 1957-1958. Positions of three bars were measured on October 21, 1957, December, 19, 1957 and March 13, 1958. The three bars moved between 0 and 80 m southward and between 110 and 240 m westward during this period.

DISCUSSION

The historical study has identified the following important features of Nauset Inlet's migration patterns: The apparent stability of the southernmost inlet entrance, the role of storms in initiating major changes in the inlet/barrier beach system, and the recent tendency for the inlet to move in a direction opposite the predominant longshore drift. Migration of the inlet with accompanying changes in the barrier beaches takes place on essentially two different time scales. Major relocations of the inlet, involving long-shore movements of hundreds of meters in several days, occur episodically during large storms. These dramatic changes have a recurrence interval of about one every ten years. The other important time scale is the recent steady migration of the inlet in a general northward direction. The combined effects of wave activity, tidal flows and longshore sand transport cause this movement. The magnitude is on the order of 100 m/yr. Northward migration of the inlet is accompanied by extension of the southern barrier and in some instances (e.g., 1973-1982) by shortening of the northern barrier.

The general stability of a southern inlet location at Nauset is not surprising. Most of the tidal prism passes through the southernmost channels of the marsh, therefore a southern inlet provides the most direct link to the ocean. The dominance of friction in Nauset's shallow inlet/estuary system (Aubrey and Speer, 1981 and 1982) makes a southern inlet location energetically favorable. The southernmost location has important effects on barrier beach configuration. In general, the northern barrier is not strongly eroded by tidal flows when the inlet is in this location as compared to a more northerly one (reasons for this are presented in the next section). Occasionally, a short, slowly growing southern spit can develop without catastrophic storm influence. Large scale growth of a south barrier is dependent on storm activity and breaching of the northern barrier.

MODEL FOR LONGSHORE INLET MIGRATION

During the past 30 years, three distinct episodes of northward inlet growth have been observed: mid 1950's, late 1960's to early 1970's, and 1973-1982. The first two involved extension of the inlet channel to the north from a southern location, stability of the north barrier, and northward growth of the south barrier. A pattern of overlapping spits resulted in both cases. The most recent phase of inlet migration is qualitatively different from the previous two. The inlet channel has migrated to the north instead of simply elongating and the north barrier has been substantially eroded while the south barrier has extended north.

Inlets generally migrate in the direction of net longshore transport if they move at all (Brunn, 1978). Three different mechanisms (figure 15) are proposed to explain the unusual northward movement of Nauset Inlet, opposite the longshore transport direction: growth of the downdrift spit through bar bypassing of longshore sand transport, storm induced shifts of the inlet location; steady northward migration characterized by "flow around a bend" during ebb tides. Each period of inlet migration is characterized by one or more of these processes.

The 1950's pattern of barrier overlap was initiated by breaching of the northern barrier during a storm. The barrier remnant south of the breach attached to Nauset Heights to form a relatively long southern spit. The base of the inlet channel retained its southern location and extended through the breach. Subsequently, the northern barrier lengthened by attachment to a marshy island in the bay. The south spit elongated by means of bar bypassing, resulting in the pattern of overlapping spits. As the south spit grew to the north, the inlet channel lengthened. The north spit remained relatively stable after attachment to the bay island.

The barrier overlap pattern of the late 1960's to early 1970's was initiated when the inlet was at its southernmost location. With the inlet at this position, the estuary channels empty directly into the ocean. No tendency exists for ebb flows to preferentially erode the north barrier. Tidal flows are strong enough, however, to prevent material transported past the north spit from filling in the inlet channel. Bar bypassing of littoral drift leads to

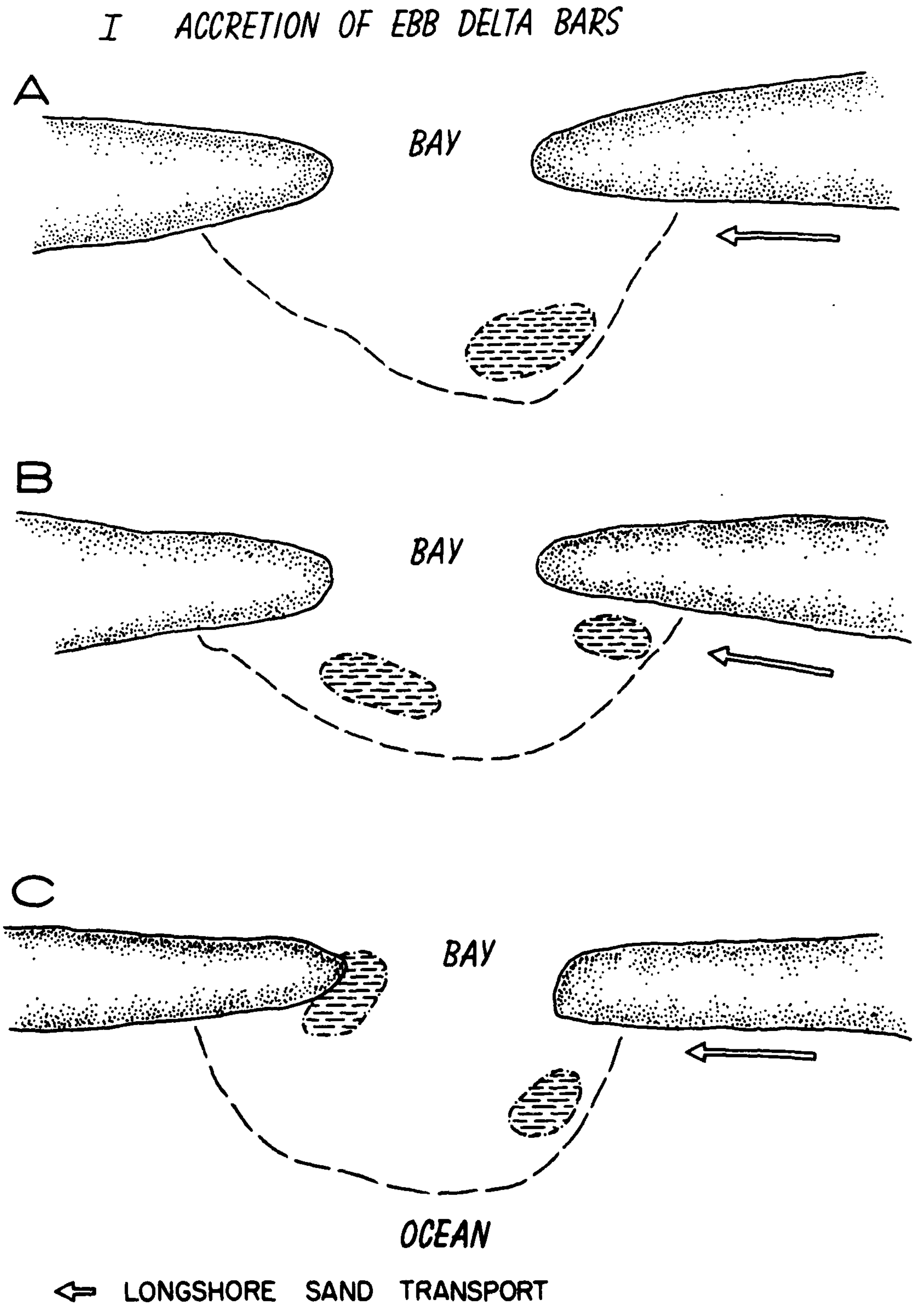
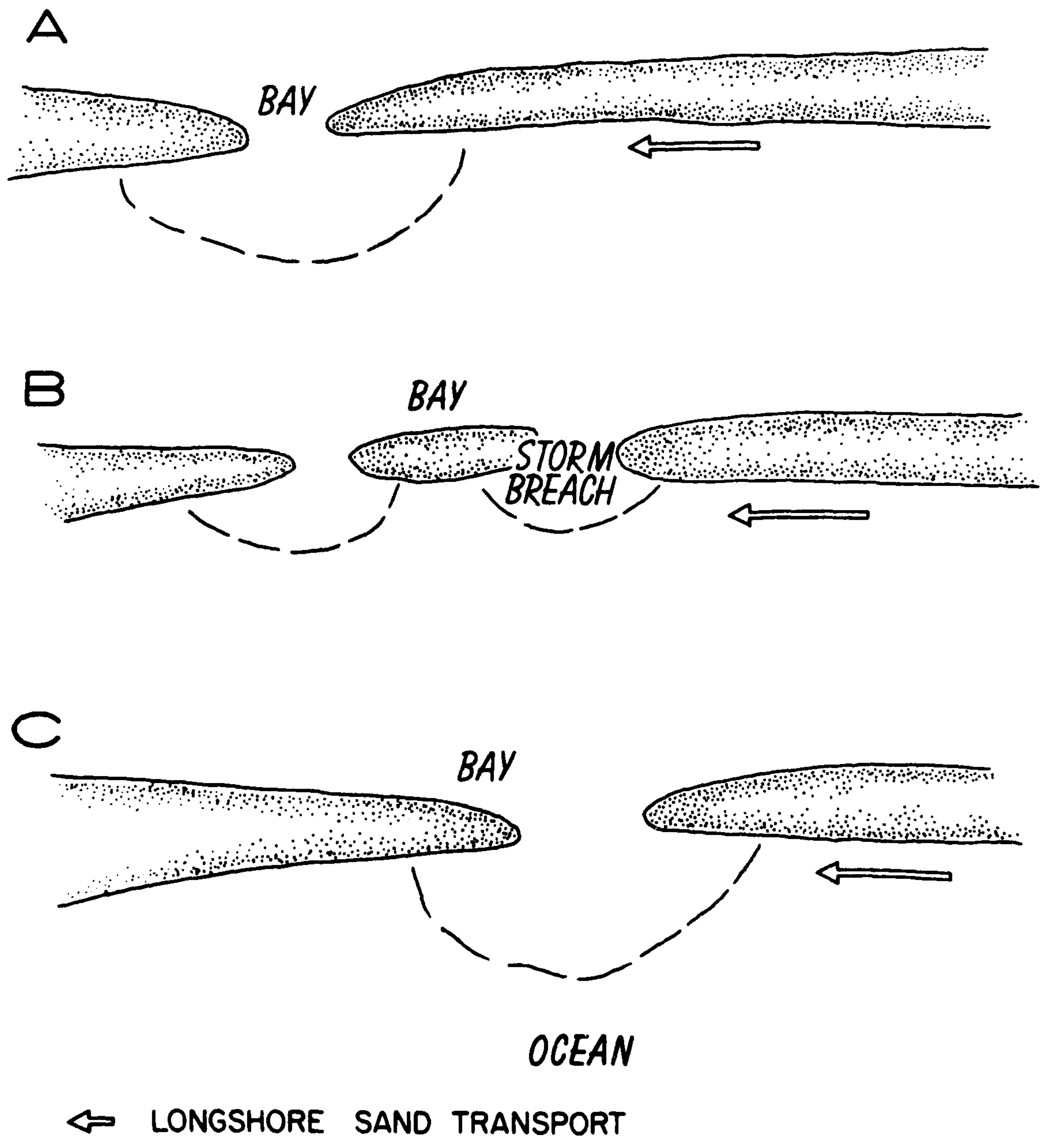
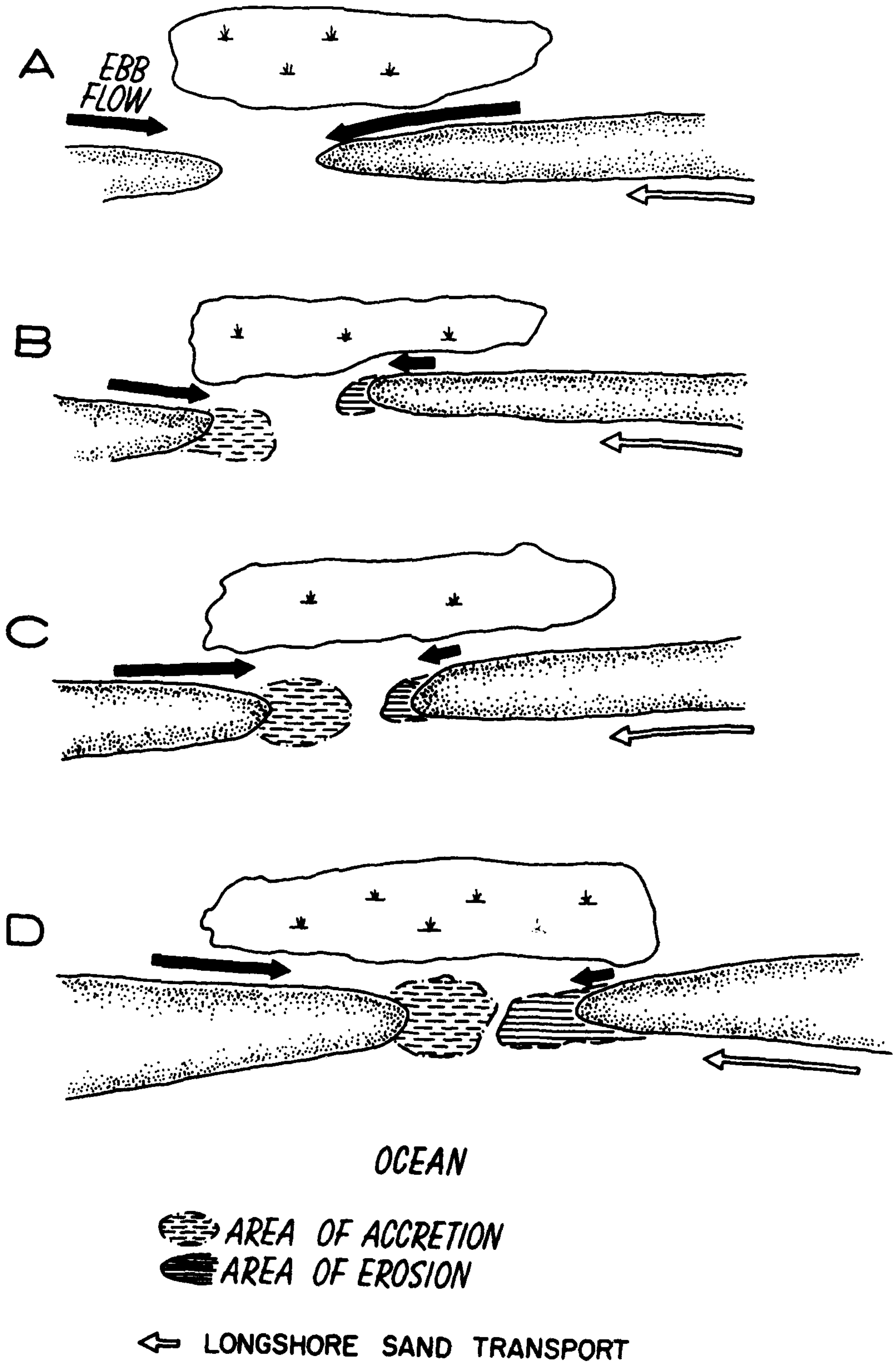


