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Source: Journal of Coastal Research, 36(sp1) : 290-299

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/1551-5036-36.sp1.290

Journal of Coastal Research	SI 36	290-299	(ICS 2002 Proceedings)	Northern Ireland	ISSN 0749-0208

Inlet Formation and Evolution of the Sediment Bypassing System: New Inlet, Cape Cod, Massachusetts

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ABSTRACT

Nauset Spit was breached during a moderate northeast storm on 2 January 1987, forming New Inlet. Factors leading to the breach included a long-term narrowing of the barrier; a 0.5-m storm surge superimposed on near perigean, perihelion, and spring tide conditions; restricted flow through existing inlets, and large differences in tidal range and tidal phase between the ocean and Pleasant Bay. Ultimately, destruction of the foredune ridge and a large hydraulic slope across the barrier (> 1.2 m) facilitated the development of an overwash channel, which led to tidal exchange and inlet formation. As the channel captured an increasingly larger portion of the bay tidal prism, the inlet grew in size from 0.5 km after two months to almost 2.0 km wide by early 1988. Opening of New Inlet increased the tidal range from 1.2 to 1.5 m, which drastically changed the hydraulic character and sediment transport patterns in Pleasant Bay.

The opening of New Inlet washed much of the sand from the eroding barrier into the bay. As the dimensions of the inlet increased, the ebb-tidal delta grew in volume reducing the amount of sediment bypassing the inlet. Sand continues to enter the backbarrier building sand shoals and bedforms. The decrease in sand supply to the downdrift barrier caused 100 m to 300 m of shoreline recession immediately south of the inlet from 1990 to 2000. During the past six years the rate of erosion has decreased slightly due to more active transport of sediment past the inlet. The major mechanism of inlet sediment bypassing is accomplished through the breaching of hydraulically more efficient channels through the outer portion of the ebb delta. This process results in the formation of swash bars along the downdrift portion of the delta. These bars are 100 m to 300 m long and attach to the landward beach every 1 to 3 years. Permanent breaching of the spit platform has not occurred at New Inlet due to rapid accretion of Nauset Spit and backbarrier shoals directing ebb flow away from the spit platform.

ADDITIONALINDEXWORDS: *Cape Cod, spit breaching, tidal inlet processes, hydraulics.*

INTRODUCTION

The 30-km long Nauset barrier system is composed of a series of spits and barrier islands that form the southern outer coast of Cape Cod, Massachusetts. Barrier construction has served to smooth an indented, irregular mainland coast composed chiefly of outwash sediments that were deposited during deglaciation 17-18 ka BP (UCHUPI *et al*., 1996). Eroding bluffs north of the region supplied sand for southward spit progradation, enclosing Nauset Harbor, Pleasant Bay, and Chatham Harbor (Fig. 1). The southern end of the spit complex is segmented due to several storm breachings. The most recent of these cuts occurred along the barrier fronting Pleasant Bay during a moderate northeaster (extratropical storm) on 2 January 1987.

Formation of a tidal inlet disrupts the longshore transport of sediment commonly resulting in severe erosion of the downdrift barrier shoreline (FITZGERALD, 1988). A dramatic illustration of this process occurred at Assateague Island when it was breached by a 1933 hurricane forming Ocean City Inlet, Maryland. As the inlet accessed an increasingly larger portion of the bay tidal prism, its channel dimensions also increased. The commensurate growth of the associated ebb-tidal delta depleted the downdrift shoreline of sand leading to an onshore retreat of northern Assateague Island by more than a full barrier width (STAUBLE, 1997).

Breaching of Nauset Spit and formation of New Inlet in January 1987 caused an influx of sand into Pleasant Bay. This process coupled with a change in backbarrier hydraulics, due to an increase in tidal energy, drastically altered lagoonal sedimentation patterns as well as beach and nearshore processes. New Inlet has provided an opportunity

