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RAPID FORMATION AND DEGRADATION OF BARRIER SPITS IN AREAS WITH LOW RATES OF LITTORAL DRIFT*

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ABSTRACT

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A small barrier beach exposed to low-energy waves and a small tidal range (0.7 m) along Nantucket Sound, Mass., has experienced a remarkable growth phase followed by rapid attrition during the past century. In a region of low longshore-transport rates, the barrier spit elongated approximately 1.5 km from 1844 to 1954, developing beyond the baymouth, parallel to the adjacent Nantucket Sound coast. Degradation of the barrier spit was initiated by a succession of hurricanes in 1954 (Carol, Edna and Hazel). A breach opened and stabilized near the bay end of the one kilometer long inlet channel, providing direct access for exchange of baywater with Nantucket Sound, and separating the barrier beach into two nearly equal limbs. The disconnected northeast limb migrated shorewards, beginning near the 1954 inlet and progressing northeastward, filling the relict inlet channel behind it. At present, about ten percent of the northeast limb is subaerial: the rest of the limb has completely filled the former channel and disappeared. The southwest limb of the barrier beach has migrated shoreward, but otherwise has not changed significantly since the breach.

A new mechanism is proposed for spit elongation when the inlet thalweg parallels the beach axis, in which material scoured from the lengthening inlet is the dominant source for spit accretion (perhaps initially deposited as a linear channel-margin bar which later becomes subaerial). The lengthening spit causes the parallel inlet to elongate, which in turn further lengthens the spit, in a self-generating fashion. This mechanism provides both a source of sediment for elongating the barrier spit, and a sink for material scoured from the lengthening inlet. The proposed mechanism for spit growth may be applicable to other locations with low wave energy, small tidal prisms and low longshore sand transport rates, suggesting that estimates of directions and rates of longshore sand transport based on spit geomorphology and development be scrutinized on a case-by-case basis.

INTRODUCTION

The development and evolution of barrier beaches along the world's coastline have long been a concern of scientists and the lay public, engendering considerable debate over possible causes of change (see, for example, Hoyt, 1967; Otvos, 1970; Bruun, 1978; Halsey, 1979; Kraft et al., 1979;

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Leatherman, 1979). The study of barrier beaches includes the development of associated tidal inlets as a major element in barrier systems. Accelerating construction in the coastal zone and increased public awareness of environmental issues in general have led to new concern over both barrier beaches and tidal inlets.

The present study examines the recent evolution of a particular barrier spit whose development cannot be explained by conventional ideas of spit elongation. The need for a new hypothesis to explain spit development reinforces the importance of careful scrutiny of many aspects of coastal processes when applied to a given coastal region.

Background

A common mechanism for elongation of barrier beaches is through accretion by longshore transport (a good example of this is Monomoy Island off Chatham, Cape Cod, Mass.). A second mechanism for spit elongation is associated with migration of a tidal inlet (an example is Nauset Inlet, Mass., where one spit lengthens and the other spit shortens as the inlet migrates). Commonly, one end of a barrier island may accrete while the updrift end erodes (e.g. Assateague Island; Shepard and Wanless, 1971). Both of these mechanisms require an active longshore transport of sand. The present paper proposes another mechanism for beach elongation, independent of longshore sand transport rates, which may occur under restricted combinations of wave conditions, tidal range and prism, and beach orientation.

Barrier beaches with their associated tidal inlets and varied morphological elements reflect the response of sediment to subaerial and subaqueous forcing. A number of features are characteristic of most tidal inlets; any given inlet may have a few or all of these features, depending on the wave and tidal regime, as well as bay size and geometry. The primary features relevant to a discussion of barrier-beach elongation are: (a) main inlet channel or throat, which may vary in maximum depth from one meter to tens of meters; (b) a flood-tide delta, composed of five or more sub-elements (see Oertel, 1972, or Hayes, 1975, for alternative morphological classification schemes); (c) an ebb-tide delta consisting of a broad platform bordered seaward by a terminal lobe with a steepened slope leading to deeper water; (d) channel-margin linear bars which border the main inlet channel across the ebb-tide delta; (e) flood channels separated from the deeper main channel by channel-margin linear bars; and (f) distal shoals or swash bars located along the ebb-tide delta.

The longshore sand transport generally cited for increasing barrier-beach length arises from the oblique incidence of water waves breaking on the beach (Komar and Inman, 1971). Sand transported along a barrier beach must bypass any inlets along the barrier, else downdrift starvation will initiate beach erosion. Two pathways for bypassing sediment past inlets have been proposed (Bruun, 1978): (a) bar-bypassing, in which sand moves along the seaward portion of the ebb-tide delta onto the downdrift shore; or (b) tidal bypassing, in which sediment enters the inlet on flood tide and exits on ebb tide, resulting in a net downdrift movement through some poorly understood mechanism. Channel-margin linear bars and other morphological features mirror this bypassing mechanism in some complex manner.

Setting

Popponesset Beach (Fig.1) is a barrier beach located on Nantucket Sound in the town of Mashpee, Cape Cod, Mass. The beach consists of sand derived from unconsolidated sediment deposited during late Wisconsinan retreat of the Cape Cod Bay glacial lobe (Oldale, 1976). These gravelly sands comprise an outwash plain (the Mashpee Pitted Plain Deposits), and ice-contact deposits (in the region west of the beach, including Great Neck).

The limits of the littoral cell for Popponesset Beach appear to be the entrance jetties to Waquoit Bay to the west, Osterville Point to the east, and the seaward (south) edge of Succonnesset Shoals offshore (Aubrey and Gaines, 1982). Net direction and rate of longshore transport within the cell are still conjectural (Strahler, 1966; U.S. Army Corps of Engineers, 1972; Brownlow, 1979; Camp et al., 1981), but probably includes a regional convergence near Cotuit Bay. Net sand transport between the Waquoit jetties and Cotuit Bay is generally to the east or northeast; net longshore transport between Osterville Point and Cotuit Bay is to the west. Considerable fluctuations in short-term longshore transport direction have been documented.

The tide near Popponesset is semidiurnal, with a mean range of 0.7 m. Tidal currents in the shallow nearshore region typically reach 0.5 m/s, due to tidal interference phenomena in Nantucket Sound (Redfield, 1980). These currents are sufficient to move sediment in the offshore regions of Popponesset. Tidal flows through Popponesset Inlet have an even higher maximum velocity. Visual observations of the wave climate at Popponesset indicate a dominance of high-frequency wind waves locally generated within Vineyard and Nantucket Sounds. Longer-period seas and swells apparently are filtered effectively by Monomoy Island, Nantucket, Martha's Vineyard and their intervening shoals.