Figure 15. Three modes of updrift inlet migration responding to different combinations of waves, tides and storms. All three modes have been observed at Nauset Inlet, Cape Cod, Massachusetts.

II STORM-INDUCED SHIFTS



III FLOW AROUND A BEND



the development of a south spit. If storms do not halt this growth, the south spit can extend to the north and overlap the north spit, as occurred during this period.

The storm which breached the north spit in 1972 caused a new migration pattern to develop. The main inlet channel stabilized further north than it had previously been located. The dominant ebb tidal flow was constrained to flow north, and then east through the inlet channel. An analogy is drawn to "flow around a bend" in a river (Aubrey, in prep.). Experiment and theory have shown that in "flow around a bend", maximum flows and bottom stress are found on the outside of the bend (figure 15). Also, the surface of the water is superelevated on the outside of the bend. In a simple case, the superelevation produces a barotropic pressure gradient which drives a secondary flow towards the inner bank of the bend. This flow pattern results in erosion on the outer bank and deposition of a bar on the inner bank leading to migration of the river meanders. We are likely observing an analogous process at Nauset as a result of the storm-induced change in inlet location. The north wall of the inlet channel is presently eroding and a large sand deposit is forming on the south bank of the channel. Bar bypassing of longshore transport continues to add sand to the south spit. The emergent pattern is northward migration of the inlet with accompanying barrier beach changes, driven largely by unequal tidal discharge through southern and northern estuarine channels. The dominance of water exchange through the south channel imparts a strong directional bias leading to erosion of the north barrier, and deposition along the southern.

FUTURE TRENDS IN INLET MIGRATION

This "flow around a bend" has been operating for approximately ten years, leading to nearly 1 km of northward inlet movement. Northward migration will probably continue until either the inlet encounters an erosion resistant substrate or a major storm changes the inlet location. In the case of Nauset, the former is unlikely (see Aubrey et al., 1982a) since inlet tidal flows are currently eroding relatively resistant peat deposits underneath the sandy barrier spits. Nothing more erosion-resistant is likely to be encountered under the north spit. The storm-induced inlet relocation is a strong possibility. The long, frictionally dominated channels carrying the tidal prism at present would probably be abandoned if a more southerly breach were created by a storm. In that case, the large longshore transport could quickly close off the present inlet. A more northerly inlet created by storm overwash is not likely to persist (as the February 1978 blizzard demonstrated) because the northern tidal prism is too small. An additional factor increasing the likelihood of breaching near Nauset Harbor is the narrow width of the barrier at this point. This narrowing is caused by erosion on the bay side of the barrier during ebb tide, as the easterly-flowing tide is redirected northwards towards the present inlet (resulting in another complex, more non-uniform flow pattern).

ONSHORE MIGRATION AND FATE OF THE ESTUARY

The long-term fate of this estuary is affected by two dominant trends: inlet migration (which contributes sediment to the estuary via flood tide delta growth) and onshore spit migration. Net onshore migration of the Nauset barrier beach is apparent in spite of large, higher frequency fluctuations. The steady shoreward migration is a result of sea level rise (a relatively minor factor) combined with overwash and inlet processes (barrier roll-over). Higher frequency oscillations superimposed on this steady retreat result from inlet migration episodes, seasonal beach changes, bar bypassing events, and large, nearshore bedform generation (Aubrey, 1980). The effect of the onshore migration is a reduction in tidal prism (specifically by reduction of the area of the back bay). Tidal prism is also reduced by deposition of sand as a flood tide delta, an important factor since 1972, as the inlet has steadily migrated northwards approximately 1 km. Vestiges of the former flood tidal deltas are visible on recent aerial photographs of the area. As a result of overwash and bay infilling, the stable inlet configuration will become narrower and shallower with time (reduced equilibrium cross-sectional area).

