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Origin and Stability of Tidal Inlets in Massachusetts

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Abstract

The origin, morphology and sedimentation processes of tidal inlets along the Massachusetts coast are highly variable due to a wide range in physical settings. The factors which have governed their development and contributed to these different morphologies include wave and tidal energy, sediment supply, origin of the backbarrier, bedrock geology, sea level history, storms, and modifications by man. Some of the variability of these individual parameters can be related to the glacial history of this region. With the use of examples, physical data sets and morphological case histories, this paper examines the evolution and stability of inlets, primarily on the mainland coast of Massachusetts.

Introduction

The morphology and physical environment of the Massachusetts coast are as diverse as any comparable stretch of shoreline along North America. To a large extent the diversity has resulted from the varying effects of glaciation on a pre-existing, fluvially-eroded landscape. This has produced numerous

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large and small embayments, a wide range in shoreline orientations, and highly variable sediment supplies. This region encompasses the bedrock/till dominated shores of northwestern Buzzards Bay and Massachusetts Bay and the sandy coastal plain of southeastern Massachusetts and the region north of Cape Ann. Tidal inlets in this area are associated with many different coastal settings including large, well-developed barrier islands, long sandy spit systems, and narrow, transgressive sand and gravel barriers (Fig. 1). These inlets exhibit a wide range of sizes and morphologies which are related to their hydrographic regime, sediment abundance, bay size, tidal prism, and man-made modifications (Fig. 2). The origin of tidal inlets in Massachusetts is equally diverse encompassing riverine processes, barrier breaching, spit accretion, and other mechanisms.

During the past 10 years many harbors along the Massachusetts seaboard have filled to near capacity due to the dramatic increase in number of boat owners and their demand for boat slips. The existing overcrowded conditions coupled with future needs for harborage explains why the entrances to harbors are being maintained despite considerable cost to individual towns and State and Federal governments.More than half of the tidal inlets in Massachusetts have undergone modification projects to improve their navigation. In addition to navigation concerns, it is important to consider how the shoaling and closure of tidal inlets impact shellfishing, the exchange of nutrients between the nearshore and bays and marshes, and the well-being of juvenile species of many fin fish that use the inlets and bays as nursery grounds. Knowledge of inlet processes as determined from field investigations and historical analyses is vital in managing these resources and planning for future coastal development.

Tidal inlets are defined as openings in the shoreline through which water penetrates the land thereby providing a connection between the ocean and bays, lagoons or marsh and tidal creek systems. The main channel of a tidal inlet is maintained by tidal currents (Bruun and Gerritsen, 1955). The second half of this definition distinguishes tidal inlets from large, open embayments or passageways along rocky coasts. Tidal currents at inlets are responsible for the continual removal of sediment dumped into the main channel by wave action. Thus, according to this definition tidal inlets occur along sandy (or sand and gravel) barrier coastlines, although one side of an inlet may abut a

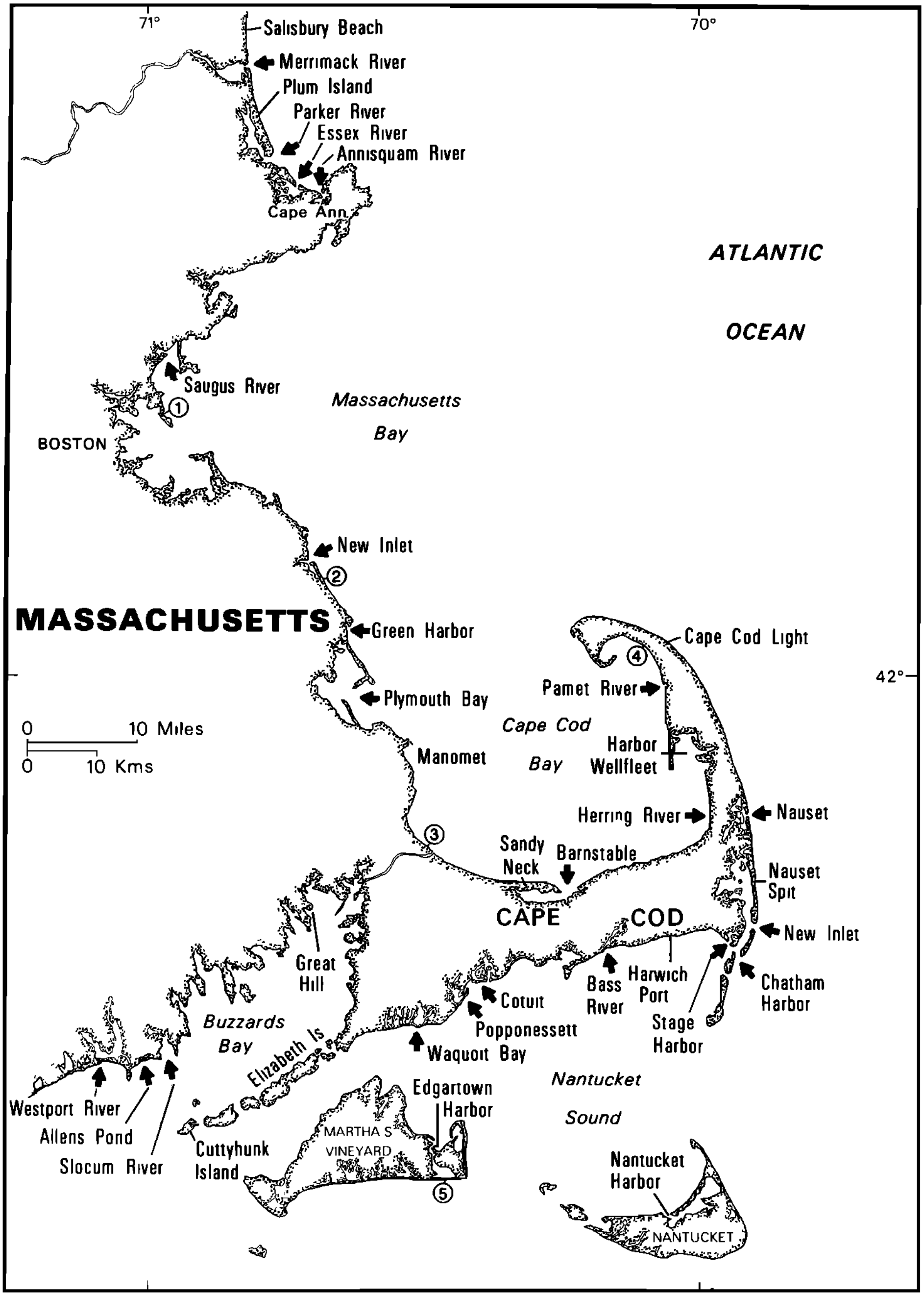

Figure 1. Location of major tidal inlets in Massachusetts and other sites discussed in the paper. Numbers 1-5 refer to locations where inlets have closed: 1. Shirley Gut, 2. South River Inlet, 3. Scusset Mills Creek Inlet, 4. East Harbor Inlet, and 5. Katama Bay Inlet.