METHODS

Charts and maps

Approximately 92 charts and maps, dating from 1670 to 1979, were studied to document trends in shoreline changes (Aubrey and Gaines, 1982, appendix 1). The charts and maps can be divided into three groups: (1) early maps (1670—1857); (2) U.S. Government charts (1857—1938); and (3) maps and charts after 1938. Early maps were generally small-scale, reproduced by hand, and many were prepared for political or economic purposes rather than for navigation. Some of them do not rigorously represent sand features along the shoreline or other features of interest to this study. For example, the 1795 Lewis map of Massachusetts, evidently copied many times through

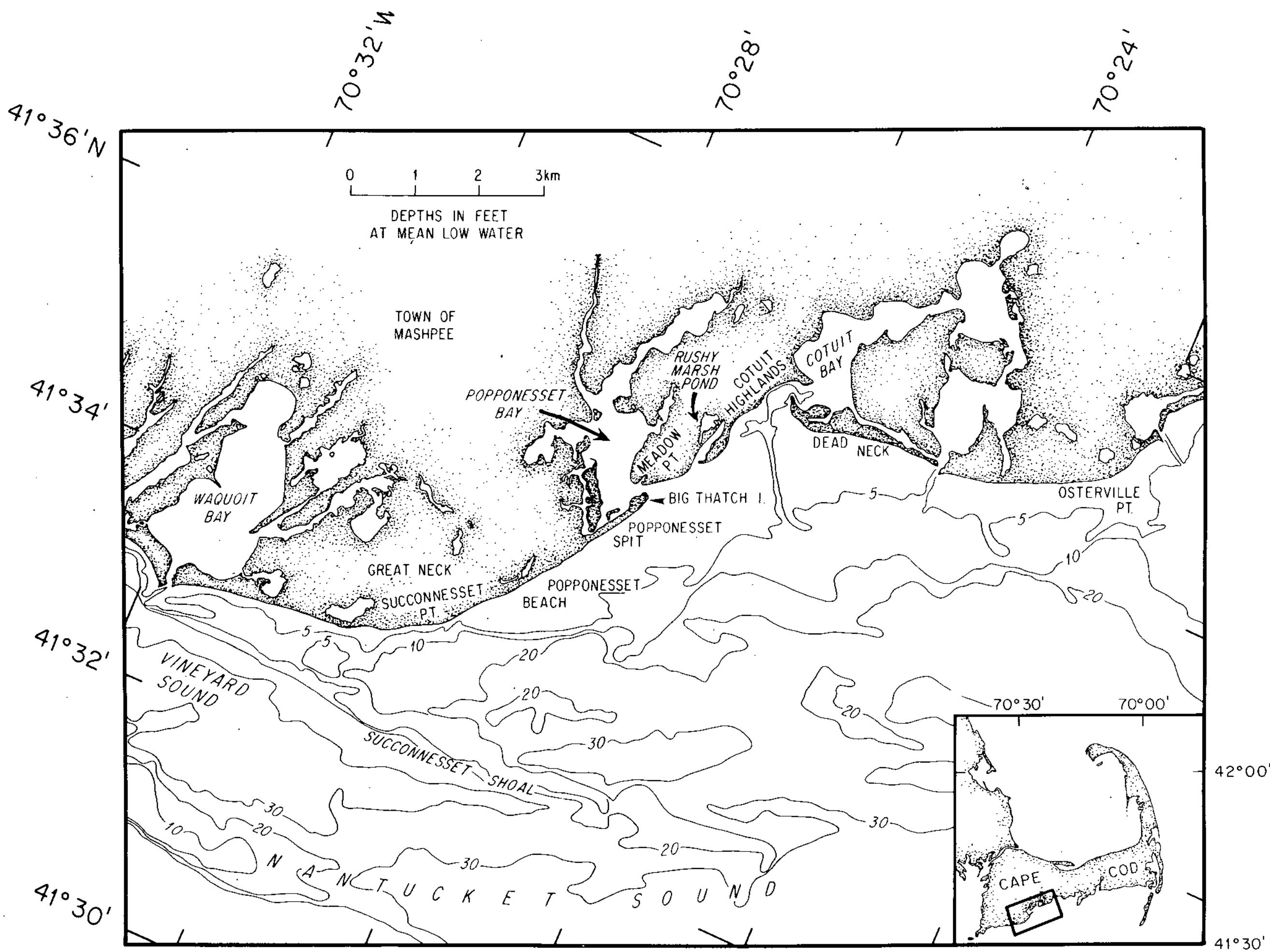


Fig.1. Location map for Popponesset Beach, Cape Cod, Mass. Popponesset Spit is in the middle of the map.

1836 (without acknowledgement) for use as a base map for political and economic purposes, did not record the date of the actual survey or special purposes influencing the accuracy of the mapped features. Therefore, while valuable for perspective, interpretation of these maps requires special caution. Maps and charts prepared and printed by government agencies became available in 1857. Most are based on better-defined survey techniques than earlier maps. Especially useful are the U.S. Coastal Survey charts (1860—1920), although irregularities in updating this series mandate careful interpretation. A chart dated 1910, for instance, might actually include portions of a survey from 1870. An apparently related series of charts by Walker (1892—1915) also provides good perspective regarding shoreline changes at the study area, although both of these series are at a small scale (1:80,000). An especially valuable map produced for the towns (at a scale of about 1:5000) is the 1894 plan of the Mashpee/Barnstable town line. This map was intended primarily to locate stone monuments defining the town boundary, but also gives detailed bathymetric information behind Popponesset Spit and in the bay. The third category of maps and charts, those prepared after 1938, were less useful to this study than the vertical aerial photographs that became available beginning that year, except for bathymetric information.

Vertical aerial photography

Aerial photographs (Aubrey and Gaines, 1982, appendices 2 and 3) are available from 1938 through the present, providing good coverage of the Popponesset Beach area, with the single exception of the period 1955—1960. Vertical aerial photographs were used to quantify shoreline changes and movement of offshore shoals. The inevitable variability in camera and image quality as well as photograph scale necessarily produced some scatter in the results. Measurements were taken relative to a baseline (parallel to Popponesset Spit) established between well-defined, permanent features identified on each set of aerial photographs. All other measurements were referenced to the known separation between two points on this baseline. Because of the equipment used and the widely diverse scales in the photographs, maximum resolution of coastal features was 10 m, even though some photo sets afforded better resolution.

RESULTS

Analysis of historical charts and photographs reveals a sequence of changes to Popponesset Beach over the past two centuries. Specific facets of change include: (a) sand-spit elongation/shortening; (b) onshore-spit migration; (c) variability of barrier-beach width; and (d) longshore sand transport rates. Other aspects of beach evolution and development (such as breaches, overwashes and changes in islands and adjacent barriers) are discussed in Aubrey and Gaines (1982).

Sand-spit elongation/shortening

Key stages in the evolution of Popponesset Spit were identified in the charts and aerial photographs (Figs.2—5). The dominant feature in beach evolution was the elongation of the spit from 1844 to 1954, and subsequent attrition since that time. Early historical charts show Popponesset Spit approximately the same length as it is now, extending only across the mouth of Popponesset Bay from Great Neck to Meadow Point (about 1.3 km; Fig.2, *1787* and *1831*). The earliest of many charts showing Popponesset Spit at this length in clear detail is the Desbarres chart (1779); charts before 1779 do not have sufficient detail to identify Popponesset Spit with confidence. Popponesset Spit appears to have remained stable in length (with one exception) through 1844. The exception (an 1810 chart by Lewis, along with exact copies by Carey in 1822 and Lucas and Fielding in 1826) shows no spit across Popponesset Bay. These charts are discounted because they show the shoreline only schematically, without details of barrier beaches, while