SUMMARY

Three distinct patterns of natural inlet migration have been identified from historical data (figure 15), and their underlying causes hypothesized. These mechanisms explain the rare case where an inlet migrates in a direction opposite the dominant longshore sand transport, such as at Nauset Inlet. Large variability in barrier spit length across a baymouth can also be a reflection of these mechanisms. This rapid, spatially variable, inlet migration contributes to infilling of some inlet/estuary complexes on a geological time scale, as the continually enlarging flood tide delta evolves at each inlet location. The result is an accelerated shrinkage of some estuaries, with consequent reduction in inlet channel depth and width (the decreased channel area responding to a reduced tidal prism). Whether or not this flood tide delta growth significantly alters the fate of the estuary depends on the hydraulic characteristics of the inlet and estuary (flood tide delta growth is a function of flood/ebb flow dominance).

The three distinct patterns of inlet migration are (fig. 15):

1) Growth of the downdrift spit by addition of sediment from ebb tide delta distal bars: some of these distal bars weld onto the downdrift spit without escaping the inlet environment. The time scale of these growth episodes is months, with an associated spit growth on a scale of 100 m. The spit growth is relatively slow compared to the other two growth mechanisms.

2) Storm-induced shifts in inlet position associated with superelevated water levels: these changes are rare but significant, with time scales of tens of years and spatial scales of hundreds of meters. Storm breaches will remain stable and replace previous inlets if they are hydraulically more efficient than alternative breaches. These major inlet relocations have played an important role at Nauset Inlet, by shifting the inlet position to the north (against the sense of net littoral drift) and allowing the flow characteristics to set up a stable, steady northward inlet migration independent of storm influences.

Storm effects in the future are expected to influence the Nauset barriers significantly, and shift the inlet to the south. Since the southernmost limit of the estuary/inlet system has historically been the preferred position (because it is the most efficient location for tidal exchanges between the ocean and bay), a breach at this narrow part of the barrier will likely become the preferred inlet position. At present, a stable dune-line is inhibiting storm overwash and breaching at this location.

3) Steady northward migration characterized by flow around a bend (erosion on outside of bend, accretion on inside of bend) during ebb tides: this migration has occurred since 1972 when a storm breach rapidly shifted the inlet location, setting up a long, confined southern barrier-parallel channel through which most tidal exchange takes place. Ebb flow through this

barrier-parallel channel must make a sharp bend through the inlet to exit into the ocean. This bend creates a distinctive three-dimensional flow pattern similar to river bend flows, eroding the north spit and accreting to the south. The result is a steady northward migration which will cease when a storm opens a breach further south of the present inlet; this new breach will likely become the preferred inlet position.

ACKNOWLEDGEMENTS

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APPENDIX 1

HISTORICAL CHARTS (1670 - 1978)

APPENDIX 1
HISTORICAL CHARTS (NAUSET)

Date	Scale[1/]	Source	Depository	Title (or Description)
1670	(1:24,000)	Anon.	WHOI 156 M	Chart of Eastham and Orleans.
1680	(1:328,000)	Anon.	WHOI 154 M	Chart of the coast of Maine, New Hampshire, Massachusetts and New Plymouth.
1694	(1:398,000)	Southhack	NA RG-23 844:1734	Chart of the coast of Massachusetts from survey made by Capt. Cyprian Southack.
1702	------	------	NPS	
1717	------	------	NPS	
1738	(1:182,000)	Anon.	WHOI 152 M	Colony of Plymouth...(Map of Cape Cod and S.E. Massachusetts).
1779	(1:135,000)	Desbarres	LC	(Map of Cape Cod)
177?	(1:450,000)	Anon.	LC	A plan of the Sea Coast from Boston Bay to the Light House near Rhode Island.
1781	(1:137,000)	Atlantic Neptune	WHOI 162 M	(Map of Cape Cod)
1788	------	Green	LC	(Map of Cape Cod)
1788-9	------	Carlton	LC	(Map of Cape Cod)
1794	------	Stockdale	LC	(Map of Cape Cod)
1795	(1:1,200,000)	Lewis	WHOI 177 M	(Map of Cape Cod)
1795	------	------	NPS	
1796	(1:1,500,000)	Morse/ Jedidiot (Denison)	LC	Map of Massachusetts

1/ Values in () are estimates.

HISTORICAL CHARTS (NAUSET)

Date	Scale 1/	Source	Depository	Title (or Description)
1798	------	Sotzman	WHOI	
1798	(1:125,000)	Anon.	WHOI 160 M	(Map of Cape Cod; Concord Public Library).
1798	(1:160,000)	Anon.	WHOI 249 M	(Map of Cape Cod; American Antiquities Society).
1803	(1:140,000)	Anon.	WHOI 114 M	(Map of Cape Cod).
1810	(1:250,000)	Lewis	LC	(Geographic and political map of Mass.).
1822	1:680,000	Carey and Lea	LC	The State of Massachusetts.
1822	------	Carleton	NA U.S. 97	Map of Massachusetts.
1822	------	Gillet	LC	(Map of Cape Cod).
1824	------	Finely	LC	(Map of Cape Cod by Lewis).
1826	(1;690,000)	Lucas/ Fielding	LC	Geographical, Historical and Statistical Map of Massachusetts. No. 12.
1827	------	Morse	LC	(Map of Cape Cod).
1827	------	Carey/Lea	LC	(Map of Cape Cod by Lewis).
183?	------	Finley	LC	(Map of Cape Cod by Lewis).
1831	------	------	NPS	(CENSUS Map).
1832	(1:160,000)	Anon.	WHOI 101	(Map of Cape Cod).
1832	------	Mitchell	LC	(Map of Cape Cod by Lewis).
1832	------	Hinton, Simpkin, & Marshall	LC	(Map of Massachusetts).
1832	------	Hitchcock	WHOI	
1833	------	Sumner	LC	(Map of Cape Cod by Lewis).

HISTORICAL CHARTS (NAUSET)

Date	Scale[1/]	Source	Depository	Title (or Description)
1833	1:830,000	Tanner	LC	Massachusetts and Rhode Island.
1836	1:400,000	Otis/Broader	LC	New Map of Massachusetts.
1836	1:490,000	Wilcox	LC	Map of Massachusetts, Rhode Island and Connecticut.
1836	------	Packard/Brown	LC	(Map of Cape Cod by Lewis).
1837	------	Mitchell	LC	(Map of Cape Cod by Lewis).
1838	------		NPS	(Town planning map).
1838	------	Bradford	LC	
1838	------	Brown Parsons	LC	
1840	------	Darr/Howland	LC	
1841	(1:830,000)	Tanner	LC	Massachusetts and Rhode Island.
1841	------	Phelps/Ensign	LC	Map of Massachusetts, Rhode Island and Connecticut.
1844	1:316,800	Hitchcock	NA RG-23 L&A 844 1844-3(2)	Geological Map of Massachusetts.
1844	1:158,400	Borden	NA RG-23 L&A 844: 1844-2(1)	(Map of Massachusetts).
1844	------	Smith	LC	(Map of Massachusetts).
1845	1:80,000	USC&GS		Chart 110-111, Map of Cape Cod.
1852	------	Anon.	------	(Map of Cape Cod in Thoreau Gasetteer).

HISTORICAL CHARTS (NAUSET)

Date	Scale[1/]	Source	Depository	Title (or Description)
1856	------	Anon.	WHOI 239-M	Nauset Harbor.
1857	------	Bache	NA RG-77	Nauset Harbor.
1858	1:81,000	Walling	LC	(Map of Massachusetts).
1871	------	Anon.	LC	(Map of Massachusetts).
1871	------	Anon.	WHOI 143 M	
1872	1:80,000	USC&GS	WHOI 230 M	Chart 110, Map of Cape Cod (Topo. 1848-68).
1874	1:80,000	USC&GS		Chart 111.
1877	1:570,000	Gray	NA RG-77 US 373-59	Massachusetts, Rhode Island and Connecticut.
1880	------	Anon.	NPS	(Town of Orleans).
1880	------	Anon.	NPS	Map No. 11.
1887	1:10,000	Marindin	WHOI 220 M	Cross Sections off Nauset beach.
1848-1888	1:40,000	Marindin	LC	Physical Survey Cape Cod, Mass.
1892	1:130,000	Walker	LC	Cape Cod and Vicinity.
1892	1:80,000	USC&GS	NA	Cape Cod Bay.
1893	------	Gannet (USGS)	NA	
1894	------	Anon.	NPS	(USC&GS).
1896	------	Eldridge	WHOI 159 M	
1898	------			
1900	------	Anon.	NPS	(USC&GS).
1901	------	Anon.	NPS	(USC&GS).

HISTORICAL CHARTS (NAUSET)

Date	Scale[1/]	Source	Depository	Title (or Description)
1902	------	Walker	LC	(Map of Cape Cod and Vicinity).
1903	------	Anon.	NPS	
1905	------	Walker	LC	(Map of Cape Cod and Vicinity).
1907	------	Walker	LC	(Map of Cape Cod and Vicinity).
1908	------	Walker	LC	(Map of Cape Cod and Vicinity).
1908	------		NPS	
1909	------	Walker	LC	(Map of Cape Cod and Vicinity).
1910	1:80,000	USC&GS	NA RG-23	Cape Cod Bay, Chart 110.
1910	------	Walker	LC	(Map of Cape Cod and Vicinity).
1911	------	Walker	LC	(Map of Cape Cod and Vicinity).
1915	1:80,000	USC&GS	NPS	Chart 111, (topography not updated).
1915	1:80,000	USC&GS	NPS	Chart 1208 (topography not updated).
1915	------	Walker	LC	(Map of Cape Cod and vicinity).
1916	------	Woodworth	WHOI 198 M	(Geology of Cape Cod).
1917	1:62,500	USGS	NA	Massachusetts, Wellfleet, Mass Quadrangle.
1920	------	Anon	LC	(Map of Postal routes on Cape Cod).
1920	(1:80,000)	US Bureau of Soils	LC	Soils Map, Massachusetts, Barnstable County Sheet.