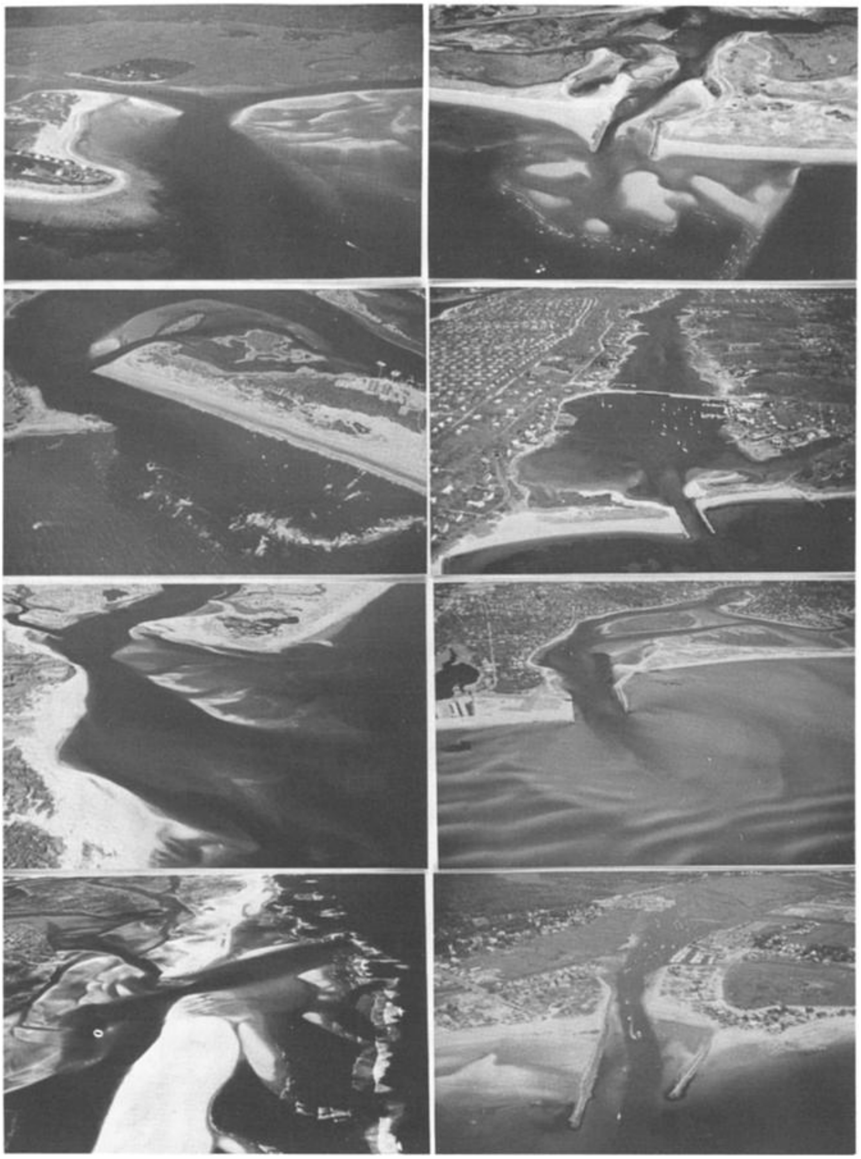

Figure 2. Oblique aerial photographs of: A. New Inlet, Scituate, B. Westport River Inlet, Westport, C. Parker River Inlet, Ipswich, D. Nauset Inlet, Eastham, E. Pamet River Inlet, Truro, F. Green Pond Inlet, Falmouth, G. Bass River Inlet, Dennis/Yarmouth, H. Green Harbor Inlet, Marshfield.

bedrock headland. Sand removed from the inlet channel is carried into the bay during the flood cycle forming flood-tidal deltas or transported seaward during the ebb phase forming ebb-tidal deltas (Fig. 3). The presence or absence of these sand shoals, their size, and how well they are developed are related to the region's tidal range, wave energy, sediment supply, and backbarrier setting. The general morphology of tidal inlets and their associated sand bodies and the processes that control sediment transport patterns are discussed in a review chapter by Boothroyd (1985) and in a recent volume on tidal inlets edited by Aubrey and Weishar (1988).

This paper will discuss the origin and variability of tidal inlets in Massachusetts and will demonstrate how natural and man-made changes to inlets affect their stability. Tidal inlet terminology will follow that of Hayes (1975, 1979).

Physical Environment

To understand the varying morphology, processes, and behavior of tidal inlets in Massachusetts, it is important to evaluate them in terms of the physical environment in which they have evolved. The morphological variability that exists along the Massachusetts coast can be explained in terms of an area's geological setting and hydrographic regime (Fig. 4). The glacial history of a particular shoreline segment dictates the sediment supply to the region and whether the coast is rocky or not. Wave energy and tidal range of the area influence how the sediment within the shoreline segment is dispersed. Major storms and the wind regime of the area also affect the pathways of sediment transport. Wave and tidal energy along the Massachusetts coast is largely controlled by the exposure of the shoreline and where it is situated with respect to major coastal bays.

Tides

The coast of Massachusetts can be divided into a number of shoreline segments and embayments based on similar tidal range (NOAA, 1991; Fig. 4). The region including Cape Cod and Massachusetts Bays and extending northward to the New Hampshire border is mesotidal ($2.0 < TR < 4.0$ m) with

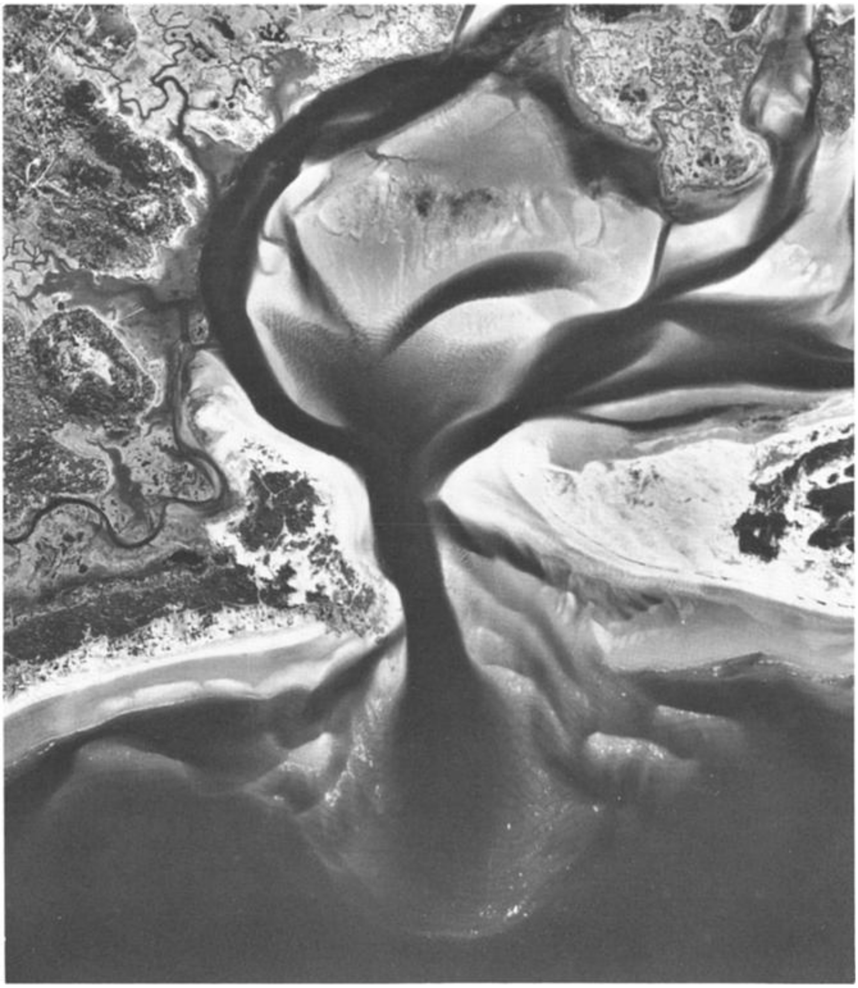

Figure 3. 1976 vertical aerial photograph of Essex River Inlet illustrating the morphology of ebb and flood-tidal deltas.

mean ranges between 2.5 and 3.1 m and spring ranges increasing to as much as 3.5 m at Wellfleet Harbor. Along the outer coast of Cape Cod the mean tidal range gradually diminishes to the south from 2.7 m at Cape Cod Light to 2.0 m at Chatham Harbor Inlet. This trend continues along Monomoy Island such that at Monomoy Point the mean tidal range is 1.1 m. Within Nantucket and Vineyard Sounds, including along the islands of Martha's Vineyard and Nantucket, the tides are microtidal (TR < 2.0 m) and generally the range decreases from east to west. At Harwich Port the mean range is 1.0 m and at Falmouth Heights 0.4 m. The shoreline in Buzzards Bay is also microtidal