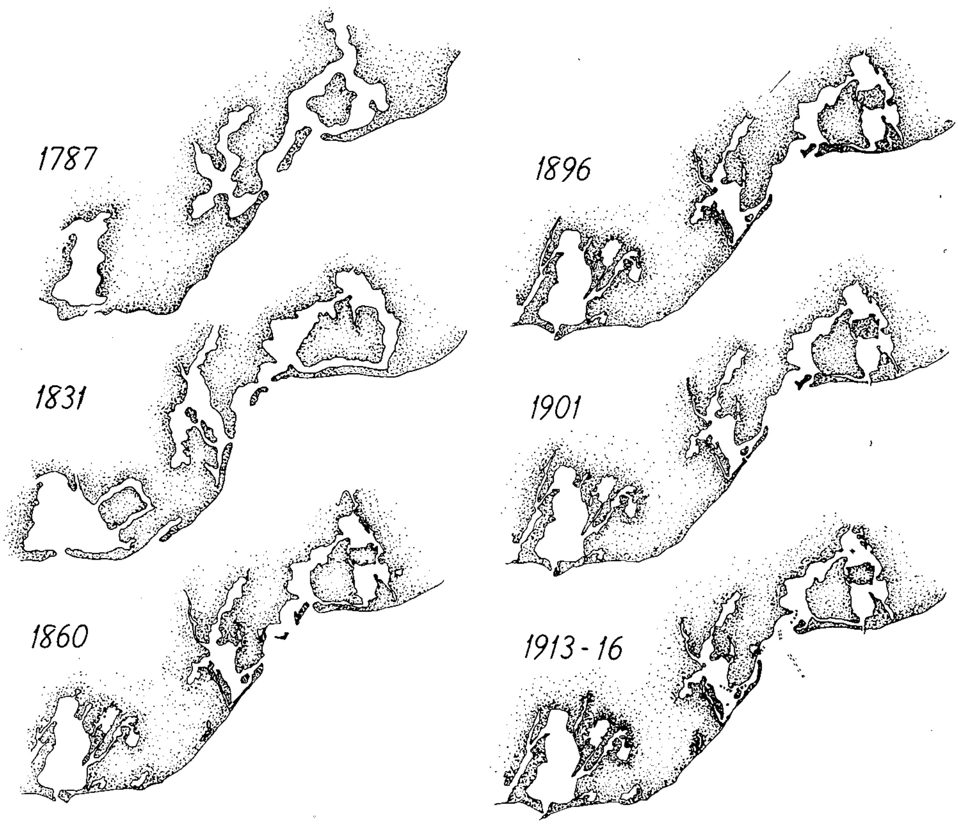
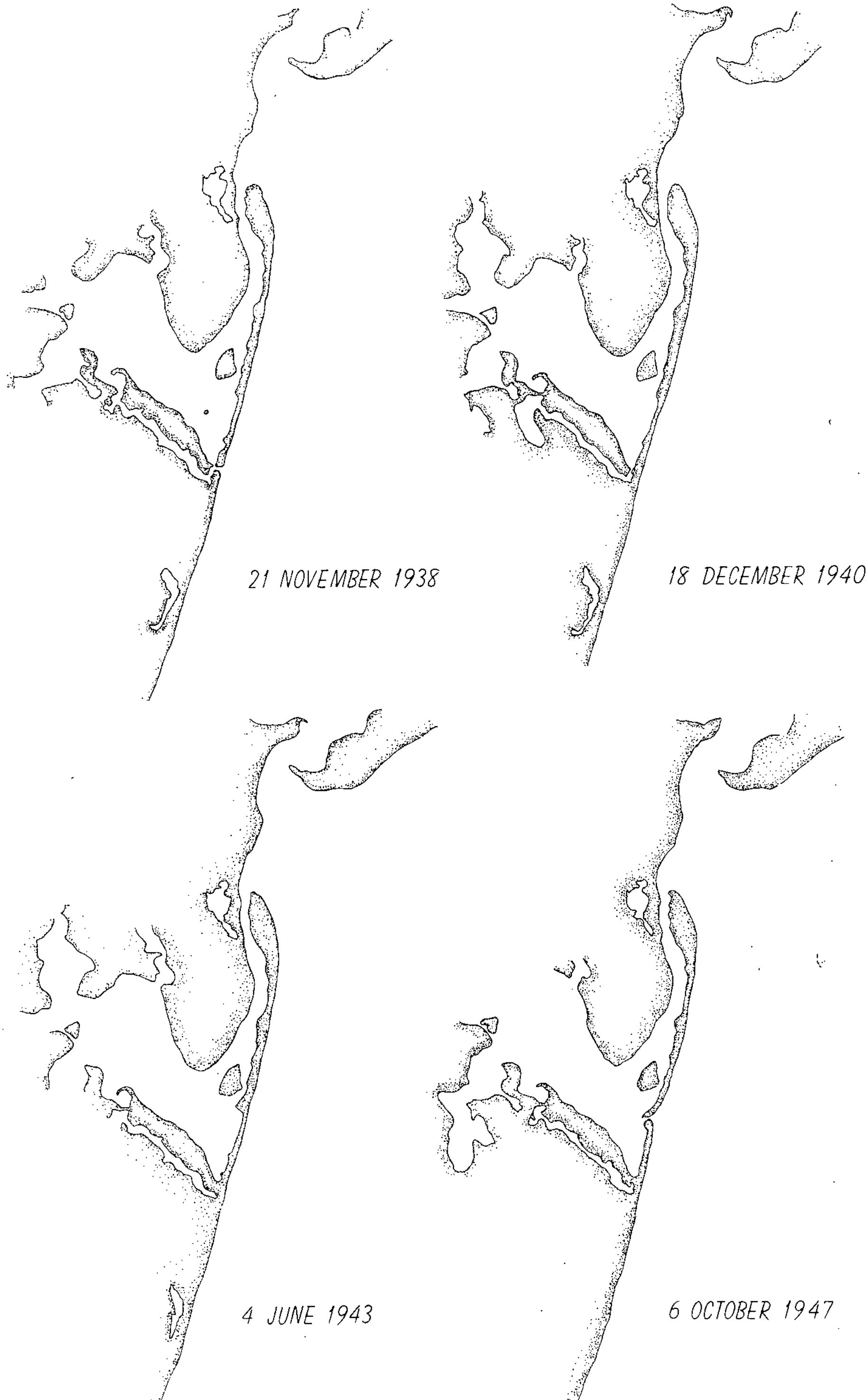


Fig.2. Outlines of selected historical charts and maps illustrating stages of shoreline evolution of Popponesset Spit, 1787—1916.

many other maps spanning the same period clearly document the existence of the spit.

The first significant change in spit configuration is depicted on an 1857 U.S. Coast and Geodetic Survey (USC&GS) chart and an 1857 chart by Bache which suggest spit elongation towards the northeast (Fig.2, *1860*), extending past Meadow Point. Subsequent charts and aerial photographs indicate this trend continued through 1954, when the spit extended past Rushy Marsh Pond. At its maximum development in 1954, the spit was approximately 2.8 km long. Early stages of the elongation process are clearly depicted on the Coast and Geodetic Survey series from 1860 through 1917 (at a scale of 1:80,000). From 1900 to 1954 the spit grew in a northeasterly direction approximately 1 km (Figs.3 and 4).

In 1954, a series of three hurricanes (Carol, Edna and Hazel) created a breach on the northeast side of Big Thatch Island, effectively separating the barrier spit into two approximately equal limbs; a northeast (NE) limb and a southwest (SW) limb. This breach occurred at the base of the main inlet channel (Fig.4, *1955*) and provided a short alternative channel for direct water exchange between the bay and Nantucket Sound, bypassing the much longer preexisting inlet channel (nearly 1 km long). The new breachway became the prime conduit for tidal exchange between the two bodies of water. Its establishment marked the initiation of the disappearance of the northeast limb of the barrier. At first, attrition of this part of the beach was rapid and gradually slowed (Fig.6) so that it had nearly disappeared by 1982. After 1960, attrition progressed by erosion of sediment from the southwest end of the northeast limb, with deposition behind the beach in the former inlet channel, which had depths up to 4 m (1894 chart). In 1982, the short remnant northeast limb of the spit still protected the relatively deep relict former inlet channel behind it (Fig.5). Since the northeast limb shortened from its southwest end, proceeding in a northeastward direction, other studies have interpreted the attrition as evidence of intense littoral drift toward the northeast. This explanation of spit attrition would require a longshore drift of more than 9000 m^3/yr; and a sink for about 250,000 m^3, neither of which has been accounted for by the proponents. Alternatively, because of the shape of the north spit since 1970 (the fact that it is similar in appearance to a southwest-growing spit) one might interpret the longshore drift as being in the opposite direction, an inference fraught with difficulties. Actual movement of sand has been principally in a landward direction — to the northwest. At its northeastern extremity, where the spit was widest, landward sand movement was sufficient not only to close the former mouth of the inlet near Cotuit Bay, but also to produce a subaerial attachment of this end of the beach to the mainland near Rushy Marsh Pond, effectively ending attrition at this end. Attrition of the northeast limb was not controlled by major storm events, but rather has occurred at a fairly regular rate since 1961 (Fig.6). Overwash and breaching appear to have had less important roles in attrition of the northeast limb than intertidal and/or subaqueous truncation of its end.