HISTORICAL CHARTS (NAUSET)

Date	Scale[1/]	Source	Depository	Title (or Description)
1922	------	Bureau of Public Works	LC	(Map of Cape Cod).
1924	------	Eldridge	WHOI 199 M	(Map of Cape Cod).
1926	------	Malanie	LC	(Pictoral chart of Cape Cod).
1926	1:62,500	USGS	NA	Chatham, Mass. Quadrangle (not updated).
1930	------	------	LC	(Pictoral map of Cape Cod).
1931	(1:160,000)	Tripp	LC	(Illustrated map of Cape Cod).
1932	------	Goffney	LC	(Map of Cape Cod).
1933	------	Crawford Press	LC	(Pictoral map of Cape Cod).
1934	------	Cape Cod Chamber of Commerce	LC	Tourist Map of Cape Cod.
1935	------	National Ocean Survey, Co.	LC	(Tourist map of Cape Cod for Copley Plaza).
1936	------	Robbins Studio	LC	Wallet Map of Cape Cod.
1938	(AERIAL PHOTO COVERAGE STARTS HERE - See Appendix 2)			
1938	------	USC&GS	WHOI 200 L	
1939	------	Gulf Oil	LC	(Road Map of Cape Cod).
1941	------	Auto	LC	(Auto Map of Cape Cod).
1944	------	USC&GS #50	WHOI 247 M	(Map of Cape Cod; based on surveys up to 1941).
1946	1:80,000	USC&GS	WHOI	Chart 1208 (Map of Cape Cod dated 1942: updated 1946).
1946	1:24,000	USGS	WHOI 300 L	Orleans, Mass. Quadrangle.

HISTORICAL CHARTS (NAUSET)

Date	Scale[1/]	Source	Depository	Title (or Description)
1947	------	Miller	LC	(Map of Cape Cod).
1952	1:10,560	Shaw	WHOI	Eastham Marsh.
1953	1:80,000	USC&GS	WHOI	Chart 1208 (Map of Cape Cod dated 1942: updated in 1953).
1954 17 May	1:2400	Zeigler	WHOI ref. # 55-12	(Plane table survey of Nauset Beach).
1954 25 June	1:2400	Zeigler	WHOI ref. # 55-12	(Plane table survey of Nauset Beach).
1954 12 July	1:2400	Zeigler	WHOI ref. # 55-12	(Plane table survey of Nauset Beach).
1954 23 Aug	1:2400	Zeigler	WHOI ref. # 55-12	(Plane table survey of Nauset Beach).
1954 2 Sept	1:2400	Zeigler	WHOI ref. # 55-12	(Plane table survey of Nauset Beach).
1954 15 Sept	1:2400	Zeigler	WHOI ref. # 55-12	(Plane table survey of Nauset Beach).
1954 14 Oct	1:2400	Zeigler	WHOI ref. # 55-12	(Plane table survey of Nauset Beach).
1954 1 Dec	1:2400	Zeigler	WHOI ref. # 55-12	(Plane table survey of Nauset Beach).
1956	------	Map Corp.	LC	(Map of Cape Cod).
1959	------	Community Advertising	LC	(Map of Cape Cod).
1961	------	USC&GS	NPS	(Topography no updated).
1962	1:24,000	USGS	WHOI 300 L	Orleans, Mass. Quadrangle.
1971	1:80,000	USC&GS	WHOI	Chart 1208.
1974	1:24,000	USGS	WHOI	Orleans, Mass. Quadrangle.
1978	1:80,000	NOAA	WHOI	Chart 13246 (1208).

ABBREVIATIONS:

LC: Library of Congress, Geography and Maps Room, Washington, D.C.

MA: Commonwealth of Massachusetts Archives. Boston, MA.

NA: National Archives, (RG = Records Group). Washington, D.C.

USC&GS: U.S. Coast and Geodetic Survey (and NOS - National Ocean Survey), Rockville, MD.

USGS: United States Geological Survey, Sioux Falls, S.D.

WHOI: Woods Hole Oceanographic Institution, Woods Hole, MA.

NPS: National Park Service, Cape Cod National Seashore, Wellfleet, MA.

APPENDIX 2

HISTORICAL PHOTOGRAPHS (1938 - 1981)

APPENDIX 2

AERIAL PHOTOGRAPHS OF NAUSET INLET

Year	Date	Photographed By	Obtained From	Vertical/ Oblique	Frame #('s)	Scale
1938	21 Nov.		NARS	V	GSF 509, 511	1:23,158
1951	20 Oct.	NOS	NOS/NOAA	V	J 5148-5154	1:9498
1952	3 June		VIMS (RJB)	V	DPL 3K G&8	1:20,220
1953	10 May	NOS(USC&GS)	NOS	V	J 0782, 0784, 0786	1:9950
1953	Aug		JMZ-WHOI Ref #55-12	O		
1954	Summer		JMZ-WHOI Ref #55-12	O		
1954	Summer		JMZ-WHOI Ref #55-12	V		
1955	18 Jan.	Stetson	JMZ-WHOI	V		
1955	15 Mar.	USC&GS	NOS	V	W 5002, 5004	1:24599
1955	11 April	Stetson	JMZ-WHOI	V		
1955	2 May	Stetson	JMZ-WHOI	V		1:10,395
1955	25 May	Stetson	JMZ-WHOI	V		1:10101
1955	15 June	Stetson	JMZ-WHOI	V		1:13,122
1955	14 July	Stetson	JMZ-WHOI	V		1:16,747
1955	20 Aug.	Stetson	JMZ-WHOI	V		1:16,463
1955	25 Oct.	Stetson	JMZ-WHOI	V		1:15,746
1955	27 Nov.	Stetson	JMZ-WHOI	V		
1956	24 Jan.	Stetson	JMZ-WHOI	V		
1956	8 Feb.	Stetson	JMZ-WHOI	V		
1956	9 Feb.	Stetson	JMZ-WHOI	V		1:16,312
1956	21 Feb.		JMZ-WHOI	V		1:15,689

AERIAL PHOTOGRAPHS OF NAUSET INLET

Year	Date	Photographed By	Obtained From	Vertical/ Oblique	Frame #('s)	Scale
1956	9 Mar.		JMZ-WHOI	V		1:15,723
1956	21 May	Stetson	JMZ-WHOI	V		1:
1956	Summer	Stetson	JMA-WHOI	V		
1956	14 Sept.		JMZ-WHOI	V		1:5168
1956	26 Oct.	Stetson	JMZ-WHOI	V		
1957	21 Oct.	Stetson	JMZ-WHOI	V		1:17,686
1957	6 Nov.	Stetson	JMZ-WHOI	V		
1957	21 Nov.	Stetson	JMZ-WHOI	V		
1957	19 Dec.		VIMS (RJB)	V		1:17,686
1958	13 Mar.		JMZ-WHOI	V		1:17,750
1958	18 Mar.	Stetson	JMZ-WHOI	O		
1958	17 July		JMZ-WHOI	V		
1958	11 Aug.		JMZ-WHOI	V		1:16,195
1958	23 Sept.		JMZ-WHOI	V		1:16,440
1959	14 Jan.		VIMS (RJB)	V		
1959	8 Sept.		VIMS (RJB)	V		
1960	27 Feb.		USNPS	V	TR-3-60-1561 thru 67	
1960	April	FAS	FAS		C-24490-P	
1960	20 April	TDG	TDG		23831-3 540,542,558 560,562	1:6955
1960	6 May	USAF	EROS	V		1:60,147
1960	13 Sept.		JMZ-WHOI	V		1:12,575

AERIAL PHOTOGRAPHS OF NAUSET INLET

Year	Date	Photographed By	Obtained From	Vertical/ Oblique	Frame #('s)	Scale
1961	10 July		VIMS (RJB)	V		
1962	23 Mar	USC&GS	NOS	V	53080, 3082	1:18,746
1965	21 April	LKBI	LKBI	V	5520; 52-624	1:40,060
1965	11 June		VIMS (RJB)	V		1:5540
1965	25 Aug.		VIMS (RJB)	V		1:6466
1966	25 Aug		VIMS (RJB)	V		1:11,445
1966	Nov.	RK	RK	O		
1967	30 May		NED	V		1:9514
1968	13 July	RK	RK	O		
1968	21 Nov.	RK	RK	O		
1968	6 Dec.	RK	RK	V	33 & 28	1:6466
1968	6 Dec.	RK	RK	O		
1969	15 July	RK	RK	O		
1969	Oct.		CERC	V		1:12,812
1970	28 May	RK	RK	O		
1970	5 Aug.	USGS	WHOI	O		
1970	5 Aug.	RK	RK	O		
1970	3 Sept.	RK	RK	O		
1970	12 Sept.	USC&GS	NOS	V		1:19,412
1970	20 Sept.	ASCS	USNPS	V	DPL I11-80	1:40,287
1970	24 Sept.	USGS	EROS	V	Roll 70-10-3	1:25,419
1971	28 April	(NED)	UMAS	V	15544, 2942 & 43;RF6813	