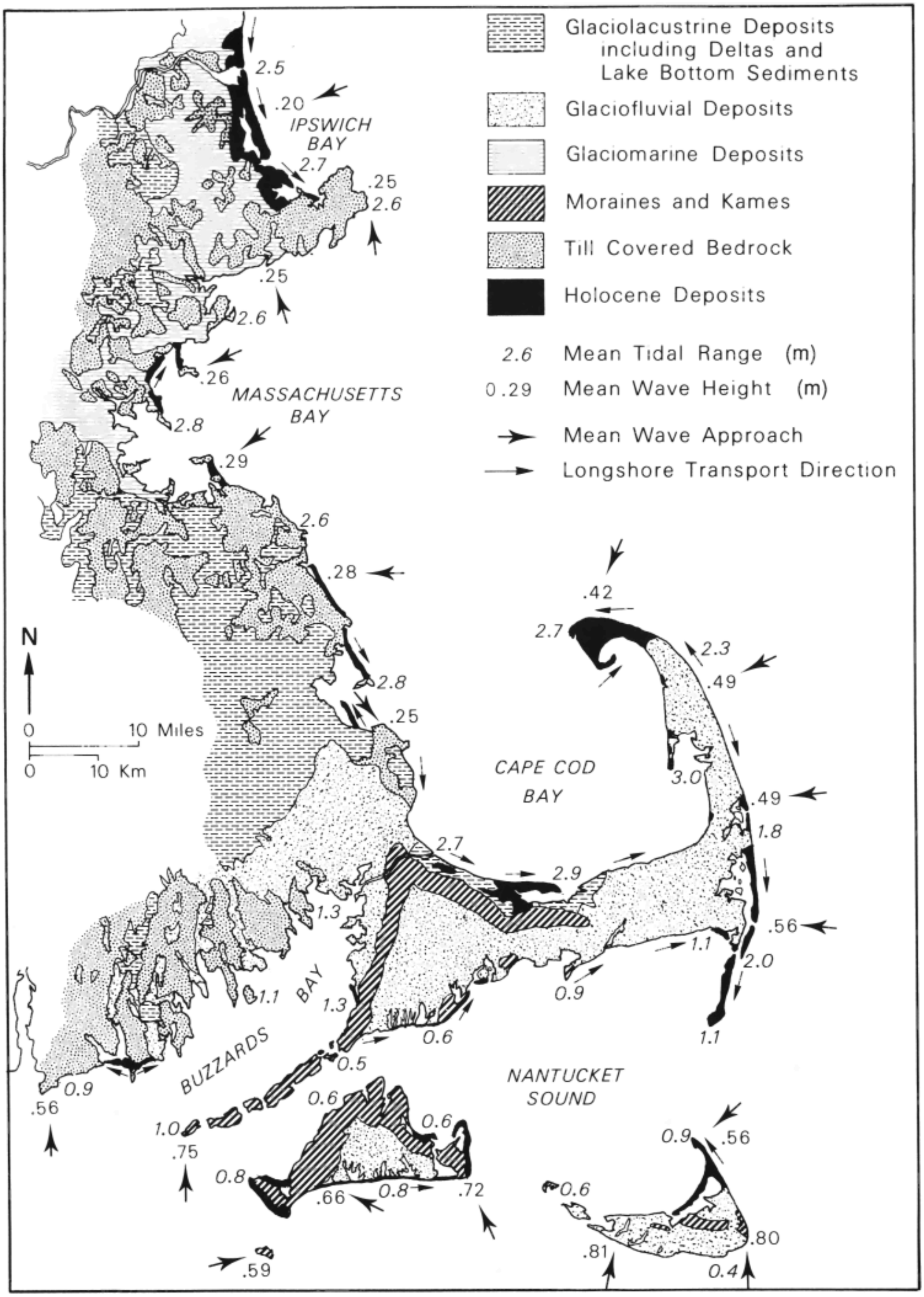

Figure 4. Physical setting of the Massachusetts coast including surficial deposits (from Larson, 1980; Stone and Peper, 1980), mean tidal range (from NOAA's tidal tables of North America), shallow water mean wave heights and dominant wave approach direction (from Jensen, 1983), and net longshore transport directions determined from spit growth, erosional-depositional trends in the vicinity of coastal structures and other coastal features.

with slightly larger ranges than the sounds to the east. At Great Hill near the entrance to the Cape Cod Canal the mean tidal range is 1.2 m and at Cuttyhunk Island near the entrance of Buzzards Bay the range is 1.0 m.

Given this distribution in tidal ranges, it can be expected that tidal inlets are larger, deeper and more stable along sandy shorelines where tidal ranges are large and bay areas are expansive. A comparison of the large, deep inlets north of Cape Ann versus the shallow inlets of Nantucket Sound illustrates this relationship well (Tables 1 and 2).

Waves

The highly variable orientation of the Massachusetts shoreline coupled with its numerous embayments causes different exposures to incident wave energy (Fig. 4). Temporal variations in wave energy are due to the seasonal distribution of storms and changing prevailing wind regime. Deepwater wave energies for this coast are known from a wave hindcast study for the region offshore of Nauset Beach, Cape Cod (U.S. Army Corps of Engr., 1957) and from a wave gauge located west of Cuttyhunk Island (Thompson, 1977). The shallow water wave energy (depth = 10.0 m) for the Massachusetts coast has been determined for 19 stations using 20 years of hindcast data (Jensen, 1983). The deepwater hindcast data indicate that the outer coast of Cape Cod and the shoreline to the north are dominated by east-northeast wave energy associated with the passage of extra-tropical northeast storms. The shallow water wave data corroborate this general trend with some exceptions due to sheltering and wave refraction processes.

The wave gauge off Cuttyhunk, which recorded three partial years of data, indicates that the deep water mean significant wave for this region is 0.9 m and the wave period is 7.5 sec (Thompson, 1977). The shallow water wave data for the southward facing shorelines show that the dominant wave energy comes from the south and that the south shores of Martha's Vineyard and Nantucket experience the largest waves along the Massachusetts coast (Jensen, 1983).

Wave energy within Cape Cod Bay, Buzzards Bay, Nantucket Sound, and Vineyard Sound is low due to limited fetch. Thus, wave processes along these coasts are tied closely to local wind conditions. The northern shores of Buzzards Bay and Nantucket and Vineyard Sounds experience greatest wave energy when extratropical storms or hurricanes pass to the west of Massachusetts generating strong southerly winds. Prevailing southerly winds also occur in these regions during the spring, summer, and early fall months. The southeastern coasts of Cape Cod Bay, Buzzards Bay, and Vineyard Sound are influenced by waves generated by prevailing northwest winds during the late fall, winter, and early spring months (Magee and FitzGerald, 1980).

The magnitude and direction of longshore sediment transport along the Massachusetts coast are highly variable and have been estimated from local erosional-depositional patterns around coastal structures, migration of inlets, growth of spits, and grain size trends. Net longshore transport directions are summarized in Figure 4.

Sediment Supply

The Pleistocene Epoch dictated the sediment distribution and abundance along the Massachusetts coast (Fig. 4) (Larson, 1982; Stone and Peper, 1982). Reworking of the glacial deposits produced the sand supply that was responsible for the development of the present day barrier and tidal inlet system. North of Cape Ann, the major source of sand for the coastal zone has been reworking of the Merrimack River delta that was deposited during the relative sea-level low stand, approximately 10,500 yrs BP (Edwards, 1988). These sediments have formed an extensive barrier system that extends from Great Boars Head, New Hampshire to Cape Ann.

The coastal region from Cape Ann south to Manomet is mostly sediment-starved containing exposures of bedrock with thin till covers (1 to 3 m thick) and some glacial marine deposits. Sediment is slightly more abundant in the vicinity of Boston Harbor and the South Shore where drumlins comprise much of the shoreline. The drumlins have a sand content of 30-40% (Newman et. al., 1990).

Table 1 Characteristics of selected tidal inlets along the Massachusetts coast.

Name of Inlet	Location	Setting	Associated Barriers	Present Backbarrier Environment	Associated Rivers and Streams	Inlet Mode of Formation
North Shore						
Merrimack River	Newburyport	Between Barrier Islands	Salisbury Beach, and Plum Island	Estuary and Marsh System	Merrimack River	Development of Regressive Barriers
Parker River	Ipswich	Between Island and Barrier Spit, and Controlled by Drumlins	Plum Island and Castle Neck	Marsh and Tidal Creeks with Open Water Areas	Parker and Ipswich Rivers	Development of Regressive Barriers
Essex River	Essex	Between Barrier Spit and Bedrock Outcrop	Castle Neck, and Coffin Beach Areas	Marsh and Tidal Creeks with Open Water Areas	Essex and Castleneck Rivers	Development of Regressive Barriers
Annisquam River	Gloucester	Between Bedrock Outcrops	Wingaersheek Beach	Marsh and Tidal Creeks	Annisquam and Jones Rivers	Development of Regressive Barrier Beach
Saugus River	Revere/Lynn	Between Mainland and Barrier Spit	Point of Pines Spit	Marsh and Tidal Creek	Saugus and Pines Rivers	Spit Accretion
South Shore						
New Inlet	Scituate	Between Barrier Spit and Drumlin	Third Cliff Spit, and Hummarock Beach	Marsh and Tidal Creeks	North and South Rivers	Storm Breaching of Barrier, 1898
Green Harbor	Marshfield	Between Bedrock Outcrop and Barrier Spit	Green Harbor Spit	Marsh and Tidal Creeks	Green Harbor Rivers	Spit Accretion
Plymouth Bay	Plymouth	Between Drumlin and Barrier Spit	Duxbury Beach, Saquish Neck, and Plymouth Spit	Bay with Peripheral Marsh and Some Tidal Flats	Jones River	Spit Accretion
Cape Cod Bay						
Barnstable Harbor	Barnstable	Between Barrier Spit and Mainland	Sandy Neck	Open Water Areas and Marsh and Tidal Creeks	No Major Streams	Spit Accretion
Sesuit Harbor	East Dennis	Between Mainland and Small Barrier Spit	Sesuit Beach	Open Water Areas and Marsh and Tidal Creeks	Assessment Creek	Spit Accretion
Herring River	Eastham	Between Mainland and Barrier Spit	First Encounter Beach	Marsh and Tidal Creeks	No Major Streams	Spit Accretion
Pamet River	Truro	Between Two Barrier Spits	Harbor Bar Beach	Tidal Flats, Marsh, and Tidal Creeks	Pamet River	Spit Accretion
Outer Cape Cod						
Nauset Inlet	Eastham	Between Two Barrier Spits	Nauset Beach	Marsh and Tidal with some Open Water Areas	No Major Streams	Spit Accretion
New Inlet	Chatham	Between Barrier Spit and Barrier Island	Nauset Spit/ Nauset Island	Bay with Intertidal Flats	No Major Streams	Storm Breaching of Barrier, 1987
Chatham Harbor	Chatham	Between Two Barrier Islands	Nauset Island/ Monomoy Island	Bay with some Intertidal Flats	No Major Streams	Spit Accretion
Monomoy Breach	Chatham	Between Two Barrier Islands	Monomoy Island	Bay	No Streams	Storm Breaching of Barrier, 1978
Nantucket Sound						
Stage Harbor	Chatham	Between Two Barrier Spits	Harding Beach, Morris Island Dike and Spit	Bay with Tidal Flats	No Major Streams	Artificial Breach, 1945
Bass River	West Dennis/ Yarmouth	Between Mainland and Barrier Spit	West Dennis Beach Spit	Marsh and Tidal Creeks	Bass River	Spit Accretion
Cotuit Inlet	Barnstable	Between Mainland and Barrier Spit	Oyster Harbor Beach Spit	Bay	Mills River	Spit Accretion
Popponesset Bay	Barnstable/ Mashpee	Between Mainland and Barrier Spit	Popponesset Spit	Bay	Santuit and Mashpee Rivers	Spit Accretion
Waquoit Bay	Mashpee/ Falmouth	Between Two Barrier Spits	South Cape Beach	Bay	Quashnet River	Spit Accretion
Green Pond	Falmouth	Between Two Barrier Spits	Unnamed Spits	Bay	No Major Streams	Artificial Breach, 1951
Buzzards Bay						
Slocum River	South Dartmouth	Between Bedrock Outcrop and Barrier Spit	Slocum Spit	Bay with Peripheral Marsh	Slocum River	Spit Accretion
Allens Pond	South Dartmouth	Between Two Barrier Spits	Little Beach/ Allens Pond Spit	Bay with Marsh and Tidal Flats	No Major Streams	Artificial Breach, 1986
Westport River	Westport	Between Bedrock Outcrop and Barrier Island	Horseneck Beach	Estuary with some Marsh and Tidal Flats	East and West Branch of Westport River	Development of Regressive Barrier