21 NOVEMBER 1938
18 DECEMBER 1940
4 JUNE 1943
6 OCTOBER 1947

In contrast, the southwest limb of the barrier beach, which lacks an appreciable sediment sink immediately behind it, has not experienced comparable attrition. Since the breach of 1954, the length of the south spit fluctuated only a little up to 1978 (Fig.6). This fluctuation probably mirrors both man-made (e.g. 1961 dredge-spoil disposal) and natural processes (such as the gradual elongation and reorientation of the spit towards the shore at Meadow Point).

Onshore spit migration

Photographic records since 1938 provide detailed information on shoreward migration of the barrier spit (Figs.3 and 4). These data indicate onshore migration has not been uniform either in time or location along the spit (Figs.7 and 8). At Station G, near Big Thatch Island, total shoreward migration from 1938 to 1978 has been about 140 m, an average rate of about 3.5 m/yr. From 1938 to 1955, the rate of retreat was about 1.7 m/yr and from 1960 to 1975 it slowed to about 1.2 m/yr. Between these periods, immediately following 1955, a shoreward displacement at this station of 65 m resulted from the hurricanes of 1954. Coalescence of the barrier beach with Big Thatch Island was associated with these storm events (Fig.4, *1951*, *1955*). A similar displacement of about 30 m appears to be due to the blizzard of 1978. Thus more than half of the shoreward migration at Station G appears to be associated with major storms, a quantity added to the more continuous onshore movement averaging about 1.5 m/yr at this station.

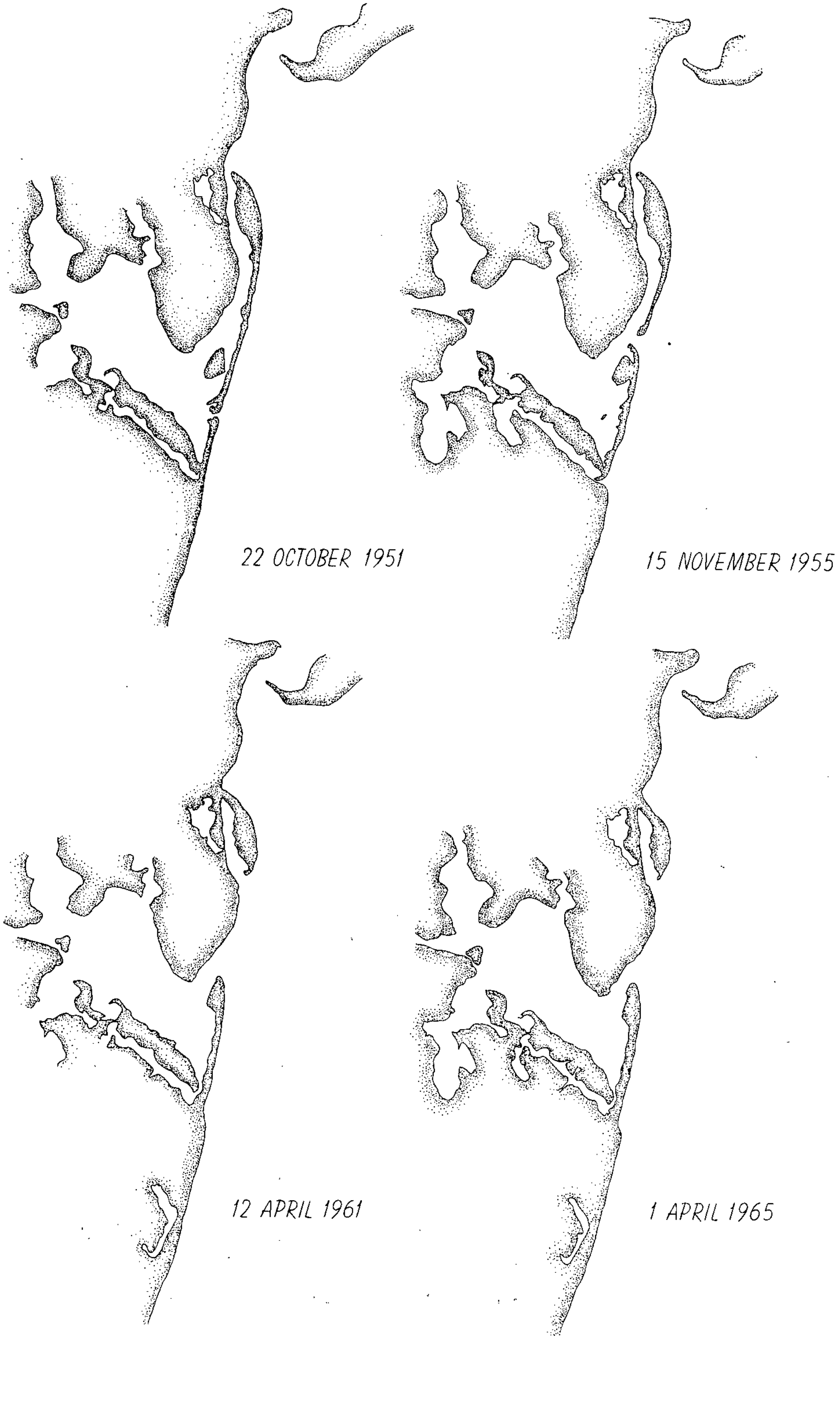
The effect of the 1954 hurricane at Station F, near Popponesset Island, is even more distinct. At this station regular shoreward migration has been slower, averaging less than 0.1 m/yr before 1954 and about 0.2 m/yr from 1955 through 1978, for a total of about 5 m movement. The storm displacement at this station, however, amounted to about 50 m, by far the more significant amount. The difference in total onshore movement from one station to the other indicates the southwest limb of Popponesset Spit has rotated counterclockwise since 1938 or earlier.

Historical changes are more complicated along the northeast limb of the spit. All stations show a period of gradual seaward movement, followed by rapid shoreward movement. Station N, to which position the spit had grown by 1947, shows a general pattern similar to that of the other stations, but displaced in time (Fig.8). Seaward movement at this station appears to have resulted from widening of the beach.

Barrier-beach width

As barrier beaches undergo onshore migration, their width may vary. Narrowing is important since it reduces effectiveness as a natural barrier

Fig.3. Outlines of selected vertical aerial photographs illustrating stages of shoreline evolution of Popponesset Spit, 1938—1947.


22 OCTOBER 1951
15 NOVEMBER 1955
12 APRIL 1961
1 APRIL 1965

against storm damage. Determination of beach-width statistics from photographs involves two complicating factors: first, the resolution of features on photographs with the techniques used is about 10 m, and second, natural beaches generally exhibit a seasonal cycle in width that must be distinguished from long-term trends.

Perhaps the most salient feature of the beach-width data is that loss of the northeast limb after 1955 is not associated with thinning of the spit (Fig.9). Along the remnants of the northeast limb of the barrier beach, widths remained fairly constant through time, even though the barrier itself moved shoreward a distance of at least 100 m. At Stations H and I beach width remained about constant, and Stations J and K actually may have widened just prior to loss of the spit at those sites. This contradicts, once again, the concept that beach attrition at Popponesset resulted from losses by longshore drift.