AERIAL PHOTOGRAPHS OF NAUSET INLET

Year Date	Photographed By	Obtained From	Vertical/ Oblique	Frame #('s)	Scale
1971 15 May	RK	RK	O		
1971 7 Aug.	ASCS	WHOI	V	DPL-2mm-211	1:26,960
1971 5 Dec.	RK	RK	O		
1972 5 April	RK	RK	O		
1972 May	RK	RK	O		
1972 27 May	LKBI	LKBI	V	2582; 2434-52-282	1:42,876
1972 20 Aug.	RK	RK	O		
1973 25 Mar.		UMASS	V	G83 193	1:18,988
1973 7 April	RK	RK	O		
1973 29 Aug.	RK	RK	O		
1973 7 Sept.	RK	RK	O		
1974 21 Feb.	USGS	EROS	V	GS VD5T	1:23,937
1974 12 Aug.	RK	RK	V	42, 43 & 44	1:8700
1974 25 Aug.	RK	RK	O		
1974 11 Oct.	NED	UMASS	V		1:16,916
1974 24 .t.	RK	RK	V		
1975 2 Jan.	RK	RK	O		
1975 18 Mar.	COL	COL	V	7247-31-26	1:9541
1975 25 Mar.	RK	RK	O		
1975 11 April	RK	RK	O		
1975 26 July	RK	RK	O		
1975 20 Aug.	USGS	EROS	02196		1:60,000

AERIAL PHOTOGRAPHS OF NAUSET INLET

Year	Date	Photographed By	Obtained From	Vertical/ Oblique	Frame #('s)	Scale
1975	28 Aug.	RK	RK	0		
1975	5 Oct.	RK	RK	0		
1975	11 Nov.	RK	RK	0		
1976	6 Jan.	RK	RK	0		
1976	23 Mar.	RK	RK	0		
1976	May/Nov.	REDI	REDI	V	49 & 51	1:11,836
1976	3 June	RK	RK	0		
1976	23 Aug.	RK	RK	0		
1976	12 Oct.	RK	RK	0		
1977	6 July	RK	RK	0		
1977	10 Aug.	RK	RK	0		
1977	9 Sept.	RK	RK	V		
1977	30 Sept.		NED	V		
1978	20 Feb.	RK	RK	0		
1978	28 Feb.	RK	RK	0		
1978	6 Mar.	NOS	UMASS	V	LMI-632; 5979 80 & 81	1:19,920
1978	18 Mar.	RK	RK	0		
1975	31 Mar.	JWS	USNPS	V		
1978	31 Mar.	RK	RK	0		
1978	6 April	RK	RK	0		
1978	10 April	RK	RK	0		
1978	23 April		UMASS	V		1:23,350

AERIAL PHOTOGRAPHS OF NAUSET INLET

Year	Date	Photographed By	Obtained From	Vertical/ Oblique	Frame #('s)	Scale
1978	April/May	LMI	LMI	V	X-12 & 13	1:5013
1978	4 May	AVIS	AVIS	V	P 77871, 2-36 5, 6 & 7	1:14,408
1978	10 June	RK	RK	O		
1978	8 Nov.	RK	RK	O		
1979	23 Jan.	RK	RK	V	51 thru 61, 10, 12, 13	
1979	22 May	RK	RK	V	62 thru 70	1:6247
1979	27 May	RK	RK	V	23 thru 26	1:8848
1979	27 June	Speer	WHOI	V/O		
1980	28 Mar.	Aubrey	WHOI	O		
1980	Aug.	WHOI	WHOI	O		
1980	12 Sept.	Aubrey	WHOI	O		
1980	27 Oct.	Aubrey	WHOI	O		
1981	14 Feb.	Aubrey	WHOI	O		
1981	28 July	Aubrey	WHOI	O		
1981	21 Sept.	COL	COL	V		

ABBREVIATIONS

See Appendix III for most abbreviations

RJB - Dr. R.J. Byrne, VIMS, Gloucester Pt., VA
JMZ - Dr. J.M. Zeigler, VIMS, Gloucester Pt., VA
USNPS - U.S. National Park Service, Cape Cod National Seashore, Wellfleet, MA
CERC - Paul Knutson, U.S. Army Corps of Engineers, CERC, Ft. Belvoir, VA
UMASS - University of Massachusetts, Amherst, MA

APPENDIX 3

DEPOSITORIES OF AERIAL PHOTOGRAPHY

APPENDIX 3

DEPOSITORIES OF VERTICAL AERIAL PHOTOGRAPHS

A. Private

APNE	Aerial Photos of New England, Inc.	Norwood Municipal Airport Access Road, Norwood, MA 02062
AGC	Aero-Graphics Corp.	Box 248, Bohemia, NY 11716
AMS	Aero-Marine Surveys	38 Green Street, New London, CT 06320
AIT	Air Image Technology	Boxboro Road, Stow, MA 01775
ANCO	Anderson-Nichols Co.	150 Causeway Street, Boston, MA 02114
AVIS	Avis Air Map, Inc.	454 Washington Street, Braintree, MA 02184
BSC	Boston Survey Consultants	263 Summer Street, Boston, MA 02210
COL	Col-East, Inc.	Harriman Airport, North Adams, MA 01247
DFS	Dutton Flying Service	239 Newton Road, Haverhill, MA 01830
FAS	Fairchild Aerial Surveys	Los Angeles, CA
RK	Mr. Richard Kelsey	20 Heritage Lane, Chatham, MA
KAS	Keystone Aerial Surveys, Inc.	North Philadelphia, PA
LKBI	Lockwood, Kessler & Bartlett, Inc.	One Aerial Way, Syosset, NY 11791
LMI	Lockwood Mapping, Inc.	P.O. Box 5790, 580 Jefferson Rd., Rochester, NY 14623
LAPS	Lowry Aerial Photo Service	234 Cabot Street, Beverly, MA 01915
NESS	New England Survey Service	1220 Adams Street, Box 412, Dorchester, MA 02122

DEPOSITORIES OF VERTICAL AERIAL PHOTOGRAPHS

NEAA	Northeast Airphoto Association, Inc.	29 Grafton Circle, Shrewsbury, MA 02576
REDI	Real Estate Data, Inc.	Northeast Division, 629 Fifth Avenue, P.O. Call Box D, Pelham, NY 10803
RAS	Robinson Aerial Surveys	
JWS	James W. Sewall Company	West Wareham, MA 02576
TDG	Teledyne Geotronics	725 E. 3rd Street, Long Beach, CA 90802
WHOI	Data Library	Woods Hole Oceanographic Institution, Woods Hole, MA 02543

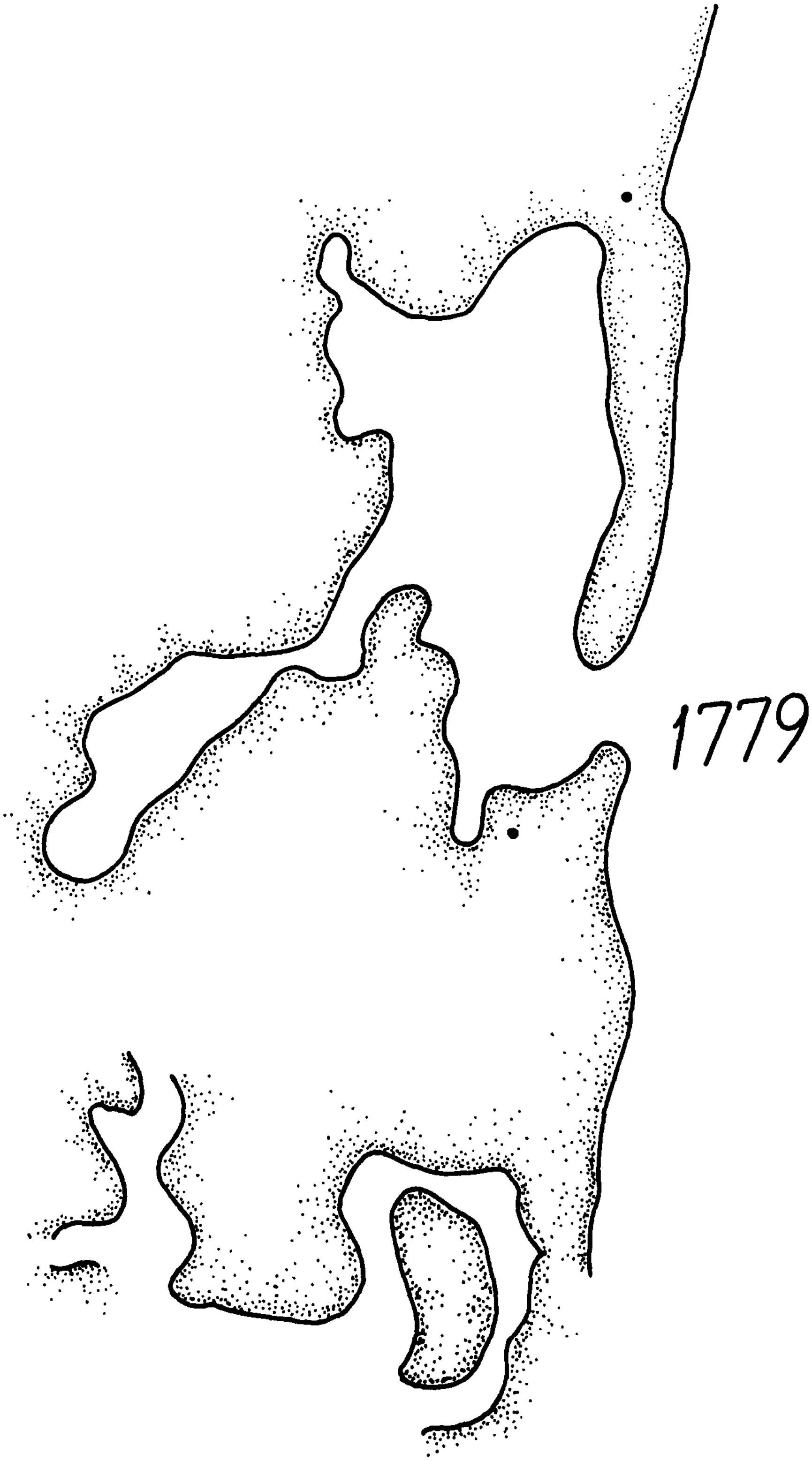
B. Government

NED	U.S. Army Corps of Engineers	New England Division, 424 Trapelo Road, Waltham, MA 02154
USDA	U.S. Department of Agriculture	Agricultural Stabilization and Conservation Service, 2222 W. 2300 South, P.O. Box 30010, Salt Lake City, Utah 84125
	and	Soil Conservation Service, Cartographic Division, Federal Center Building No. 1, Hyattaville, MD 20782
NARS	National Archives and Record Service	General Services Administration, Cartographic Archives Division Rm 2W, 8 Pennsylavnia Avenue, NW, Washington, DC 20408
NCIC	U.S. Department of Defense	Central Film Library, U.S. Geological Survey, National Cartographic Information Center, National Center, Mail Stop 507, Reston, VA 22092
EROS	U.S. Department of Interior	EROS Data Center, Sioux Falls, SD 57198
NOS	Chief, Photo Map & Imagery Section	Coastal Mapping Division, C3415, National Ocean Survey, NOAA, Rockville, MD 20852