Table 2 Morphology and stability of selected tidal inlets along the Massachusetts coast

Name of Inlet	Location	Structure and Improvements	Stability	Inlet Dimensions Depth	Width	Flood Deltas	Ebb Deltas
North Shore							
Merrimack River	Newburyport	Double Jetties	Prior to Jetty Construction History of Southerly Migration and Breaching Back to North	10 1	323	Well-Developed, Intertidal	Subtidal
Parker River	Ipswich	None	Outer Channel Migrates South, Throat Stable	9 7	926	Well-Developed, Intertidal	Well-Developed, Intertidal
Essex River	Essex	None	Stable	12 2	354	Well-Developed, Intertidal	Well-Developed Sub/Intertidal
Annisquam River	Gloucester	Dredged Outer Channel	Stable	9 4	343	None	Subtidal/ Intertidal
Saugus River	Revere/Lynn	Revetments along Inner Channel	Stable	20 0	350	None	None, Modification by Man
South Shore							
New Inlet	Scituate	None	Stable in Present Location	8 5	230	None	Moderately Well, Subtidal
Green Harbor	Marshfield	Double Jetties and Dredged Channel	Channel Shoaling	8 0	140	None	None
Plymouth Bay	Plymouth	None	Stable	20 0	2000	Well-Developed, Intertidal	Well-Developed, Sub/Intertidal
Cape Cod Bay							
Barnstable Harbor	Barnstable	None	Stable	12 8	1400	Well-Developed, Intertidal	Well-Developed, Sits on Shallow Shelf
Sesuit Harbor	East Dennis	Double Jetties and Dredged Channel	Channel Shoaling	2 8	83	None	None
Herring River	Eastham	None	Stable	1 0	35	Well-Developed, Intertidal	Well-Developed, Sub/Intertidal
Pamet River	Truro	Double Jetties and Dredged Channel	Significant Channel Shoaling	2 3	90	Well Developed, Intertidal	Well-Developed, Intertidal
Outer Cape Cod							
Nauset Inlet	Eastham	None	History of Northerly and Southerly Migration	3 2	265	Well-Developed, Intertidal	Well-Developed, Intertidal
New Inlet	Chatham	None	Still Equilibrating (see other papers this volume)	5 0	150	Well-Developed, Intertidal	Well-Developed, Mostly Subtidal
Chatham Harbor	Chatham	None	History of Southerly Migration	6 0	700	Moderately Well, Intertidal	Well-Developed, Sub/Intertidal
Monomoy Breach	Chatham	None	Continued Shoaling	2 0	220	Well-Developed, Intertidal	Poorly Developed, Subtidal
Nantucket Sound							
Stage Harbor	Chatham	Dredged Outer Channel	Channel Shoaling	3 0	80	None	Well-Developed, Intertidal
Bass River	West Dennis/ Yarmouth	Double Jetties and Dredged Channel	Channel Shoaling	3 0	130	None	Subtidal, Sits on Platform
Cotuit Inlet	Barnstable	Dredged Outer Channel	Channel Shoaling	3 4	240	Well-Developed, Subtidal	Moderately Well, Subtidal
Popponesset Bay	Barnstable/ Mashpee	None	History of Northerly Migration and Breaching Back to North	2 0	75	Well-Developed, Intertidal	Poorly Developed, Intertidal
Waquoit Bay	Mashpee/ Falmouth	Double Jetties	Channel Shoaling	3 0	35	Moderately Well, Sub/Intertidal	Poorly Developed
Green Pond	Falmouth	Double Jetties and Dredged Channel	Channel Shoaling	2 1	80	Intertidal	Subtidal
Buzzards Bay							
Slocum River	South Dartmouth	None	Widening Due to Spit Erosion	3 4	90	Moderately Well, Sub/Intertidal	Intertidal, Sits on Intertidal Platform
Allens Pond	South Dartmouth	Occasional Artificial Breaching of Spit when Inlet Closes	Migrating Westward	1 0	60	None	Poorly Developed, Subtidal
Westport River	Westport	Dredged Channel	Stable	7 6	260	Intertidal	Subtidal

South of Manomet, including most of Cape Cod and much of the Martha's Vineyard and Nantucket shorelines, sand is abundant due to the presence of extensive glacial outwash deposits. Areas with less sand resources coincide with coasts composed of glaciolacustrine deposits (e.g., parts of southern Cape Cod Bay). or moraine deposits (e.g., northern shore of Martha's Vineyard and the Elizabeth Islands).

The northern shore of Buzzards Bay is also sediment starved and is characterized by till covered peninsulas separated by deep embayments (FitzGerald et. al., 1987). Sediment is slightly more abundant along the southwestern half of the shoreline due to the presence of some glaciofluvial and glaciolacustrine deposits in addition to some thicker till deposits such as Gooseberry Neck, a drumloidal feature offshore of Horseneck Beach.

Occurrence of Tidal Inlets

Introduction

The formation of a tidal inlet requires the presence of an embayment and the development of barriers. In coastal plain settings, often the embayment or backbarrier is formed through the construction of the barriers themselves, like much of the East Coast of the United States or East Friesian Islands of the North Sea. In Massachusetts, the origin of the embayment may be related to drowned river valleys, rocky or sandy irregular coastlines, kettles, groundwater sapping channels, or the formation of a barrier chain. In these settings, tidal inlets are formed when the opening to the embayment becomes constricted by barrier construction across the embayment or when an existing barrier is breached during a storm or cut artificially. Various settings of tidal inlet development in Massachusetts are listed in Table 1 and discussed below.

Drowned River Valleys

The best example of tidal inlet development in a drowned river valley setting is Merrimack River Inlet located between Salisbury Beach and Plum Island

(Fig. 1). The Merrimack River, which drains much of New Hampshire and northeastern Massachusetts, delivered a large quantity of sand to the coastal region during deglaciation. Much of this sediment was deposited in the form of three major deltas at 33 m and 16 m above present mean sea level and 50 m below mean sea level (Edwards, 1988). The last delta was deposited during the Holocene lowstand and was formed, in part, through the cannabalism of the 16 m elevation delta (Edwards, 1988). Subsequent drowning of this erosional valley during the late Holocene formed the present day embayment at the river mouth. Later, the embayment was constricted during the evolution of Plum Island and Salisbury Beach, resulting in the formation of Merrimack River Inlet. The major sand source for these regressive barriers and the barriers to the south was the onshore reworking of the top portion of the 50 m delta during the Holocene transgression.

The formation of Plymouth Bay and location of its entrance are also closely related to deglaciation processes (Fig. 5). As the Buzzards Bay Lobe of the continental ice sheet retreated northward across southeastern Massachusetts, sometime after 15,300 yrs BP (Larson, 1982), glacial Lake Taunton was formed covering an area of approximately 140 km^2. During much of its existence the lake drained to the south through a spillway just north of Fall River (Larson, 1982). However, after the Cape Cod Bay Lobe retreated northeastward removing the lake's eastern dam, the water drained through the Jones River valley, which was 4 to 7 m lower than the lake level (Larson, 1982). Presently, the river forms the estuarine headwaters of Kingston Bay within Plymouth Bay (Fig. 6). The greatest thickness of sediments above the acoustic basement (> 20 m) in the Plymouth Bay area is along two troughs; one coinciding with the north-south long dimension of the bay and the other defining the present course of Plymouth Inlet's main ebb channel (Hill et al., 1990; Fig. 6). This inferred paleodrainage system inside the bay joins with the Postglacial drainage patterns outside the bay as reported by Oldale and O'Hara (1977). Thus, it would appear that drainage established during the early Holocene has dictated, to a large extent, the geometry of Plymouth Bay and the position of its inlet. The barriers that front Plymouth Bay have evolved from landward migrating transgressive barriers and through spit accretion from sediment eroded from nearby drumlins and till cliffs (Hill and FitzGerald, in press).