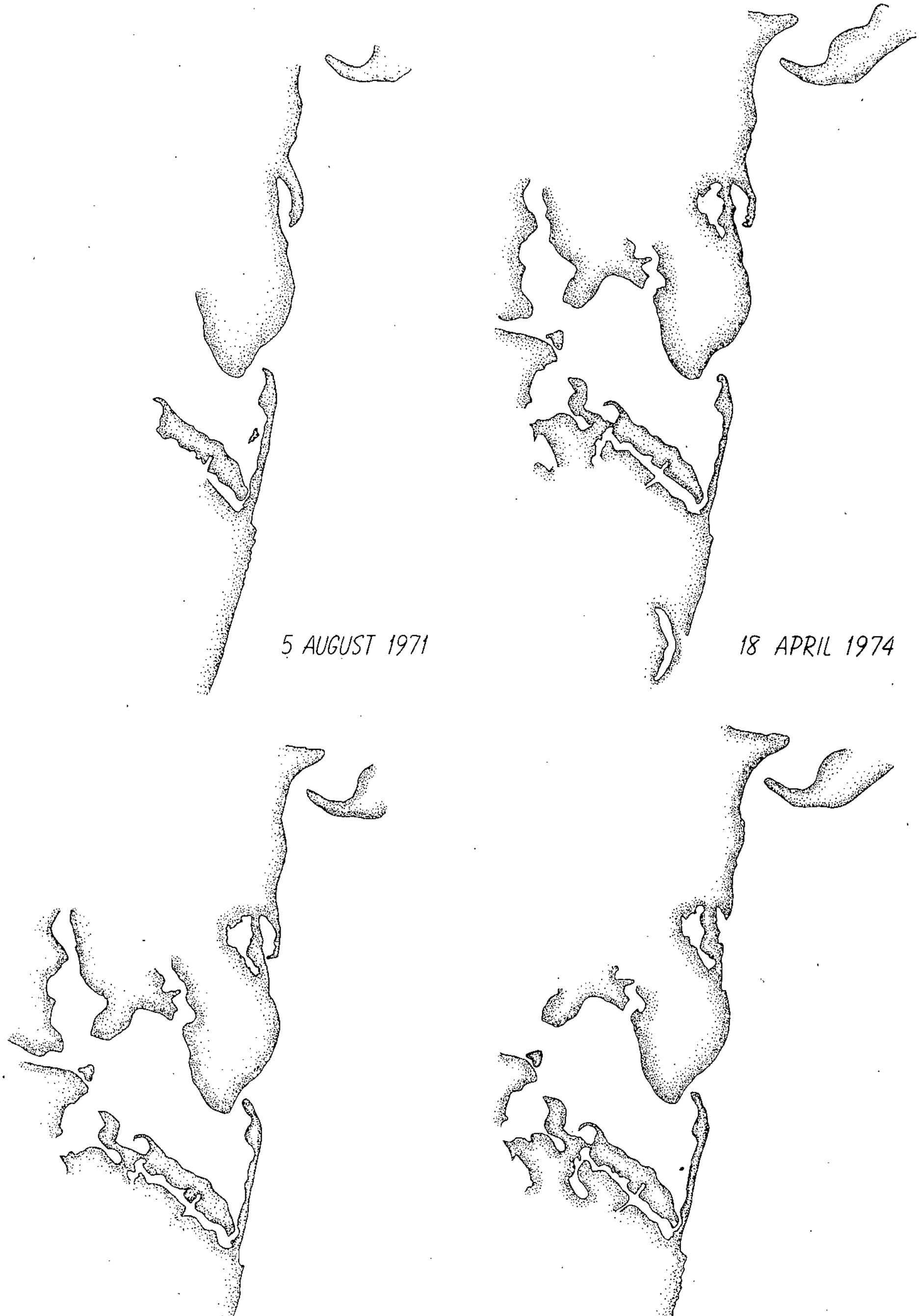
Along the southwest limb the trend varies with location. At the extreme southwest end (Station F), the beach has maintained a constant width of 40—50 m (disregarding temporary breaching events there). The central portion of this spit (Station G.) has been narrowing since 1938, from a width of about 70 m in 1938 to a minimum of 35 m in 1978, with significant short-term variability superimposed (Fig.9). Other sites on the present spit do not show this long-term thinning trend (e.g. Station F). The beach near Station G has been overwashed and breached since 1892, including several events since 1970. At the north end of the present spit, the width temporarily increased due to incorporation of Big Thatch Island onto the spit (which occurred by 1955). After the merger, however, the beach has been narrowing at this point.

Longshore sand transport

Direct field measurements of longshore sand transport are rarely available for coastal studies, so indirect lines of evidence are generally used to estimate this quantity. Since the directional wave climate for the Popponesset area is not known, calculations of longshore transport using momentum-flux arguments are not possible. Three lines of evidence pertain to indirect determination of longshore transport rate at Popponesset Beach: (a) entrapment of sand by structures; (b) analysis of sediment sources; and (c) persistence of nearshore depressions. These indirect lines of evidence suggest that the net longshore transport rate past Popponesset Beach is much less than previously assumed.

(a) Entrapment of sand by structures — Between 1950 and 1955, nine short (40 m) groins were constructed along the shore southwest of Popponesset Spit. Often these groins are only partly filled by sand, and the accretion fillet alternates orientation, suggesting that the longshore transport rate is

Fig.4. Outlines of selected vertical aerial photographs illustrating stages of shoreline evolution of Popponesset Spit, 1951—1965.


5 AUGUST 1971
18 APRIL 1974
8 MAY 1978
19 APRIL 1981

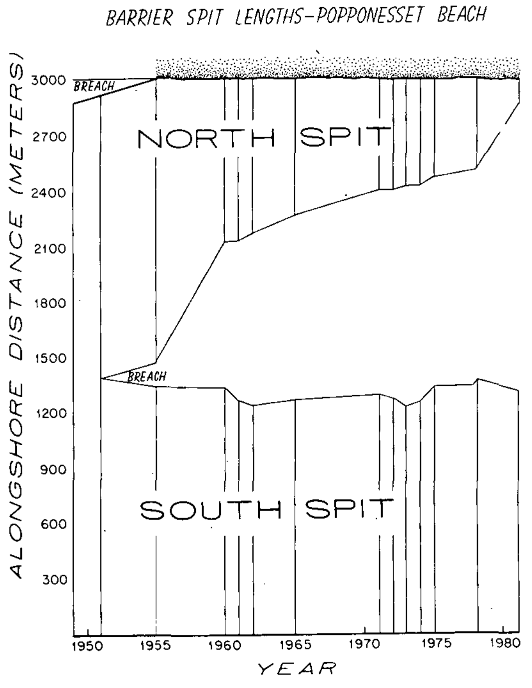


Fig.6. Changing length of Popponesset Spit since 1938. The inlet was initially located at the north of a single long spit; in 1954 a breach occurred midway on the barrier, separating it into two nearly equal limbs. The northeast and southwest limbs subsequently underwent different patterns of change.

low and variable in direction. If the longshore transport rate were large, the groins would be filled to capacity and overtopped. Construction of these nine groins a few years preceeding the attrition phase of Popponesset Spit led to the belief that they were responsible for the breakup of the spit. A simple calculation indicates the volume of sediment trapped by the groins is small (order of 1000 m^3) and unlikely to have such a significant impact on the development of the spit (involving about 250,000 m^3 of sand).