APPENDIX 4

TRACINGS OF SELECTED HISTORICAL MAPS AND PHOTOGRAPHS

DOTS ON TRACINGS MARK REFERENCE POINTS.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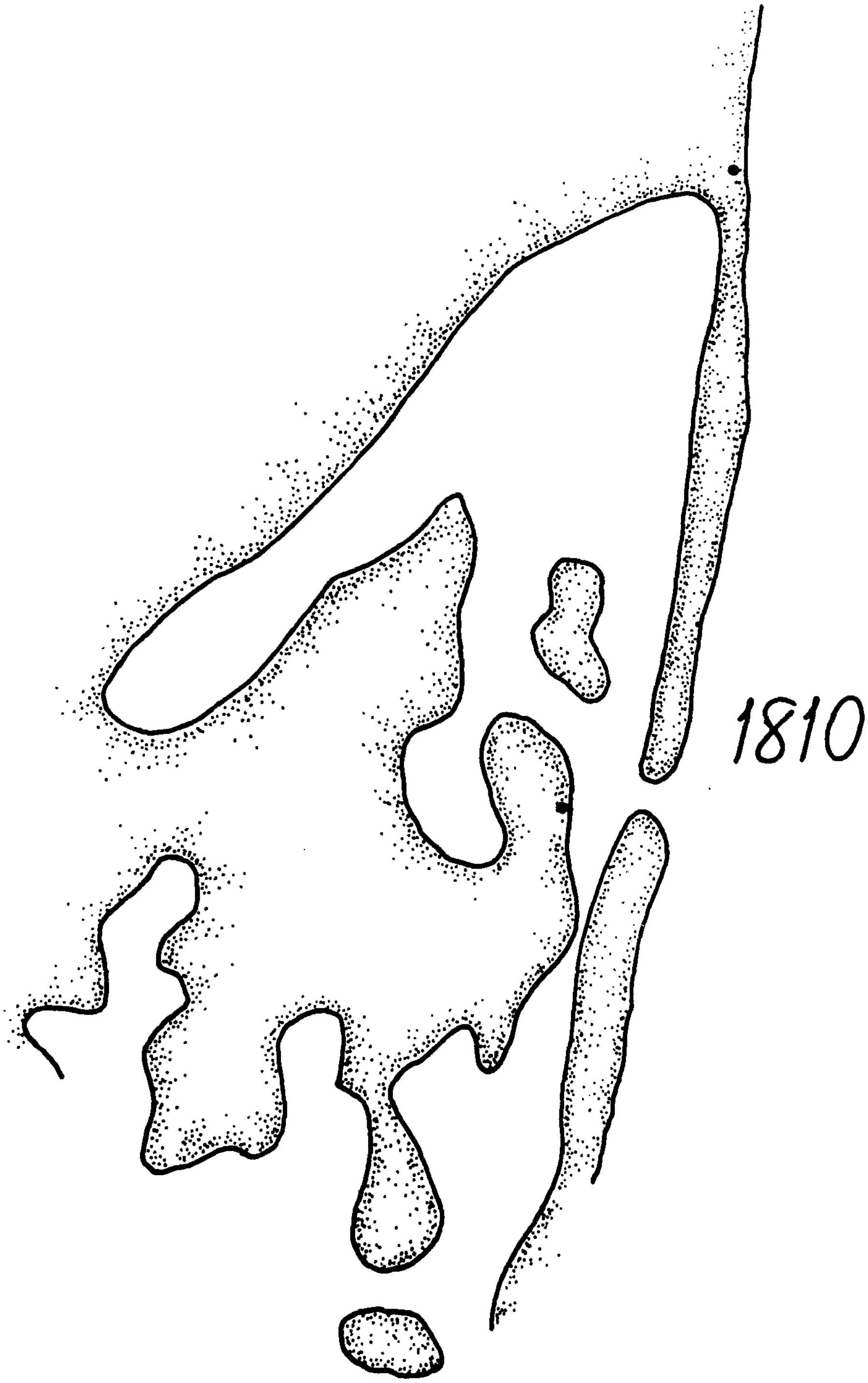
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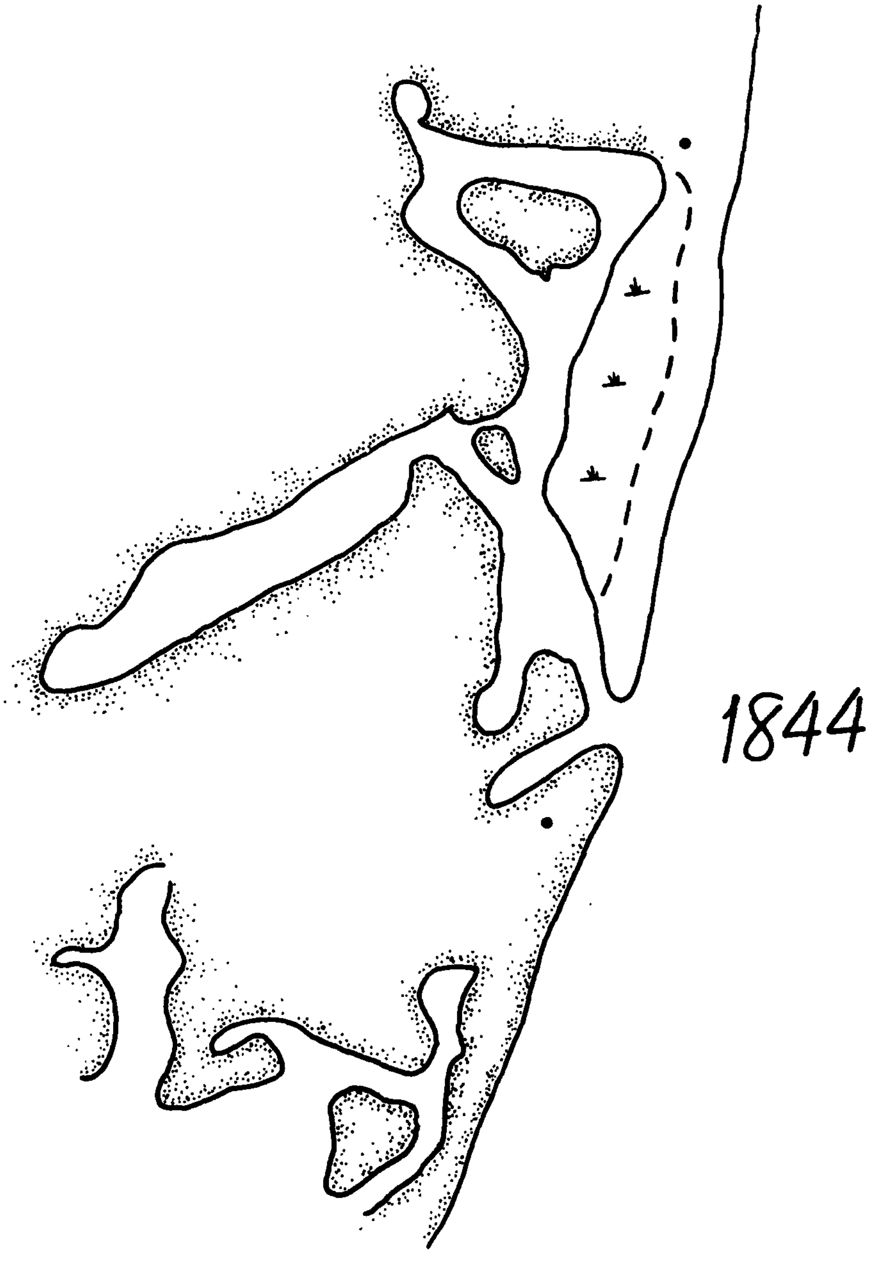