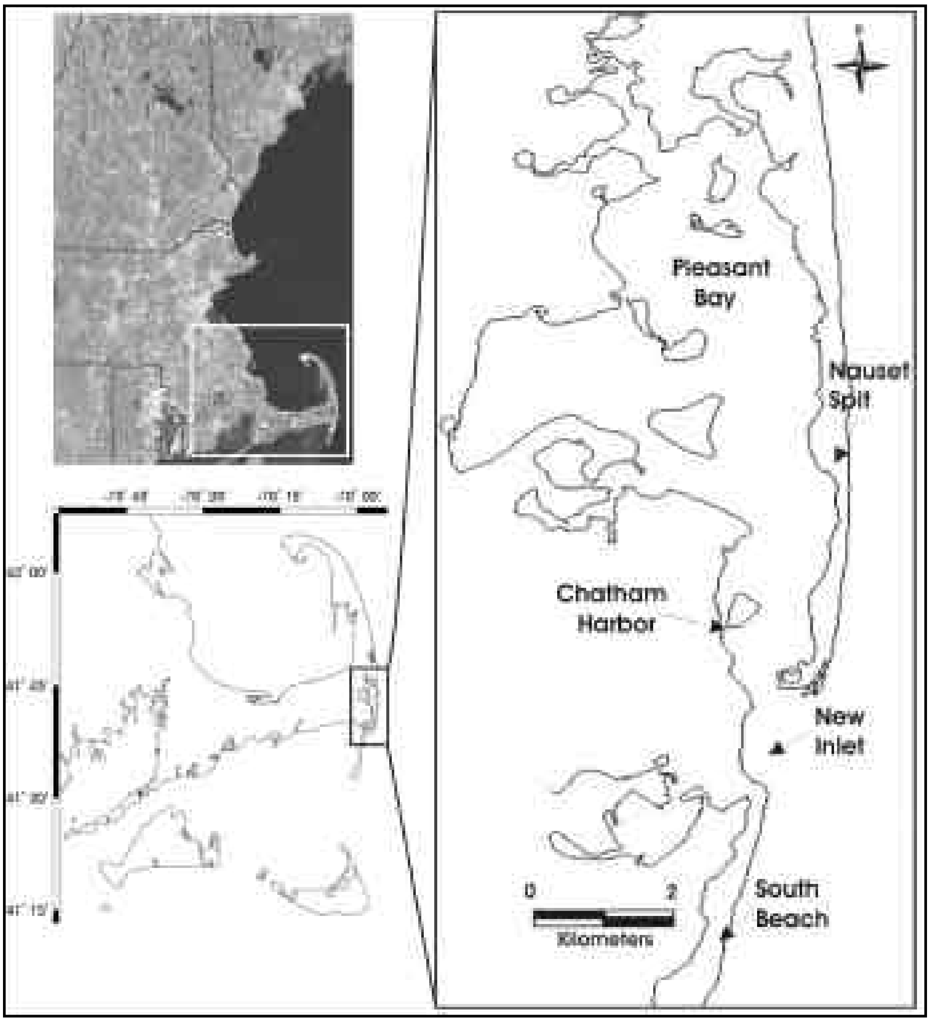

Figure 1. New Inl*et al*ong the outer coast of Cape Cod was formed during a moderate northeast extratropical storm on 1-2 January 1987. Long-term shoreline recession and development of a hydraulic head across the barrier facilitate storm breaching of Nauset Spit.

to document the evolution of a tidal inlet (LUI *et al*., 1993; STAUBLE, 2001), the backbarrier system (FITZGERALD and MONTELLO, 1993; PENDLETON *et al*., 2001) and, in particular, the development of the ebb-tidal delta. The intent of this paper is to discuss the conditions that led to the breaching of Nauset Spit. Next, we will describe the morphological evolution of the ebb-tidal delta and explain how the inlet bypasses sediment.

BACKGROUND

The southern outer coast of Cape Cod is dominated by southerly longshore transport, which is driven by northeast storm waves. Sediment is sourced from glacial cliffs north of Nauset Inlet consisting primarily of sand and fine gravel. The deepwater wave approach is from the east-northeast with mean height of 1.5 m as determined from wave hindcast studies (USACOE, 1957; BROOKS and BRANDON, 1995). Based on wave data, the net southerly longshore transport rate is estimated to be between 3.6 and 5.0 m^3/yr (WEISHAR *et al*., 1989; LUI *et al*., 1993). The net southerly movement of sand has been manifested historically by a southerly progradation of the Nauset Spit. As seen in Figure 2, prior to the formation of New Inlet the end of Nauset Spit accreted southward 3.4 km between 1938 and 1986.

Northeast storms impact the Cape Cod region primarily during late fall through early spring with a frequency of about 10 to 15 storms each year. The mean tidal range outside the inlet is 2.0 m (NOAA, 2001) and increases to 2.3 m during spring tide conditions. In Chatham Harbor inside the inlet gage measurements indicate a mean tidal range of 1.4 m.

Figure 2. Shoreline changes of Nauset Spit from 1938 to 1982 as determined from vertical aerial photographs. Note that the amount of shoreline recession during this period increased in a southerly direction along the spit.