(b) Analysis of sediment sources — The area defined by Aubrey and Gaines (1982) as the littoral cell encompassing Popponesset Beach has limited source potential. Little sand can bypass either Waquoit jetties or West Bay jetties, and streams or rivers provide little sediment to the coast on Cape Cod. Onshore sediment transport has not been rigorously evaluated, although historical information suggests longshore movement of sediment in the sandwave field offshore, and not onshore movement. Erosion of cliffs bordering the coast from Succonnesset Point to Popponesset Spit would provide a maximum of 3000 m^3 of sediment per year to the nearshore, only a fraction of

Fig.5. Outlines of selected vertical aerial photographs illustrating stages of shoreline evolution of Popponesset Spit, 1971—1981.

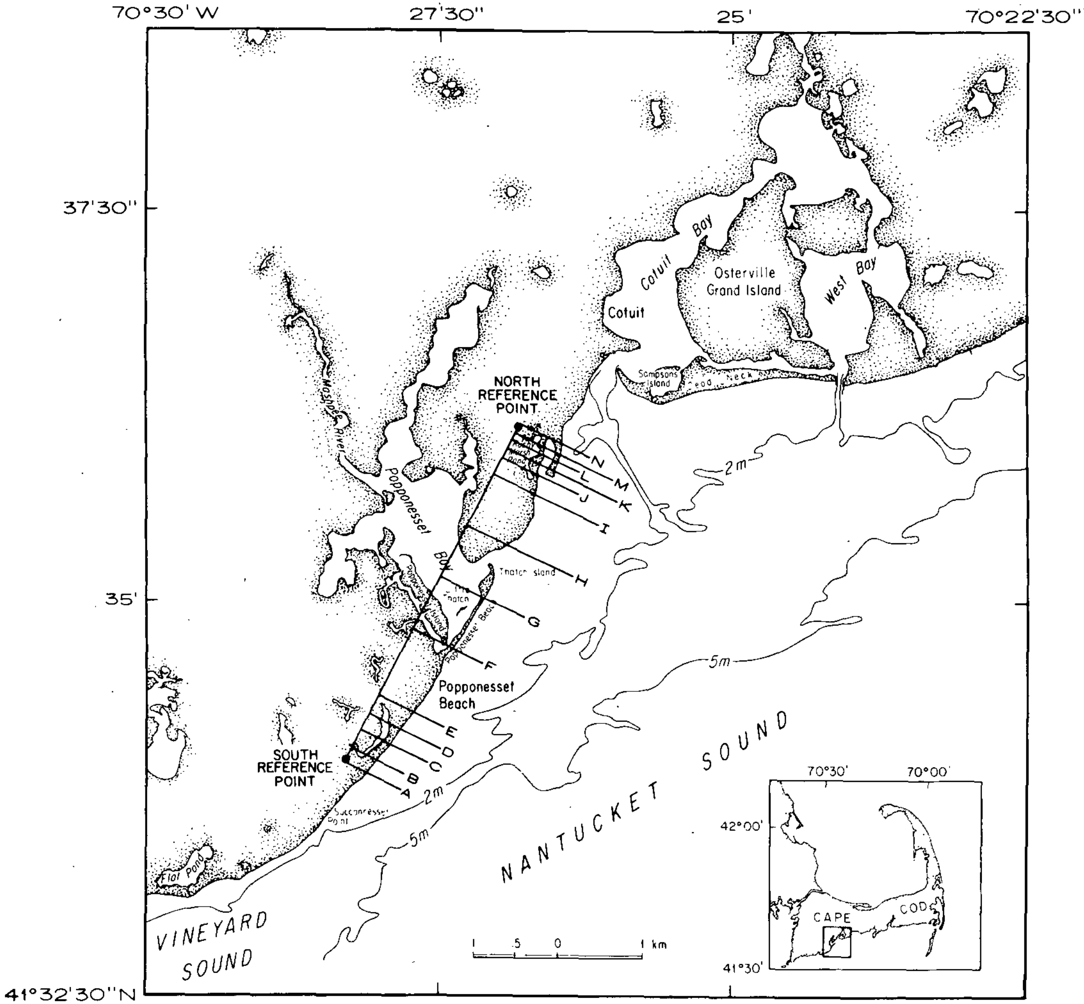


Fig.7. Reference line and perpendicular station lines used for shoreline measurements on vertical aerial photographs for Popponesset Spit. The north and south references are defined points readily visible on all photographs.

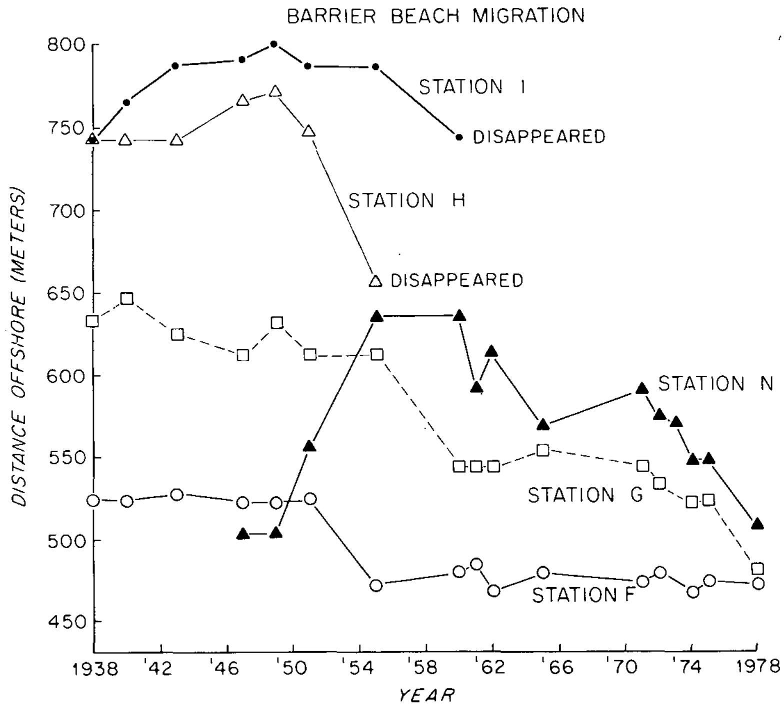


Fig.8. Onshore/offshore movement of the seaward shoreline at stations along Popponesset Spit (see Fig.4), 1938—1978.

which would move alongshore (Aubrey and Gaines, 1982). Consideration of available sources, therefore, suggests that the longshore transport rate is low.

(c) Persistence of nearshore depressions — Part of the former inlet mouth off Cotuit Highlands has not filled over the 27 years following its demise as the primary channel, which implies negligible gross and net longshore transport rates. In addition, a number of temporary breaches in the southwest limb of the spit persisted for several years, apparently in equilibrium with the primary inlet, suggesting again that longshore transport has been small. In fact, one breach persisting from 1951 to 1953 filled from the northeast — not from the southwest. The volume of sediment required to fill these temporary breaches was only of the order of 2000 m^3.