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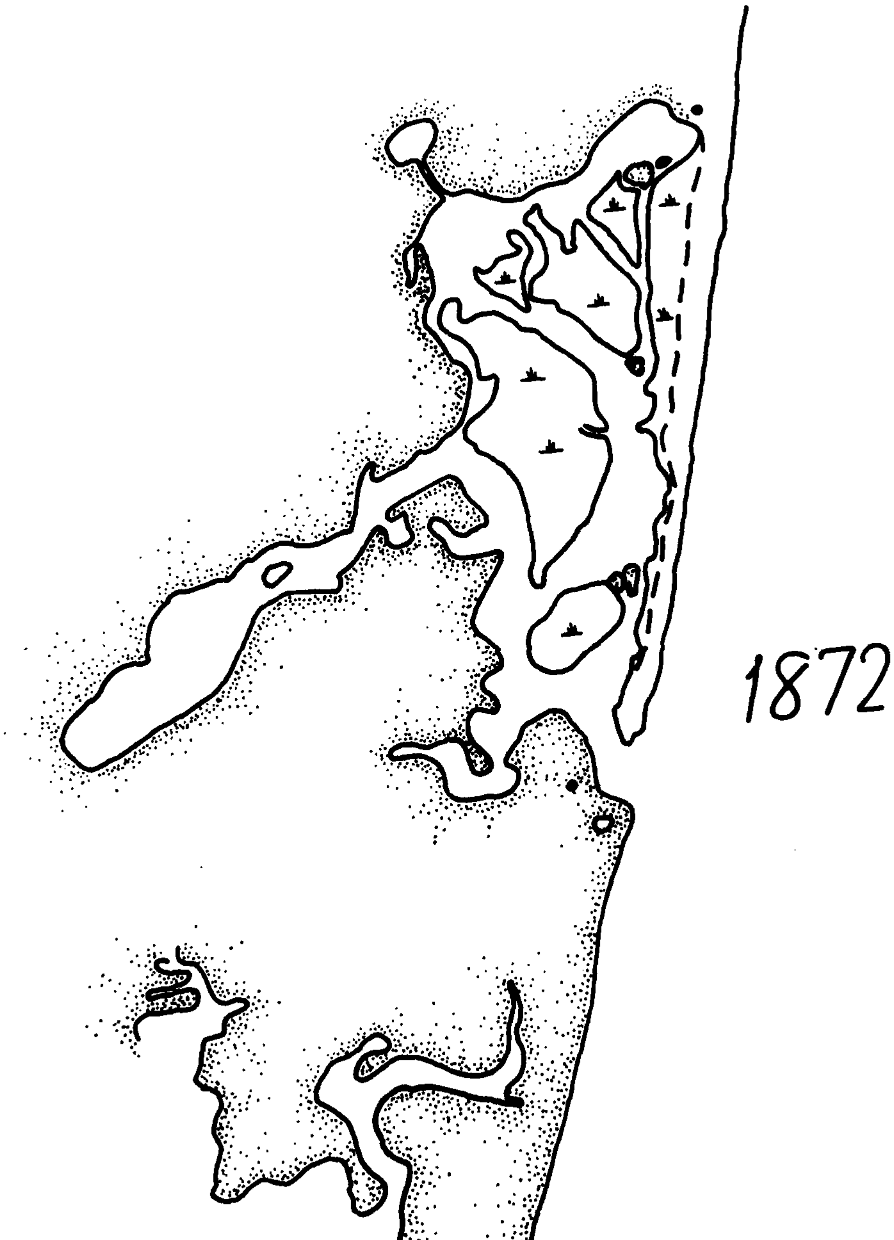
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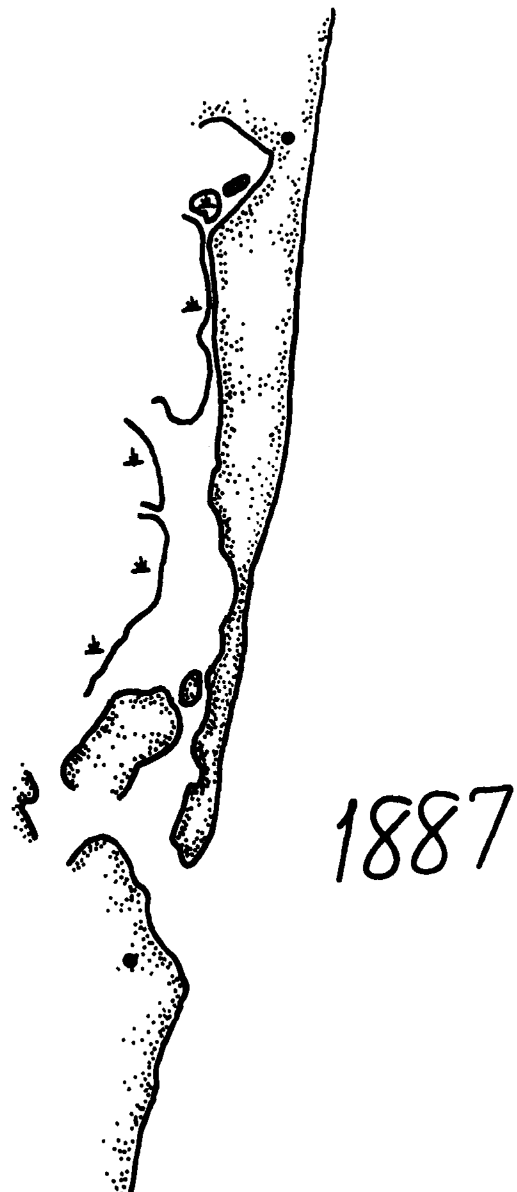
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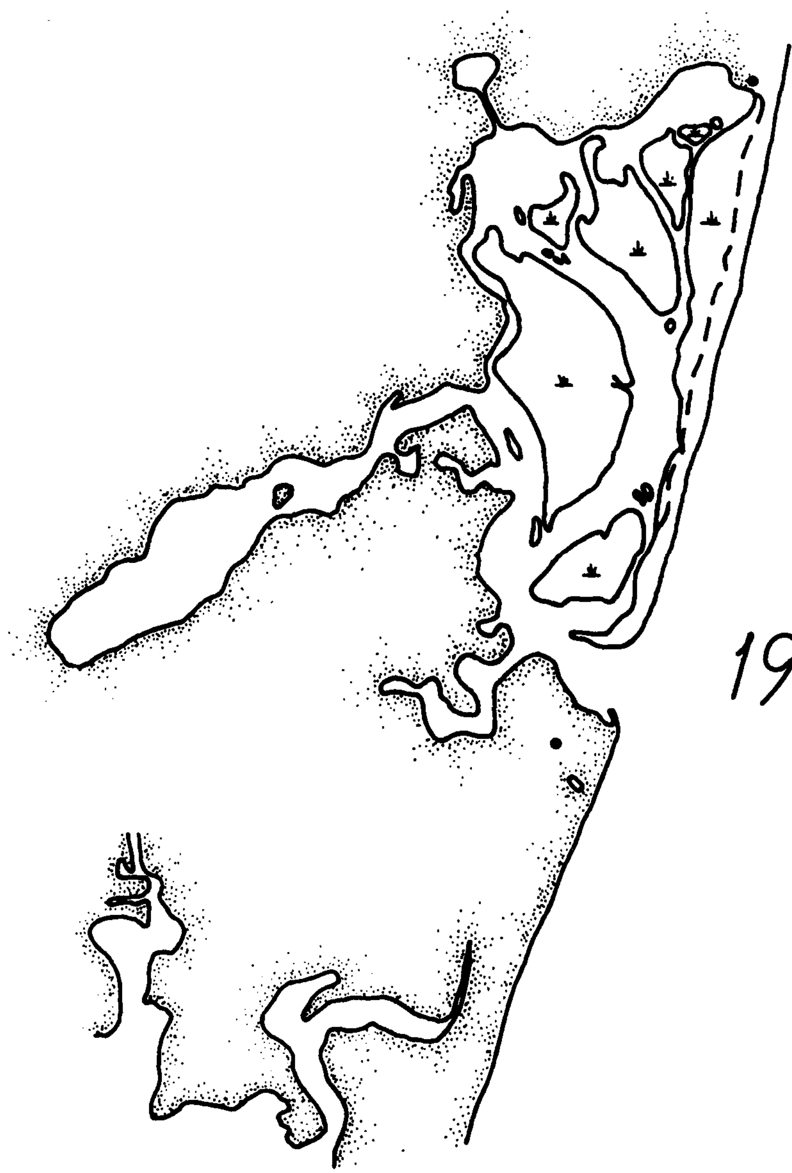
1893