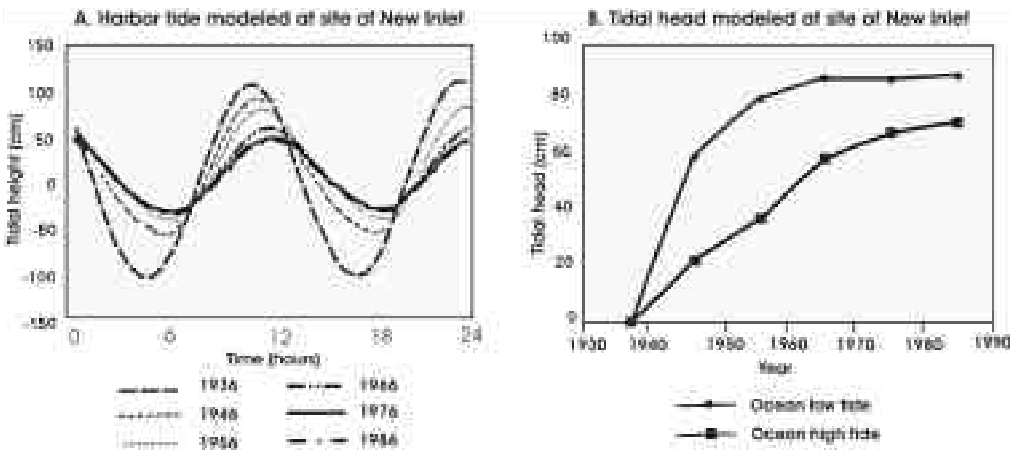

Figure 3. Numerical model results depicting the evolution of tidal exchange between Pleasant Bay and the ocean from 1936 to 1986: A. tide in Pleasant Bay/Chatham Harbor, and B. tidal elevation differences across the barrier (redrawn from FRIEDRICHS *et al*., 1993).

INLET FORMATION

Long-Term Trends

The barrier spit system that extends south of Nauset Heights to Chatham Harbor Inlet experiences periods of southerly accretion followed by a destructional phase whereby the spit becomes segmented and portions of the barrier migrate onshore (McCLENNEN, 1979; GIESE, 1988). Segmentation of Nauset Spit is related to a gradual reduction in tidal exchange between Pleasant Bay and Chatham Harbor and the ocean, which is caused by a restriction in tidal flow through the existing inlets (GIESE, 1988). The cycle of spit extension followed by barrier segmentation and destruction has a periodicity of approximately 150 years (GIESE, 1988).

Historical changes in tidal exchange between the ocean and Chatham Harbor have been modeled by FRIEDRICHS *et al*. (1993) using a one-dimensional nonlinear tidal propagation model. Their model indicates that as Nauset Spit builds to the south, which lengthens and shoals the channel connecting the harbor and ocean, the tidal amplitude gradually diminishes in Pleasant Bay. Applying this model to the period between 1936 and a time just before the breach, they calculated that the tidal range in the harbor decreased from 2.0 m in 1936 to 0.8 m by 1986 (Fig. 3a). The model also demonstrates that historical dampening of the tidal wave's propagation into the bay was concomitant with a steady increase in tidal head between the ocean and harbor (FRIEDRICHS *et al*., 1993). According to their model, by 1986 the tidal head across the barrier reached 0.86 m at low tide (toward the bay) and 0.70 m at high tide (toward the ocean) (Fig. 3b). It is reasoned that under these conditions the barrier is susceptible to breaching, particularly during storms when water level set up and set down may increase the hydraulic head across the barrier.

1987 Breach

During a severe northeast extratropical storm on 2 January 1987, Nauset Spit was breached forming New Inlet. After one day the inlet was approximately 100-m wide and storm waves were breaking through the opening (FRIEDRICHS *et al*., 1993, his figure 1). As the channel captured an increasingly larger portion of the bay tidal prism, the inlet grew in size from 0.5 km after two months to almost 2.0 km wide by early 1988. A broad intertidal spit platform comprised 1.2 m of this width.

At least four factors facilitated the breach: 1. Storm and astronomic conditions, 2. Tidal head across the barrier, 3. Long-term shoreline trends, and 4. Bay bathymetry.

Storm Conditions.- The early January northeaster of 1987 was not a record storm. However, it was slow moving and had sustained wind velocities of 40 km/hr, which produced a 0.5 cm storm surge and waves approaching 3.0 m in height (GIESE, 1990). The storm coincided with near perihelion, perigean, spring tidal conditions. The predicted high tide was 60 cm greater than mean high tide conditions.