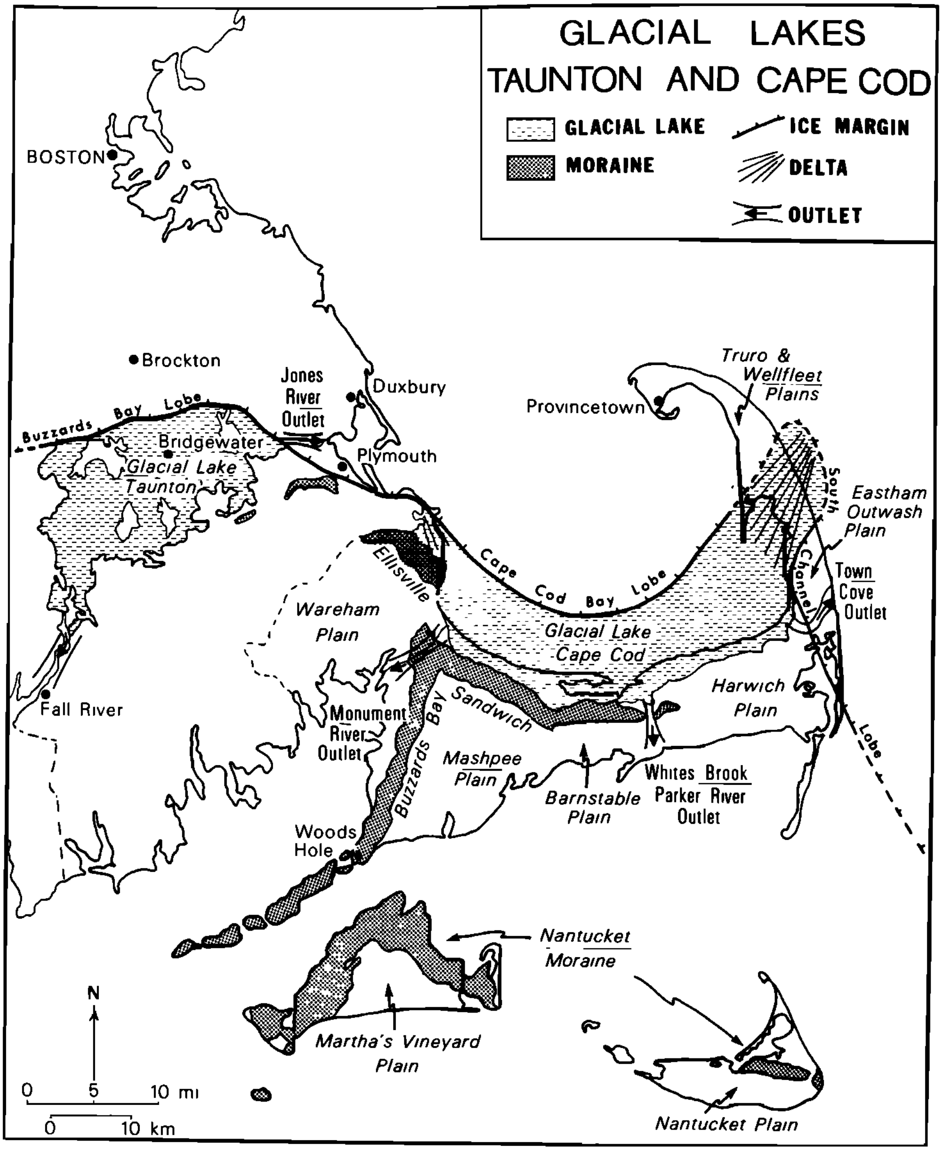

Figure 5. Map of southeastern Massachusetts depicting deposits and features of late Wisconsinan glaciation (modified from Larson, 1982).

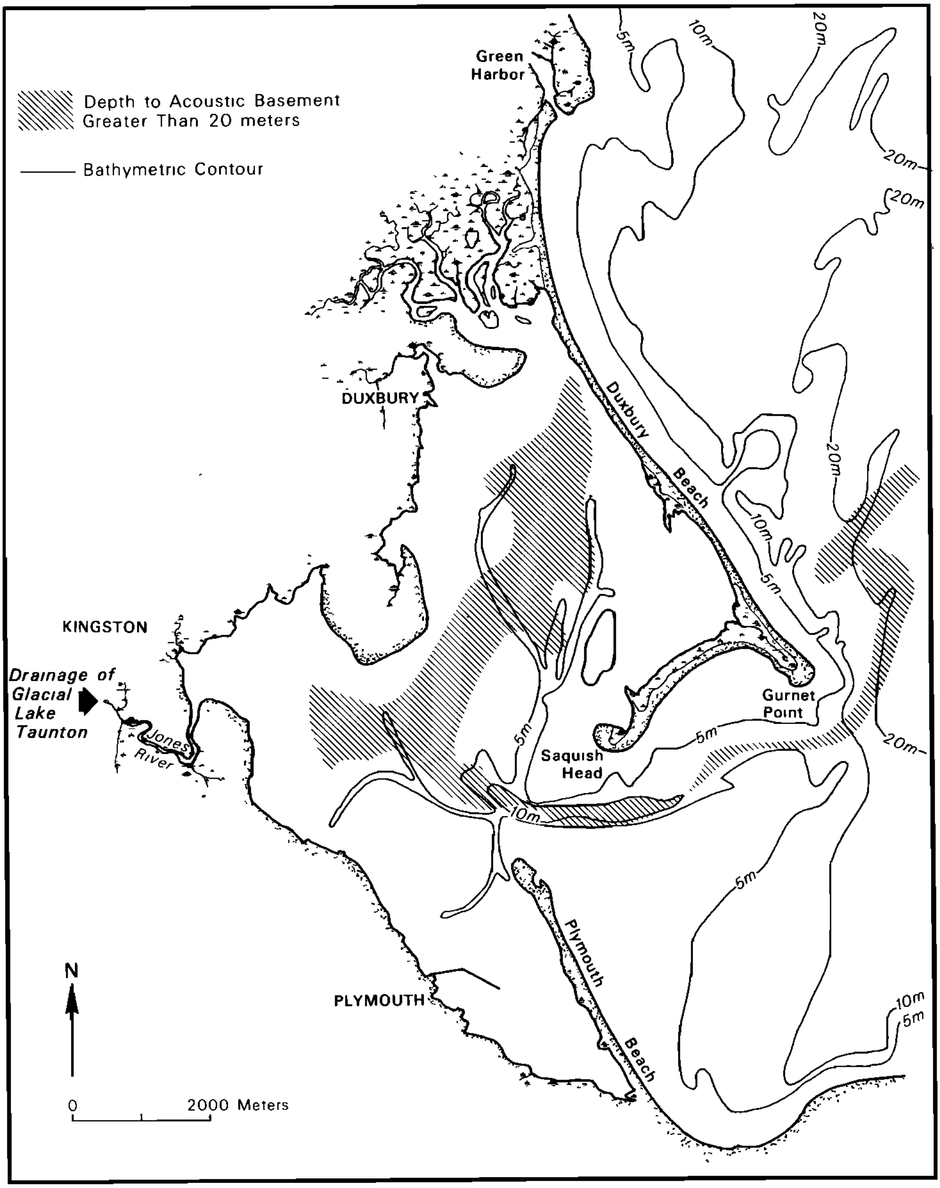

Figure 6. Map of Plymouth Inlet and embayment showing bathymetry and structure contours of the depth to the acoustic basement. Note that the northern portion of the bay and the inlet channel coincide with where sediment thickest is greatest. The two arms are believed to be major channels that were active when Glacial Lake Taunton was draining to the east (after Hill et al., 1990).

Rocky Irregular Shorelines

The Cape Ann promontory and the northern coast of Buzzards Bay are the major rocky coastlines in Massachusetts. Along these shorelines pocket beaches are the dominant accretionary landform and tidal inlets exist only where the sediment supply was abundant enough to develop significant barriers (Fig. 3). The lack of sand along Cape Ann has prohibited barrier and inlet development except for a small inlet associated with the pocket barrier of Good Harbor Beach. Sediment is slightly more abundant along the northwest coast of Buzzards Bay and tidal inlets are more numerous (Fig. 3; Table 1). This shoreline is characterized by deeply incised embayments fronted mostly by thin, sand and gravel barriers. In this region inlets were formed by spit accretion derived from sediment that had been eroded from adjacent shorelines, as well as sediment moved onshore from nearshore glacial deposits (FitzGerald et al., 1987). The larger inlets in this area, including Slocum and Westport River Inlets, are positioned next to bedrock outcrops. Several inlets along this coast have closed in historical times due to the transgression of the barriers.