DISCUSSION

The remarkable growth and disappearance of more than 1100 m of barrier beach along a coast exposed to low tidal range and low wave energy cannot adequately be explained by longshore transport. Although the average rate of spit growth from 1900 to 1950 requires a net influx of sediment of only 5000 m^3/yr, this appears to exceed the upper limit for possible net longshore transport in this region. A second enigma resulting from the growth of the

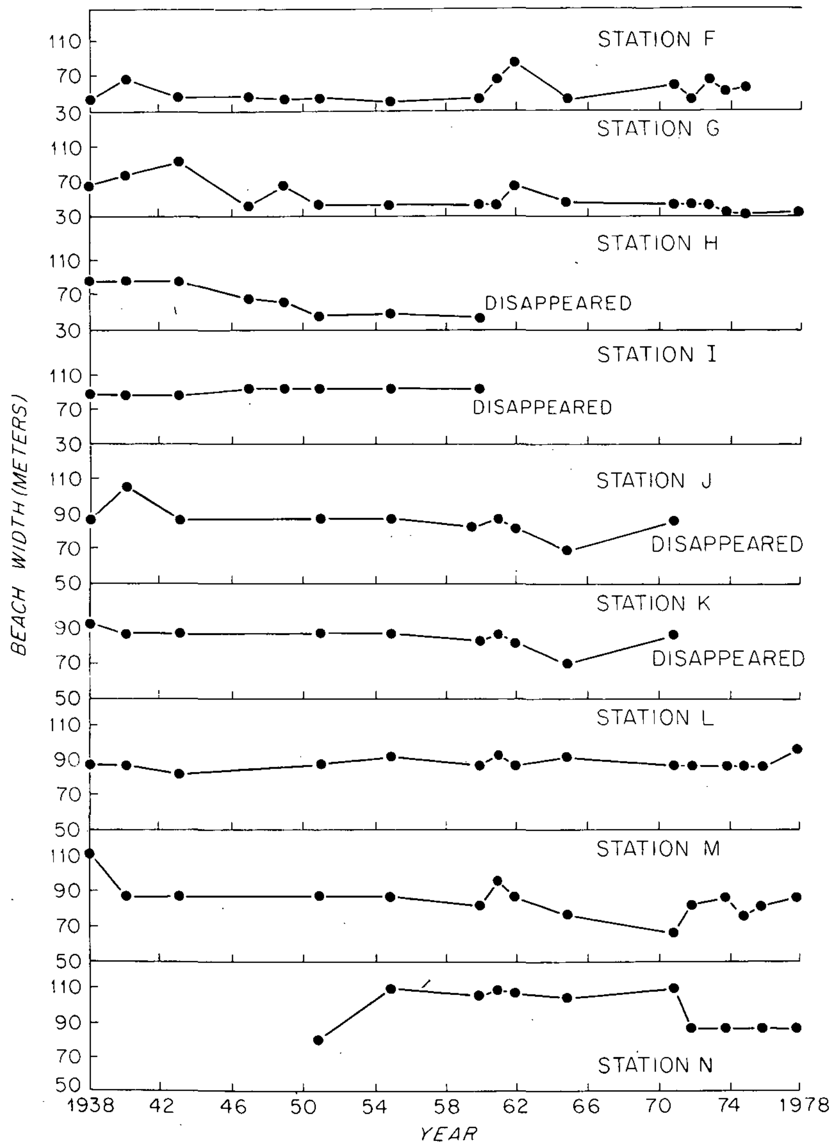


Fig.9. Beach widths at stations along Popponesset Spit, 1938—1978 (see Fig.7).

spit is the sink for sediment eroded from the inlet channel as it deepened and lengthened. Measurements of the inlet channel from accurate hydrographic surveys show a volume of approximately 250 m^3 per linear meter along channel, a quantity nearly identical with that accreted to form a linear meter of barrier beach. Ebb and flood tidal delta growth were not large enough to balance the sand lost from the channel.

Aerial photography shows a well-developed channel-margin linear bar along the barrier side of the inlet, parallel to the flood and ebb flows. Only a single channel-margin bar occurs because the opposite side of the inlet is a headland, not a barrier beach. Single channel-margin bars have been observed in other inlets around the United States. Byrne et al. (1977) documented a single (ephemeral) channel-margin bar at Wachapreague Inlet, Va., opposite a downdrift offset barrier; similar examples exist at Capers and Dewees Inlets in South Carolina as well as many other inlets (Shepard and Wanless, 1971).

We propose that the growth and degradation of Popponesset spit, in a regime of low longshore sand transport, can be explained by the following model (Fig.10). Initiation of the process of barrier-spit elongation is triggered as a barrier spit slightly overlaps an adjacent headland, directing the ebb-tidal flow sub-parallel to the coastline and existing barrier beach. In regions of low wave activity a channel-margin linear bar forms on the barrier side of the inlet, parallel to the barrier beach. This bar growth further channelizes the ebb flow, accelerating scour along the channel axis. Part of this eroded material builds up the linear bar (perhaps to a subaerial state), while part builds the ebb-tide delta. The channel scour and resulting linear bar buildup continue progressively parallel to the coast, further channelizing the ebb

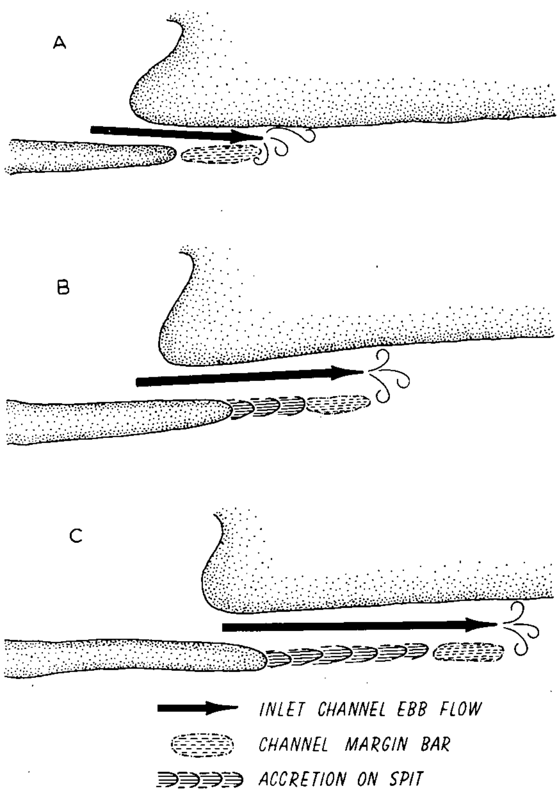


Fig.10. Schematic of spit genesis suggested by the present hypothesis. Ebb-tidal flows build up a linear channel-margin bar (A) which becomes subaerial (B), and finally lengthens the inlet throat parallel to the coast (C), in a self-generative fashion.

flows. The channel-margin linear bar accretes with material added from channel scour (and perhaps some longshore transport input). This process would continue indefinitely, increasing the hydraulic resistance in the channel until either a marked change in coastline orientation was reached, or a new inlet was formed with superior hydraulic characteristics (lower frictional losses, increased water exchange).

Material scoured from the lengthening inlet channel is moved and redeposited primarily during ebb tide because of inlet hydraulics. During flood tide, channel flow does not become fully developed until about midway along the inlet channel. This fully developed flood flow is in some balance with the cross-sectional inlet area over the remainder of the inlet throat (away from the ocean entrance), as is generally the case in any stable inlet. The jet-like flood flow expands and becomes more diffuse as it enters the bay, depositing any entrained sediment as a delta. On ebbing tide, however, the jet-like flow is fully developed when it reaches the ocean. If the channel is partly constricted by an emergent linear bar, the intense ebb flow will scour the channel further, until it passes the linear bar, finally expanding and losing its momentum. The ebb flow therefore accelerates scour near a linear bar, providing sediment to lengthen the linear bar and enlarge the ebb tide delta. In contrast, the flood flow has less scouring capability, since by the time it is fully developed it is in a region of the inlet whose cross-sectional area is already in some balance with the current. The tendency for scour during ebb flow is reinforced by the relationship between water level and maximum tidal currents. At maximum flood current, the water surface is above mean low water; at maximum ebb flow, the water surface is below mean low water.