Tidal Head.- As explained previously, the long, narrow, and shallow connection between Pleasant Bay and the ocean produced phase lags and tidal range differences between the bodies of water. The hydraulic head across the barrier was greater at low tide than at high tide (FRIEDRICHS *et al*., 1993). This is important because most inlets are cut from the backside during a falling tide.

Shoreline Trends.- Historical shoreline trends for the outer Cape are known from studies by GATTO (1978) and ALLEN *et al*. (1998). Their data show significant temporal and spatial variability in cliff retreat rates north of Nauset Spit suggesting that the supply of sand to the southern barrier system may have been equally variable. Since 1938, the Nauset Spit shoreline south of Nauset Heights extending in front of Pleasant Bay has steadily retreated. The rate of retreat increases with distance from Nauset Heights (Fig. 2). Between 1938 and 1982 the barrier shoreline along northern Pleasant Bay eroded 70 m, while the shoreline at the 1987 breach retreated 340 m.

Bay Bathymetry.- Prior to the breach, flood-tidal deltas, broad ebb spillover lobes, and intervening channels characterized Pleasant Bay. The channels ranged in depth from 2 to 6 m and were floored by ebb- and flood-oriented bedforms. The bay shoreline of Nauset Spit was lobate-shaped and a product of recurved ridges building into the bay during spit accretion. A narrow, shallow intertidal platform abutted the bay shore. At the site of the eventual breach, the bay was relatively deep and tidal shoals were absent.

It should be noted that none of the factors by themselves would have created the 1987 breach. As seen in Figure 3b, the modeled low tide reached a maximum hydraulic head across the barrier in 1966 and even the modeled high tide neared its maximum by 1976. Thus, It can be argued that if differences in water level across the barrier were the paramount cause of breaching, then it should have occurred 10 to 20 years earlier. Rather, before the tidal head could aid in cutting the barrier, an incipient channel had to be present. Formation of this feature was facilitated by long-term erosion of Nauset Spit, which thinned the barrier eventually causing a segmentation of the foredune ridge. When the 1-2 January 1987 northeast storm struck the coast of Cape Cod, the high astronomic tides coupled with a moderate storm surge allowed waves to break high on the beach. Vestiges of the frontal dune system funneled the ensuing wave surge

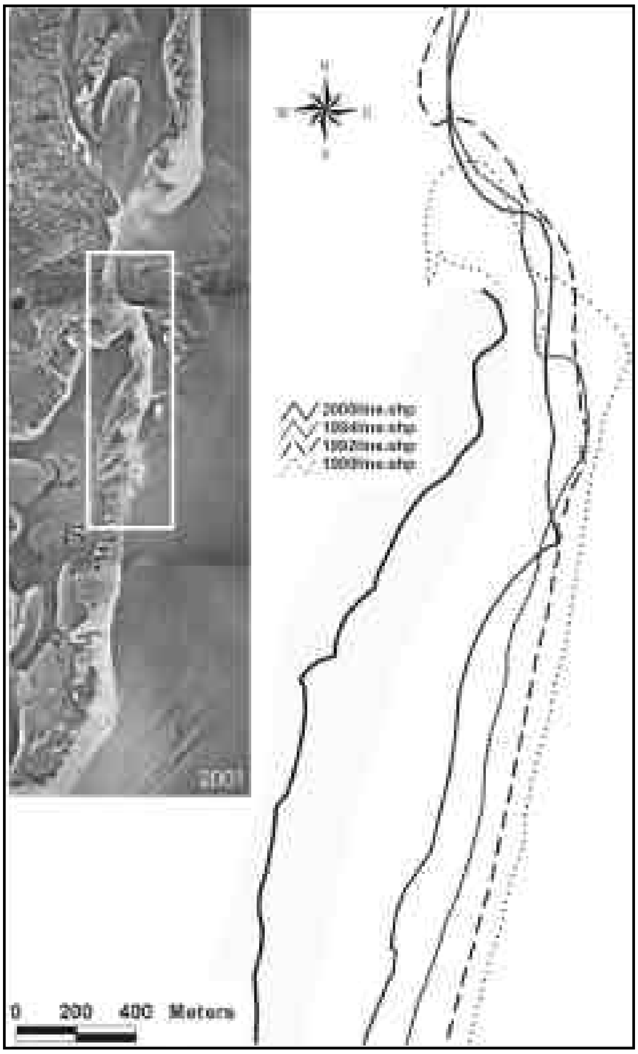

Figure 4. Shoreline changes along the barrier south of New Inlet between 1990 and 2000. During the period of record, sand trapping by the bay, ebb-tidal delta, and updrift spit have reduced the sand supply to the downdrift barrier resulting in severe erosion.

across the barrier forming an overwash channel. It was this diminutive channel that would become proto-New Inlet. The fact that the adjacent Pleasant Bay was wide and relatively deep aided the development of the inlet by preventing formation of a broad overwash fan which would have impeded the access of the bay tidal prism. The GIESE (1988) model and breaching of a barrier, in general, involve numerous factors that must work synergetically before a stable tidal inlet can be formed.