Sandy Irregular Shorelines

The original Cape Cod shoreline that was formed by rising sea level during late Holocene (approximately 3,000 to 4,000 yrs BP) was probably highly irregular due to the nonuniform topography of the moraines, outwash plains and other glacial sediments that comprise Cape Cod. It is likely that proto-Cape Cod had the same general "arm" form but with numerous embayments and small islands (Davis, 1896). This shoreline has been smoothed through erosion of headlands, disappearance of some of the islands, and development of spits across the bays. Numerous tidal inlets were formed as a result of spit accretion including Barnstable Harbor Inlet, Nauset Inlet, Chatham Harbor Inlet, and many others (Fig. 1; Table 1).

A basal peat sample collected at a depth of 5 m below the present marsh surface at Scorton Neck near the beginning of Sandy Neck was radiocarbon dated at 3,170 yrs BP (Fig. 7; Redfield, 1967). This date and others were used by Redfield (1967) to hypothesize that Sandy Neck began forming not more than 4,000 yrs BP. The sand that comprises Sandy Neck was eroded from the Wareham Pitted Plain, Ellisville Moraine and other surrounding glacial deposits (Fig. 5) and transported south by littoral processes. The sandy cliffs along the Manomet and Sagamore shoreline are evidence of this erosion. It is likely that the formation of other tidal inlets along Cape Cod also occurred approximately 3,000 to 4,000 yrs BP, coincident with rising sea level and spit accretion. However, the barriers that front the other inlets are considerably younger than Sandy Neck due to the transgressive nature of most of them. This has been documented at various inlets on Cape Cod by FitzGerald and Levin (1981), Aubrey and Gaines (1982), Aubrey and Speer (1984), and Giese (1988).

Kettles

A unique means of coastal bay development and tidal inlet formation occurred along the Cape Cod Bay shoreline in Eastham. This portion of Cape Cod is composed of the Eastham Outwash Plain (Fig. 5) which contains numerous kettles. One of the largest of these kettles (1,200 m across) is located on the coast and forms the embayment behind Herring River Inlet (Fig. 8). Thirty-six auger cores taken throughout the marsh system landward of First Encounter Beach indicate that the base of the kettle is at least 8 m deep (Fig. 9). The cores reveal that the marsh peats and organic muds are thickest in the eastern side of the embayment and thin toward the inlet mouth and barrier spit. The marsh deposits are underlain by medium-to-coarse sands that are moderately well-sorted. The western third of the embayment contains little or no marsh deposits at the surface and is covered by supratidal vegetation (Fig. 9). The shallowness of the cores in this region does not allow for a determination of the presence of marsh peats at depth (> 2.5 m).

The stratigraphy of the kettle and morphology of the present barrier spit and tidal inlet system suggest that during the Holocene transgression, rising sea level flooded the kettle forming a large embayment (Fig. 10). Sand eroded from the coast to the north and transported south built a spit across the mouth of the embayment forming Herring River Inlet. A scenario for the filling of the bay begins with the contemporaneous deposition of sediment along the fringe of the bay with marsh growth toward the center, and the deposition of

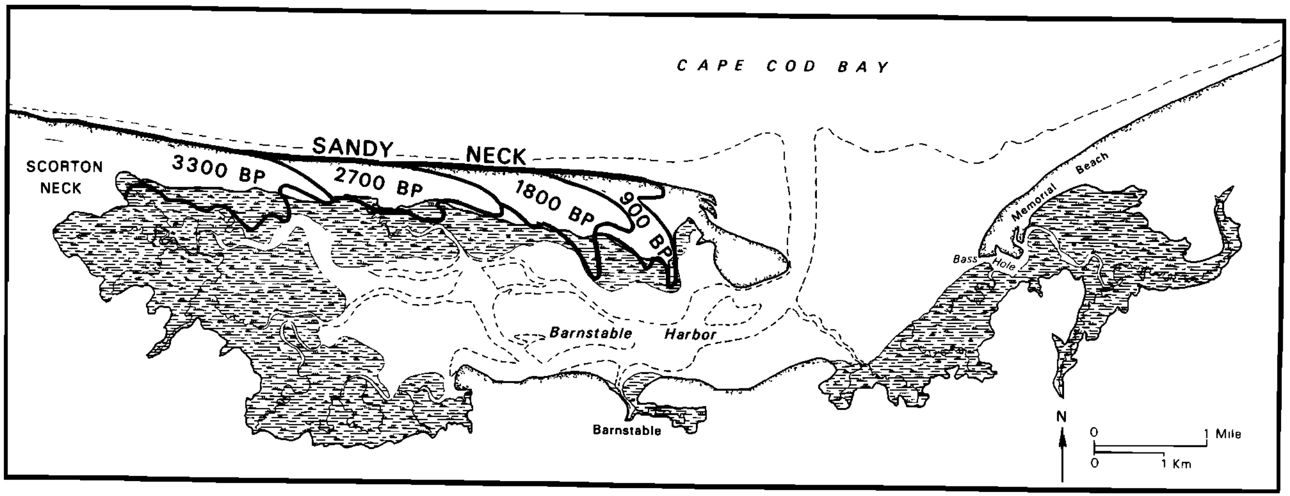

Figure 7. Chronology of the growth and development of Sandy Neck. The sediments that built this spit were derived from the erosion of glacial cliffs to the north (after Redfield, 1967).

Figure 8. Oblique aerial photograph of Herring River Inlet and marsh system. This inlet is located on the pitted Eastham Outwash Plain. The bay of this inlet was originally a kettle that became connected to the sea.

sheet sands and flood-tidal deltas along the seaward side of the embayment. Storm waves overwashing First Encounter Beach during events like the Blizzard of 1978 would have introduced large quantities of sand into the bay and may explain the lack of surface peat and organic mud deposits in the eastern third of the embayment. Sediment deposited along the margin of the bay would have come from overland sources and from fine-grained sediments carried in suspension by tidal currents. As the bay was converted to high marsh with small tidal creeks, the tidal prism was greatly reduced, resulting in a smaller equilibrium inlet cross section and elongation of the spit system. Spartina marsh peats cropping out in the intertidal zone seaward of First Encounter Beach suggest that the decrease in bay area is also a result of the transgression of First Encounter Beach.

Groundwater Sapping Channels

One of the noteworthy coastal morphologies along the south shores of Cape Cod, Martha's Vineyard, and Nantucket is the north-southward trending, flooded valleys that form the inlet-associated bays of this region (Fig. 11). The depressions that resulted in the formation of these elongated bays were once considered to have originated from meltwater streams (FitzGerald, 1985) due to permafrost conditions (Oldale and Barlow, 1986); recent work

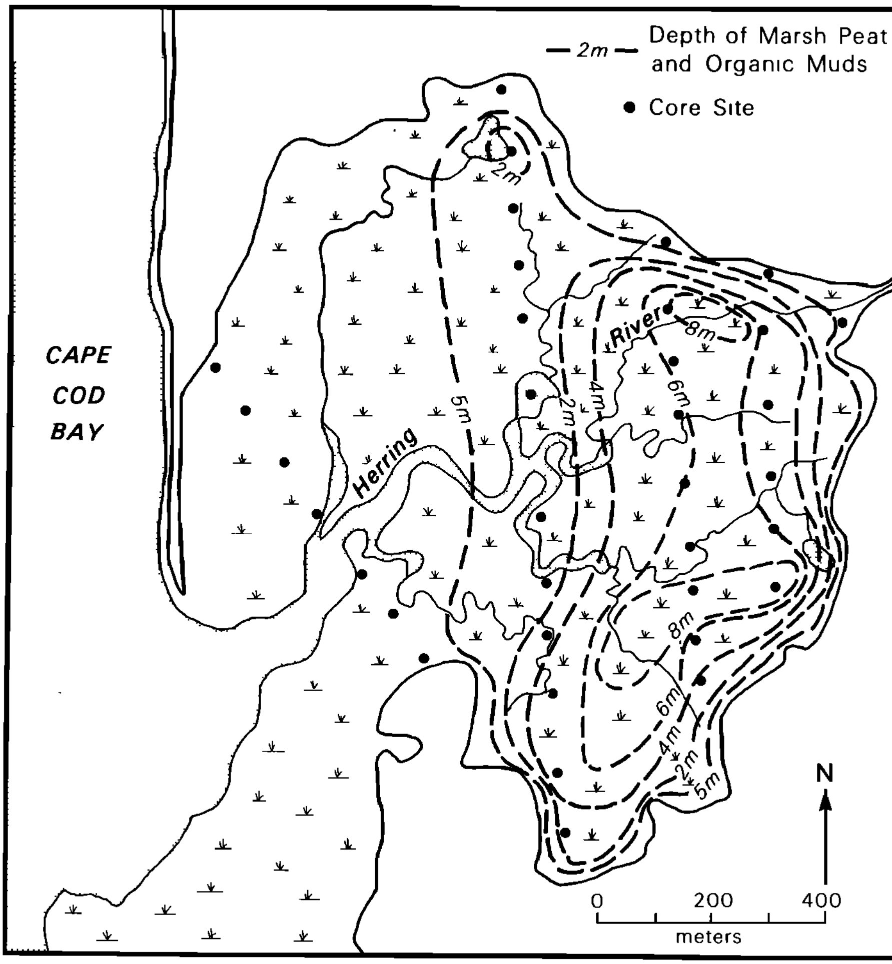

Figure 9. Location of auger cores and thickness of marsh peats and bay-fill mud deposits at Herring River backbarrier region.