The attrition phase begins with a breach in the barrier spit, dividing it into two limbs and relocating the primary inlet. Under the influence of wave activity and perhaps tidal flows (for an appropriate geometry), the ends of the detached limb would migrate shoreward, filling in the former inlet channel as it does so. Again, depending on the orientation of the spit relative to the direction of dominant wave approach and wave energy, the detached limb may move shoreward through conventional overwash processes, or progressively from one end to the other by truncation of one or both of the ends, as proposed here.

Popponesset Spit, the prototype for the proposed model, clearly demonstrates these developmental stages (Figs.2—5). From 1844 to 1954, the barrier elongated parallel to the coastline, extending and deepening the inlet channel. On photographs between 1938 and 1954, a channel-margin linear bar generally is visible off the end of the barrier. During the final years of barrier elongation, longshore sand transport provided some contribution to the spit growth, as revealed by a series of recurved spits near the barrier tip. In 1954, a breach off Big Thatch Island separated the barrier into two limbs; the northeast limb progressively shortened from the southwest, and migrated landward, filling in the former inlet channel. In 1981, there was little evidence of the elongated spit and former channel, other than three small, deep ($\sim$3 m) depressions along the former channel axis, and the segment of spit attached at its northern end near Rushy Marsh Pond. Otherwise there is no geomorphic evidence for past spit behavior.

Self-generative barrier spit elongation relies on the formation of a channel-margin linear bar, and small ebb- and flood-tide deltas. It is enhanced by a small (but not necessarily negligible) input of sediment through longshore transport. Given these restrictions, the same mechanism might occur in other locations having low tidal range, relatively small tidal prism (about 1.5×10^6 m^3), low wave energy and small longshore transport rate. Although probably not as widespread a mechanism for spit growth as longshore transport, the proposed self-generative sequence may cause spit growth in a number of locations. Existence of this mechanism suggests that longshore transport rates inferred solely from spit elongation must be interpreted with care.

SUMMARY

Three possible mechanisms cause barrier spits to elongate; two are generally known while a third is proposed here. The most commonly cited mechanism for spit elongation is downdrift buildup on the tip of a barrier spit from sand introduced by longshore transport. Examples of this mechanism abound; Cape Cod, Mass., has many examples such as Nauset Spit and Monomoy Island. A second mechanism is accretion on the end of a barrier spit bordering a tidal inlet; this is generally accompanied by erosion of the spit on the opposite side of the inlet. An example of this mechanism is Nauset Inlet. Sand is moving alongshore to the south, bypassing the inlet along the ebb delta, and occasionally welding to the south spit, episodically elongating that feature. If erosion of the updrift spit occurs at the same time (such as at Nauset inlet, Mass., where ebb flows erode the north spit), the inlet can migrate in a direction opposite that of longshore transport.

A third mechanism, proposed here, is self-generative in the sense that it does not require an external sediment source to elongate a barrier spit (although an external source could accelerate the process). This mechanism operates under a restrictive set of conditions, so it is not as common an occurrence as the previous mechanisms discussed. Small tidal range, small tidal prism (about 1.5×10^6 m^3), low wave energy and small longshore transport rates all must coincide with a particular inlet geometry. The inlet channel must be parallel to a barrier beach and adjacent shoreline, so the ebb tidal flow is also directed parallel to shore. Given the specified physical forcing, a channel-margin linear bar forms of material derived from scour of the lengthening inlet channel. This bar increases in length, augmenting the sediment supplied to the linear bar from channel scour, and progressively elongating the barrier spit. The process continues until the hydraulics of the lengthened inlet prevent efficient tidal exchange (due to increased friction), or until a breach opens along the barrier spit, forming a new inlet channel which is hydraulically more efficient. The spit end which becomes detached with formation of the new inlet will gradually migrate shoreward, either because of gradual barrier "roll-over", or by truncation of the ends by wave action. As the detached barrier migrates shoreward, it fills the former inlet channel.

The prototype for this self-generative spit elongation is Popponesset Beach, Mass., which elongated a distance of almost one kilometer in fifty years. Indirect evidence here suggests that net longshore transport rates are low. The self-regenerative hypothesis for spit elongation is consistent with the patterns of change at Popponesset, with the forcing present in this region, and with the requirement for a sink for sand scoured from the lengthening inlet channel. This unconventional method for increasing barrier spit length suggests that estimates of directions and rates of longshore sand transport based on spit development must be scrutinized on a case-by-case basis.

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REFERENCES

Aubrey, D.G. and Gaines, A.G., 1982. Recent evolution of an active barrier beach complex, Popponesset Beach, Cape Cod, Mass. WHOI Tech. Rept. No. 82-3, 77 pp.

Brownlow, A.H., 1979. Cape Cod Environmental Atlas. Dept. of Geology, Boston University, Boston, Mass., 62 pp.

Bruun, P., 1978. Stability of Tidal Inlets. Elsevier, Amsterdam, 506 pp.

Byrne, R.J., DeAlteris, J.T. and Sovich, J.P., 1977. Recent History and Response Characteristics of Wachaperague Inlet, Va. Final Rept. to ONR Geography Programs, VIMS, Gloucester Pt., Va., 127 pp.

Camp, Dresser and McKee, Inc., 1981. Environmental Review Record, Popponesset Barrier Beach Restoration. September 1980. Mass. Disaster Recovery Team, Boston, Mass., 89 pp.

Halsey, S.D., 1979. Nexus: new model of barrier island development. In: S.P. Leatherman (Editor), Barrier Islands. Academic Press, New York, N.Y., pp.185—210.

Hayes, M.O., 1975. Morphology of sand accumulation in estuaries: an introduction to the symposium. In: L.E. Cronin (Editor), Estuarine Research, V. 2. Academic Press, New York, N.Y., pp.3—22.

Hoyt, J.H., 1967. Barrier island formation. Geol. Soc. Am. Bull., 78: 1125—1136.

Komar, P.D. and Inman, D.L., 1971. Longshore sand transport on beaches. J. Geophys. Res., 75: 5914—5927.

Kraft, J.C., Allen, E.A., Kelknap, D.F., John, C.J. and Maurmeyer, E.M., 1979. Processes and morphologic evolution of an estuarine and coastal barrier system. In: S.P. Leatherman (Editor), Barrier Islands. Academic Press, New York, N.Y., pp.149—183.

Leatherman, S.P., 1979. Migration of Assateague Island, Maryland, by inlet and overwash processes. Geology, 7: 104—107.

Oertel, G.F., 1972. Sediment transport on estuary entrance shoals and the formation of swash platforms. J. Sediment. Petrol., 42: 858—868.

Oldale, R.N., 1976. Notes on the Generalized Geologic Map of Cape Cod. U.S. Geol. Surv., Open File Rept. 76-765, Woods Hole, Mass., 23 pp.

Otvos Jr., E.G., 1970. Development and migration of barrier islands, northern Gulf of Mexico. Geol. Soc. Am. Bull., 81: 241—246.

Redfield, A.C., 1980. The Tides of the Waters of New England and New York. Sullwold, Taunton, Mass., 108 pp.

Shepard, F.P. and Wanless, H.R., 1971. Our Changing Coastline. McGraw Hill, New York, N.Y., 579 pp.

Strahler, A.N., 1966. A Geologist's View of Cape Cod. The Natural History Press, Garden City, N.Y., 115 pp.

U.S. Army Corps of Engineers, 1972. Survey Report, Popponesset Bay, Mashpee and Barnstable, Massachusetts. New England Division, Waltham, Mass., 23 pp.

Woodworth, J.B. and Wigglesworth, E., 1934. Geography and Geology of the Region including Cape Cod, The Elizabeth Islands, Nantucket, Martha's Vineyard, No Mans Land and Block Island, Vol. LII. Mem. Museum of Comparative Zoology, Harvard University, Cambridge, Mass., 322 pp.