INLET AND EBB-TIDAL DELTA EVOLUTION

Accounts of the morphological development of New Inlet and the ebb tidal delta can be found in LIU *et al*. (1993) and STAUBLE (2001). One of the immediate effects of the breaching was a continuous widening of the inlet over the next year and half, which involved the northward and southward retreat of the inlet shorelines. During this time much of the eroded barrier sand was washed into the inlet enlarging the flood-tidal delta and other sand shoals (FITZGERALD and MONTELLO, 1993; PENDLETON and FITZGERALD, 2001; STAUBLE, 2001). Using the configuration of the pre-breach shoreline and 1990 bathymetry (FITZGERALD and MONTELLO, 1993), it is estimated that between 0.7 and 1.0 x 10^6 m^3 of barrier sand was washed into the bay. Some of this sediment was subsequently transported seaward becoming part of the ebb-tidal delta and spit platform. Some of the sand also fed the spit system that eventually attached the downdrift inlet shoreline to the mainland.

Almost from the beginning the main ebb channel has been located along the downdrift side of the inlet. This position is a result of ebb-tidal flow approaching the inlet only from the north (Pleasant Bay) (FITZGERALD and FITZGERALD, 1977), due to the fact that the downdrift spit attached to the mainland closing off access to the southern bay tidal prism. Since the latter part of 1988, the inlet mouth has consisted of an expansive updrift spit platform (1.0 to 1.3 km in length) and downdrift channel thalweg. From 1990 to 1996 the spit platform maintained approximately the same configuration and aerial extent, except for small-scale changes associated with the formation and migration of swash bars and minor channels. In 1997 the northern recurved spit began accreting southward 600 m across the intertidal platform, a process that continues to the present time. Re-initiation of spit growth may be a consequence of increased supply of sand to the inlet and/or a period of mild northeast storms during the past five years (ZHANG *et al*., 2001; http://ocean-beach.com/weather_norester_history.htm).

The ebb-tidal delta is composed of the spit platform and an arcuate group of sand shoals associated with the main ebb channel. Ebb flow through the main channel causes a seaward excursion of the delta lobe beyond the limits of the spit platform. Throughout most of the nineties (1990-1999) the outer portion of the main ebb channel was skewed along the downdrift shoreline. This asymmetry was a result of the southerly longshore transport system and the preferential accumulation of sand on the updrift side of the ebb delta (FITZGERALD, 1988). Changes in the configuration of the ebb-tidal delta during past few years are evidence of a more active sediment-bypassing regime.

INLET SEDIMENT BYPASSING

When a new inlet is formed, sand is withdrawn from the longshore transport system until the ebb-tidal delta attains an equilibrium volume (WALTON and ADAMS, 1978). At New Inlet the decade-long retreat of the downdrift inlet shoreline is evidence of sand sequestering by the ebb-tidal delta. Littoral sand has also been diverted into Pleasant Bay enlarging the flood-tidal delta and other sand shoals (PENDLETON and FITZGERALD, 2001; STAUBLE, 2001). During the past five years the southward extension of the updrift recurved spit has trapped additional sand. Reduction in sand nourishment to the downdrift beach amounted to 200 to 300 m of shoreline recession between 1990 and 2000 (Fig. 4). The rate of erosion lessened slightly in the mid- to late nineties when greater quantities of sand began bypassing the inlet.

Short-Term Processes

A review of yearly vertical aerial photographs and field observations of New Inlet between 1989 and 2001 demonstrate that the outer portion of the main ebb channel switched locations on several occasions and a number of small swash bars, 100 to 300 m in length, migrated onshore (Fig. 5). As described by FITZGERALD *et al*. (2000) these processes at a migrating inlet indicate that sediment is moving past the inlet mouth. At New Inlet the dominant southerly longshore transport of sand produces an extension of the spit platform and a deflection of the distal part of the main ebb channel past the downdrift inlet shoreline. This gradual lengthening of the main channel decreases flow efficiency between the ocean and bay, eventually resulting in the breaching of a new shorter channel through the ebb-delta. The breaching event commonly occurs during a storm when elevated water levels and a stronger than normal ebb discharge cause tidal currents in the main channel to flow directly across the outer ebb shoals. Once the outer main channel occupies the new short-cut channel, the sand shoals that have been displaced to the downdrift side of delta are moved onshore by wave action. This process of outer channel shifting has occurred repeatedly at New Inlet with a frequency of every 1 to 3 years (Fig. 5).