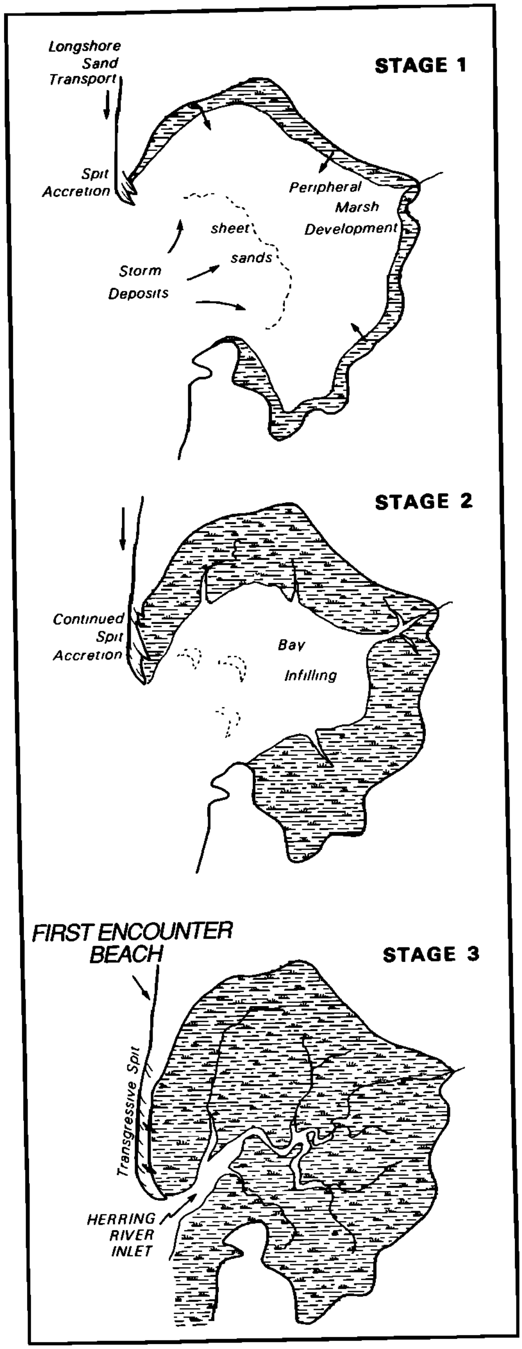

Figure 10. Conceptual model of tidal inlet formation and marsh development of Herring River

suggests that they developed through the process of groundwater sapping (Caldwell, pers. comm.; D'Amore, 1983). Topographic maps show that the bays are fairly evenly spaced along a given stretch of shoreline and have a pinnate drainage structure which is unlike the pattern that would have resulted if the valleys formed from a braided stream network associated with an outwash plain. Secondly, it is reasonable to assume that the hydraulic head produced by Glacial Lake Cape Cod (Fig. 5), which was at least 29 m (Larson, 1982; Oldale, pers. comm.), coupled with the coarse-grained Mashpee outwash plain would have caused piping as groundwater flowed toward the depression which is now Nantucket Sound. This process is known to move sand-sized material and create channels that migrate headward as they develop (D'Amore, 1983). The draining of Lake Cape Cod would have terminated this process and rising sea level would have eventually flooded the stream valleys. During the same period, sand that eroded from the intervalley headlands would have fed spit systems that built across the flooded bays forming tidal inlets.

Barrier Chains

The Massachusetts coast has two major barrier chains; one extending from Great Boars Head in New Hampshire to Cape Ann and another that stretches along the outer coast of Cape Cod from Coast Guard Beach to Monomoy Island (Fig. 12). The mode of inlet formation along these two chains was quite different and related to differences in barrier development and river drainage patterns.

Outer Cape Cod Chain

The barriers forming the Nauset Spit-Monomoy Island chain formed through spit accretion from sediment eroded mostly from the glacial cliffs north of Coast Guard Beach (Fig. 12) (Fisher, 1987; Giese, 1988 and this volume). Periodically, storm breaching has segmented these barrier spits, such that at various times there are two or more quasi-stable inlets. Quite recently Monomoy Island was breached during the 6-7 February Blizzard of 1978 and Nauset Beach was breached during the northeast storm of 2 January 1987.

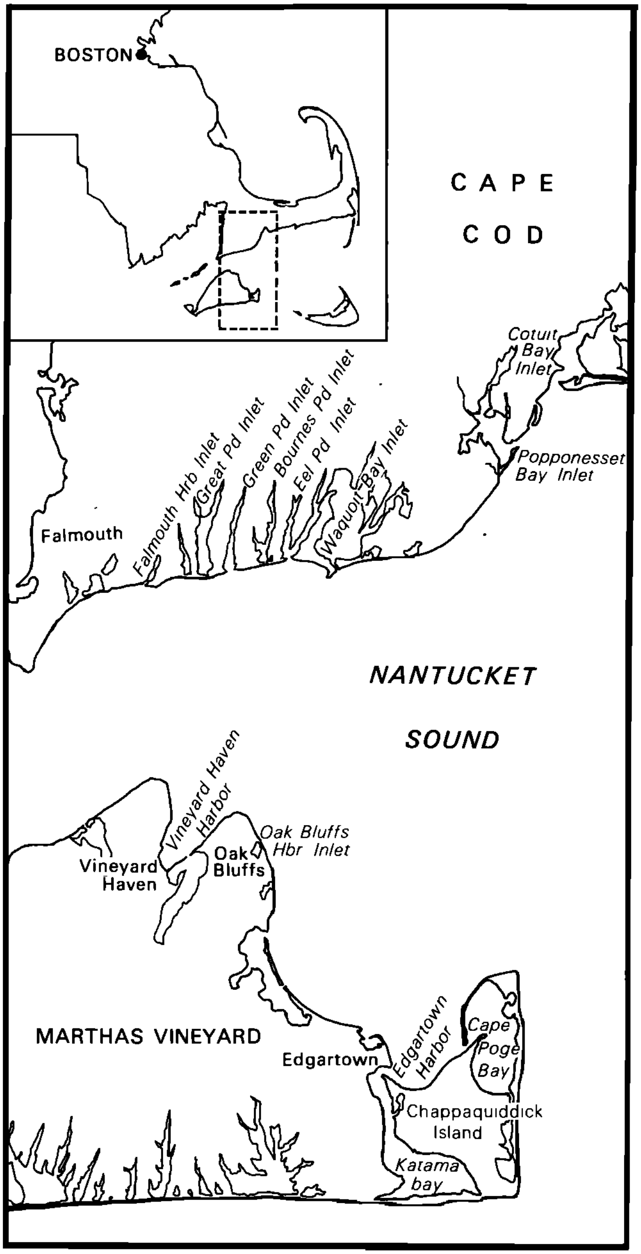

Figure 11. Groundwater sapping channels along the southern shores of Cape Cod and Martha's Vineyard. Inlets are unstable along the south shore of Martha's Vineyard due to small bay areas, small tidal ranges and moderate wave energy. On the southwest coast of Cape Cod similar conditions have necessitated the construction of jetties to keep inlets open and navigable.