1910



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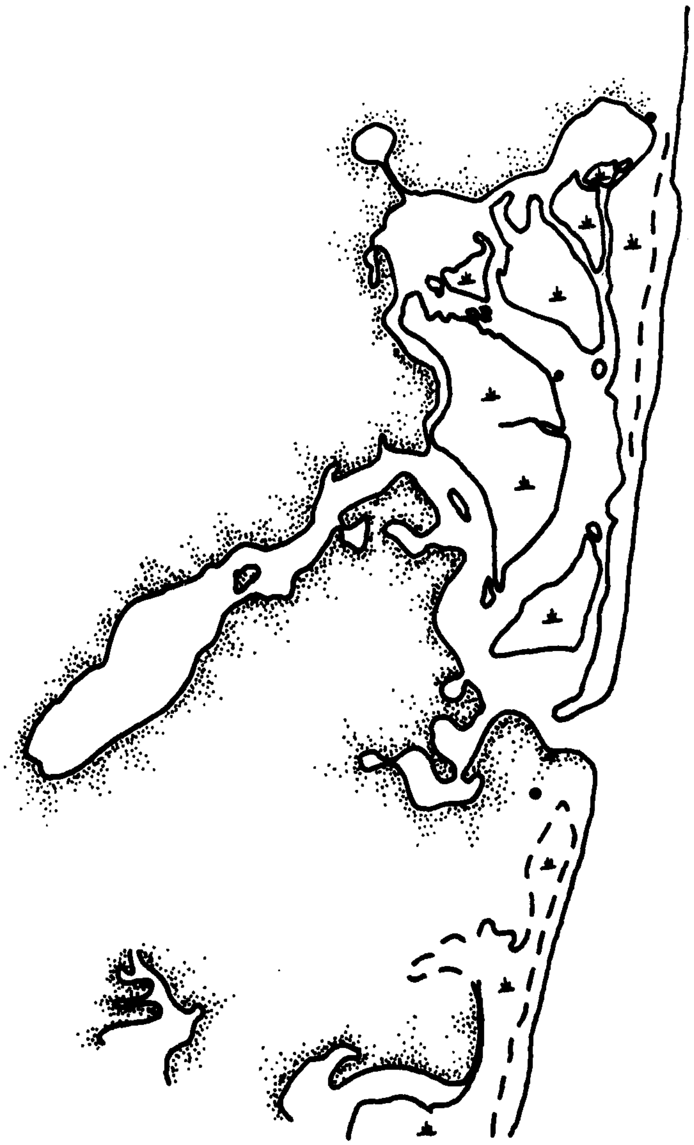
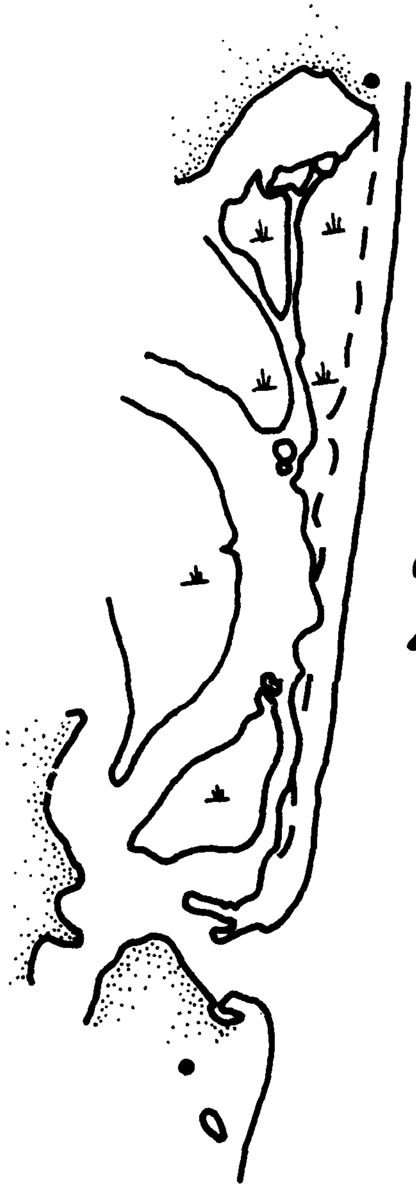
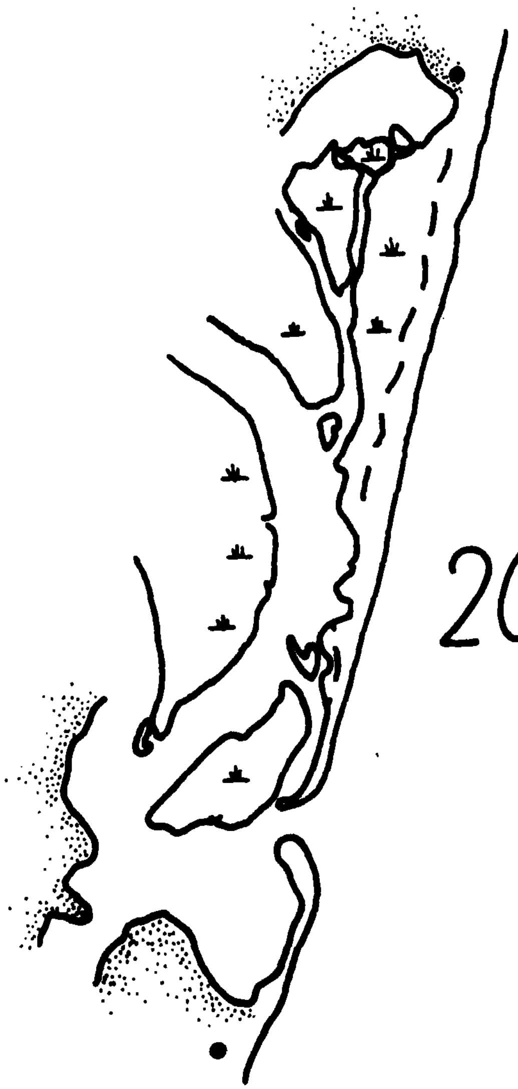


1946



21 NOVEMBER
1938



20 OCTOBER
1951


3 JUNE
1952


15 MARCH
1955

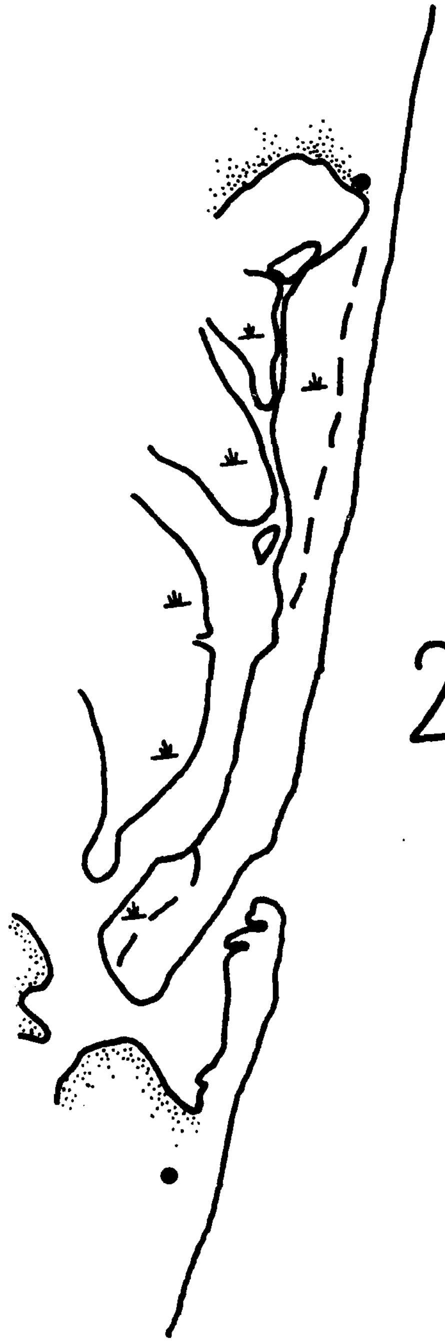
23 SEPTEMBER 1958


20 APRIL
1960

13 SEPTEMBER
1960


23 MARCH
1962

21 APRIL 1965



24 SEPTEMBER
1970


27 MAY
1972

21 FEBRUARY
1974


18 MARCH
1975

MAY
1976


4 MAY
1978


22 MAY
1979

AD-A119 916 WOODS HOLE OCEANOGRAPHIC INSTITUTION MA F/G 8/6
BEACH CHANGES AT NAUSET INLET, CAPE COD, MASSACHUSETTS 1670-198--ETC(U)
AUG 82 P E SPEER, D G AUBREY, E RUDER
UNCLASSIFIED WHOI-82-40 ARO-16710.7-GS NL

2 of 2

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5. Report Date
August 1982

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7. Author(s)
P.E. Speer, D.G. Aubrey and E. Ruder

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts 02543

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C)
(G) NA80-AA-D-00077 (R/B-21)
DAAG29-81-K-0004

12. Sponsoring Organization Name and Address
NOAA, Office of Sea Grant
U.S. Army Research Office

13. Type of Report & Period Covered
Technical Report

14.

15. Supplementary Notes
This report should be cited as: Woods Hole Oceanog. Inst. Tech. Rept. WHOI-82-40.

16. Abstract (Limit: 200 words)

A historical study of barrier beach and inlet changes for the Nauset Inlet region, Cape Cod, Massachusetts, was performed to document patterns of beach and inlet change as a preliminary to designing and carrying out field studies of inlet sediment transport. 120 historical charts from 1670 and 125 sets of aerial photographs from 1938 formed the basis for this study. Specific aspects of barrier beach and inlet change addressed include onshore barrier beach movement, longshore tidal inlet migration, and longshore sand bypassing past the inlet. In an effort to correlate forcing events with barrier changes, an exhaustive study of the local storm climate was performed. Detailed treatment of the specific mechanisms responsible for Nauset Inlet migration episodes in a direction opposite the dominant littoral drift are treated in a companion paper by Aubrey, Speer, and Ruder (1982). Documentation of the data base available for the Nauset Area is presented herein as appendices.

17. Document Analysis a. Descriptors

1. Barrier beaches
2. Tidal inlets
3. Inlet bypassing

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report) Unclassified	21. No. of Pages 92
	20. Security Class (This Page)	22. Price

(See ANSI-Z39.18)

OPTIONAL FORM 272 (4-77)
(Formerly NTIS-35)
Department of Commerce

Woods Hole Oceanographic Institution
WHOI-82-40

BEACH CHANGES AT NAUSET INLET, CAPE COD, MASSACHUSETTS 1670-1981 by P. E. Speer, D. G. Aubrey and E. Ruder. 92 pages. August 1982. Prepared for NOAA, Office of Sea Grant under Grant NA80-AA-D-00077 (R/B-21) and the U.S. Army Research Office under Grant DAAG29-81-K-0004.

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3. Inlet bypassing

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II. Aubrey, D. G.
III. Ruder, E.
IV. NA80-AA-D-00077 (R/B-21)
V. DAAG29-81-K-0004

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