Spit Platform Breaching

The sediment bypassing process described above involves the transfer of relatively small volumes of sand (2,000-10,000 m^3) to the downdrift shoreline. A potentially much larger volume of sand would bypass the inlet if the main channel breached a new pathway through the spit platform. KANA and MASON (1988) and FITZGERALD *et al*. (2000) have discussed this mechanism of inlet sediment bypassing. Sequential aerial photographs of New Inlet illustrate that subtle changes in the backbarrier dramatically influenced flow patterns through the ebb-tidal delta.

As seen in figure 5, when the downdrift spit attached to the mainland cutting off the southern bay tidal prism in 1991, the throat position of New Inlet effectively shifted northward to a location between the updrift spit and adjacent mainland. In this configuration the exchange of water between Pleasant Bay and the ocean was through a long and circuitous pathway between the spit platform and adjacent mainland. This channel pattern is analogous to flow through a river meander bend consisting of a point bar (spit platform) and channel cut bank (downdrift side of main channel). A much shorter route would be formed if a new channel were cut through the northern spit platform. However, for New Inlet to achieve this shorter course would require a radical change in flow direction of the ebb currents. During the early and mid-1990's the orientation of

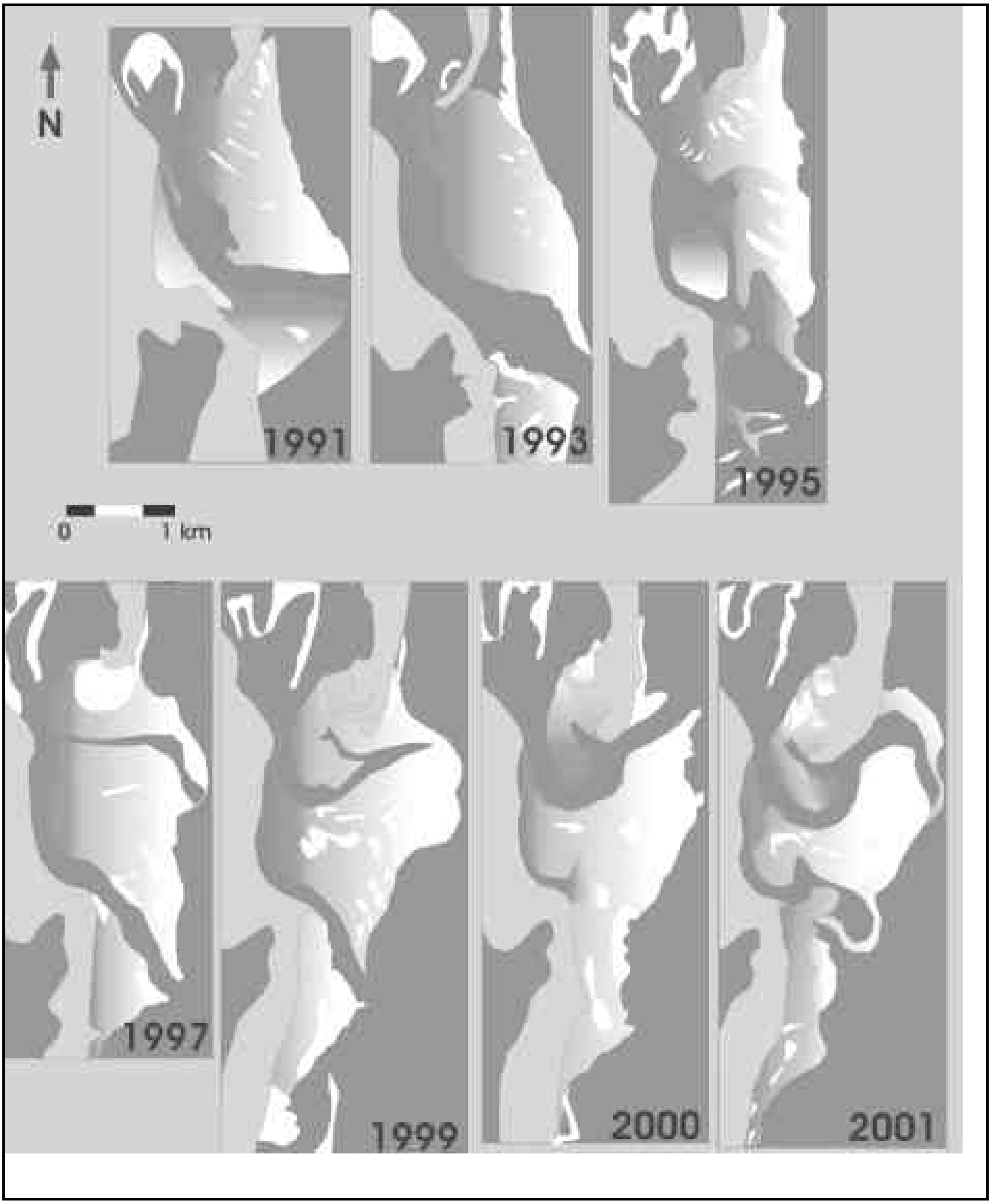

Figure 5. Morphological changes of the New Inlet regions as traced from vertical aerial photographs. See text for description of inlet evolution.

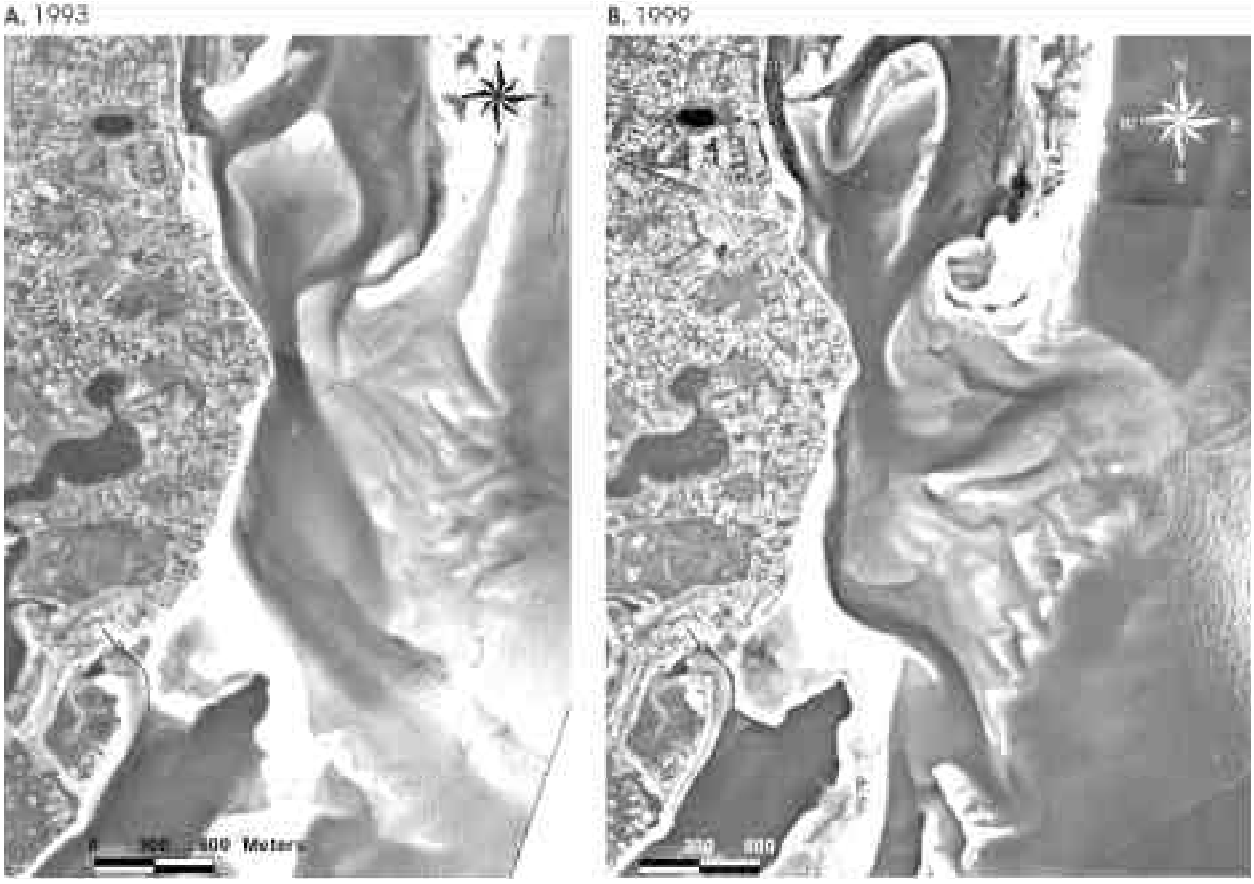

Figure 6. 1993 and 1999 vertical aerial photographs of New Inlet depicting changes to the flood-tidal delta, swash platform and recurved spit, and main ebb channel and ebb-tidal delta system. Note that by 1999 a short-cut channel had formed across the spit platform and that sandbars were migrating onshore to the downdrift shoreline.

the inner inlet channel was controlled by the location and configuration of the flood-tidal delta and position of the spit platform and recurved spit system.

As viewed in the 1993 aerial photograph, the ebb spits of the flood delta and the westerly extent of the spit platform funneled ebb flow in the main channel toward the southern end of the spit platform (Fig. 6). However, by 1999 the flood delta had migrated 327 m northward and the landward extent of the spit platform was displaced southward. This movement of shoals changed the direction of ebb discharge coming out Pleasant Bay. The end result was a deflection of ebb flow off the mainland headland to a route across the spit platform (Fig. 6). Erosion in the channel next to the headland reached depths over 12 m. Some of this scoured sand was transported southward forming a broad sand shoal that partially filled the outer main ebb channel. As shoaling in the old main channel continued, the new channel through the spit platform captured an increasingly larger portion of the bay tidal prism. At most migrating inlets a breach through the spit platform is tantamount to closure of the old channel and bypassing of the sand comprising the severed platform. This process has not occurred at New Inlet due to a growth spurt of the updrift spit, which amounted to 0.4 km between 1999 and 2001. Progradation of Nauset Spit has deflected the main channel to the more southerly course causing inefficient flow between ocean and bay. Consequently, the old main channel has been rejuvenated, while moderate tidal flow persists through the new channel (Fig. 5). Moreover, the inlet continues to bypass sand in relatively small quantities in the form of individual swash bar 100 to 300 m in length welding to the beach every 1 to 3 years.

DISCUSSION

As originally reported by BRUUN and GERRITSEN (1959), the rate of longshore sand transport toward the inlet versus the maximum tidal discharge in the channel govern the different mechanisms of inlet sediment bypassing. The ratio between these two parameters determines whether sand bypasses an inlet primarily by wave action along the outer bar or through a combination of wave and tidal processes. FITZGERALD (1982) and FITZGERALD *et al*. (2000) presented conceptual models of sediment bypassing at tidal inlets building on these early ideas. Recently GAUDIANO and KANA (2001) have quantified the volume and rate at which bar complexes bypass inlets along the coast of South Carolina. Sediment bypassing at New Inlet is highly dynamic involving both channel switching and the formation and landward migration of swash bars. Added complexity stems from the impact changes in the backbarrier can impose on flow patterns through the ebb delta and swash platform. Complex sediment bypassing processes occur at many other inlets and eventually these types of processes need to be studied and quantified.

CONCLUSIONS

1. Formation of New Inlet was a product of several processes working synergetically to breach the barrier: A. Decreasing sediment supply causing long-term shoreline recession, B. Elevated water levels due to storm surge and high astronomic tides, C. Segmented dunes funneling overwash and development of an overwash channel, D. Tidal head which promoted flow across the barrier.

2. Sediment began bypassing the inlet once the ebb-tidal delta achieved an equilibrium volume. Most sand bypassing is accomplished through short breachings of the outer main channel through the ebb delta. This process results in the formation of swash bars (100 to 300 m in length) that migrate onshore and weld to the beach every 1 to 3 years.

3. Although New Inlet is a migrating inlet and contains a well-developed spit platform, sediment bypassing due to breaching of the spit platform has not occurred. Short-cut channels have developed across the spit platform but these channels have been unable to capture the bay tidal prism over the long-term. Migration of sand shoals and tidal channels in the backbarrier together with progradation of Nauset Spit control ebb tidal flow in the main channel and ultimately the unstable nature of the short-cut channels through the spit platform.

ACKNOWLEDGEMENTS

This study was supported by the U.S. Army Corps of Engineers' Coastal Inlets Research Program at the Waterways Experiment Station in Vicksburg, MS. We wish to thank Ted Keon, Director of Coastal Resources, Town of Chatham, MA for assistance in data collection. Special thanks to Nick Kraus, Thad Pratt, and Don Stauble at the Waterways Experiment Station and Ed O'Donnell of the New England District Office for collaboration with this project.

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