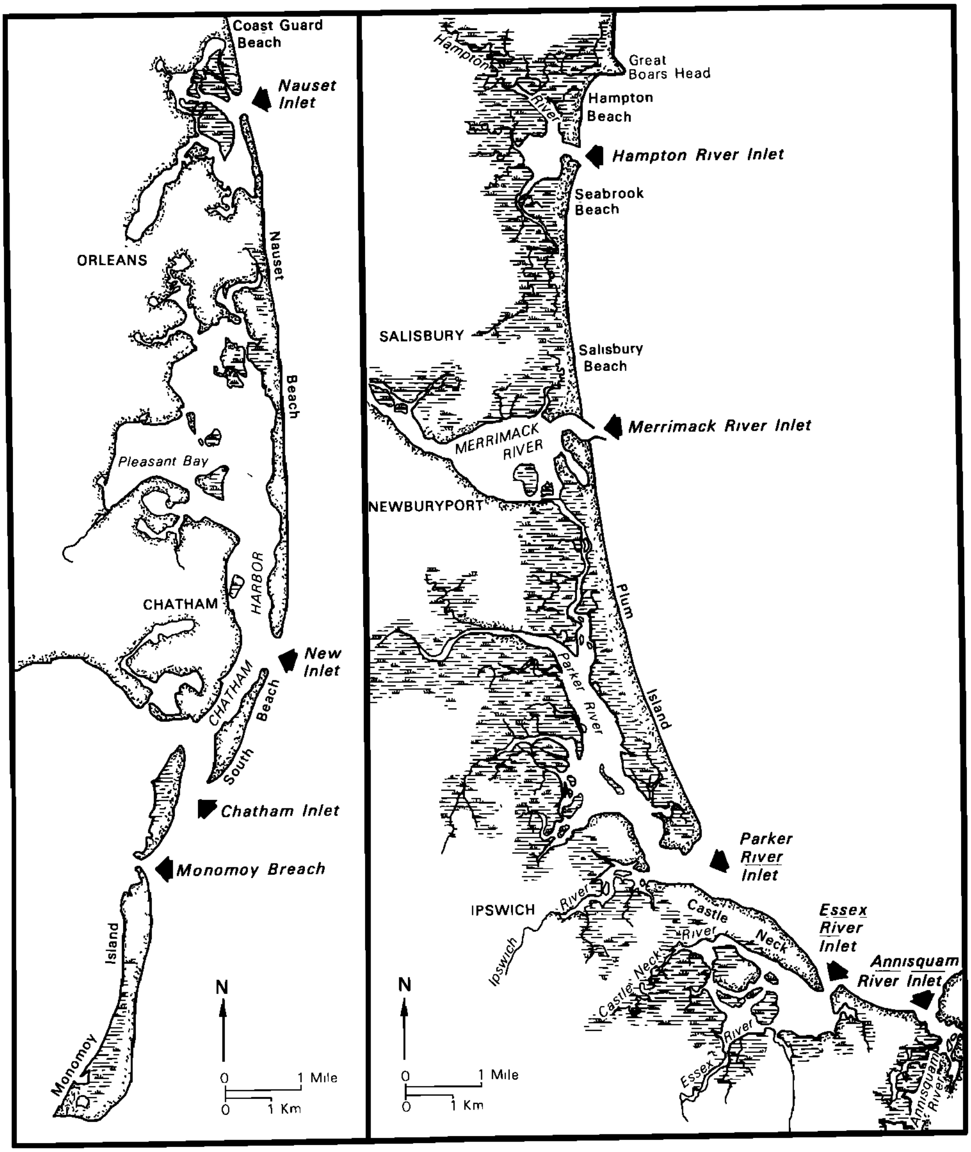

Figure 12. Major barrier coasts in Massachusetts.

The segmentation of the barriers and the development of inlets along this coast are related to a gradual restriction of tidal flow through existing inlets due to spit accretion and inlet migration (Giese, 1988; this volume). This produces differences in tidal range and tidal phase between the ocean and bays which can produce a substantial hydraulic head across the barrier. Under these conditions the barrier is susceptible to breaching, particularly during storms when the hydraulic head increases due to the storm surge.

Thinning of barriers is also a key factor in controlling when spits are breached. If the barrier is wide and has a well-developed frontal dune ridge and secondary dune system, breaching is difficult regardless of the hydraulic head. In contrast, destruction of the foredune ridge and thinning of the barrier allows barrier overwashing, channelization of the return flow, and subsequent inlet formation. Historical shoreline change data of the glacial cliffs north of Nauset Spit indicate that for the period between 1938 and 1974 there were significant temporal and spatial variations in shoreline location (Gatto, 1978). Thus, it can be reasoned that during the same period of time the supply of sand to the southern barrier system may have been equally variable, which may have influenced the retreat and advance of the barrier shoreline. Changes in the trend of shoreline retreat and advance are probably related to natural variations in wave energy and the frequency of major storms. Thus, breaching of the outer Cape Cod barrier system occurs when a sufficient hydraulic head has been established and the barrier has sufficiently thinned to facilitate overwashing during a major storm (see Friedrichs et al., this volume).

Northern Massachusetts Chain

The barrier chain north of Cape Ann contains five major barriers and five tidal inlets (Fig. 12). Although various workers have proposed littoral currents and spit accretion as responsible for the formation of these barriers (Nichols, 1941; McIntire and Morgan, 1964; Rhodes, 1973), these authors were unaware of the large accumulation of sand that exists in the Merrimack River delta (vol. = 1.4 x 10 m) 6 km offshore of the present river mouth in 50 m of water (Edwards, 1988). It is now believed that sand which formed this barrier chain came primarily from a reworking of the 50 m depth Merrimack marine delta and to lesser extent from the reworking of other glacial deposits on the continental shelf and some sediment discharged from the Merrimack River. Using the shallow seismic reconstruction of the 50 m delta by Edwards (1988), Som (1990) calculated that erosion and onshore transport of the top 2.5 m of the delta during the Holocene transgression could account for the entire volume of sand comprising the barrier chain and tidal delta shoals. It has been widely reported that marine deltas can be a significant source of sediment in development of barriers, including the coasts of Maine (Belknap, 1987; FitzGerald et al., 1990), North Carolina (Hine et al., 1979), Georgia (Oertel, 1979), and Louisiana (Penland et al., 1988).

It is believed that the present barrier chain began forming during the Mid-Holocene from transgressive barriers containing numerous ephemeral tidal inlets. In a stratigraphic study of northern New England, McIntire and Morgan (1963) dated the initial stage of Plum Island development as occurring sometime prior to 6,300 yrs BP. The other barriers to the north and south probably formed shortly thereafter from sand delivered onshore from the shelf and from sand moved alongshore by wave action. As the barriers stabilized and increased in width, tidal inlets probably decreased in number and also became more stable. Tidal inlets along this chain are associated with one or more river systems, although with the exception of the Merrimack River, they are small and discharge little freshwater compared to their saltwater tidal prisms (Table 1). Although the rivers are small, their valleys provided ideal locations for inlets to stabilize and the development of backbarrier marshes and tidal creeks. The association of tidal inlets with former river valleys is common along many barrier coastlines (Morton and Donaldson, 1973; Oertel, 1975; Halsey, 1979). Inlets along this chain are also partially stabilized or anchored next to bedrock outcrops (Hampton, Essex, Annisquam River Inlets).

Thus, the inlets along these two chains differ in that the Cape Cod inlets are associated with spit systems, are formed as a result of barrier breaching, and tend to migrate. In contrast, inlets north of Cape Ann are associated with a barrier coast that evolved from transgressive barriers, formed in paleo-river valleys, and are relatively stable.

Morphological Variability

Variability in tidal inlet morphology along the Massachusetts coast is a product of the vastly different physical settings under which inlets have formed and evolved. Tidal inlets may differ from one another in size and channel geometry, shoreline configuration, associated sand shoals, back-barrier setting and other components. Many of the major differences among the inlets can be explained in terms of varying wave and tidal conditions (Hayes, 1975; 1979). Sediment supply and tidal prism are other important variables that govern inlet morphology (Davis and Hayes, 1984). Characteristics of the tidal inlets discussed in this section are listed in Tables 1 and 2.

Inlet Size

The cross-sectional area of an inlet is dictated by its tidal prism (O'Brien, 1931; 1969) which, in turn, is primarily a function of bay size (open water area) and bay tidal range. The largest inlets in Massachusetts occur along mesotidal shorelines where backbarrier areas are expansive and composed chiefly of open water. Plymouth Inlet (Fig. 6) is such an inlet, having three large contiguous bays composed of open water areas and tidal flats. It has a spring tidal range of 3.3 m. These conditions combine to produce a spring tidal prism of 1.2×10^6 m^3 and an inlet cross-sectional area of 9,160 m^2 (Hill et al., 1990). Other large tidal inlets occur along the barrier chain north of Cape Ann (Merrimack, Parker, Essex Inlets) and in Cape Cod Bay (Barnstable Harbor Inlet). These inlets have mesotidal ranges (TR = 3.0 m) and large backbarrier areas (Table 1).

Tidal inlets are relatively small along the microtidal shorelines of Buzzards Bay (TR = 1.0 to 1.3 m) and Nantucket (TR = 0.4 to 1.2 m) and Vineyard Sounds (TR = 0. 5 to 0.8 m). In these regions the low tidal ranges added to the diminutive size of most of the inlet associated bays result in small tidal prisms and small equilibrium inlet channels (Table 2). Even at Westport River Inlet (Fig. 2) which drains both the East and West Branch of the Westport River Estuary, the inlet throat is only 250 m wide with a stable cross-sectional area of 850 m and an average depth of 3.4 m (Magee and FitzGerald, 1980). In comparison, the bay areas of both the Parker River and Essex River Inlets, north of Cape Ann, are smaller than that of Westport River Inlet, however their inlet throat cross sections are more than twice as large (3,097 m^2 and 1714 m^2, respectively; FitzGerald, unpub. data).

Along the southern coast of Cape Cod the effect of small tidal ranges on inlet size is particularly well illustrated. Despite the relatively protected environment within Nantucket Sound, which produces low wave energy and small longshore transport rates (4,400 m^3 net easterly transport in the vicinity of Bass River Inlet; Slechta and FitzGerald, 1982), most tidal inlets are jettied and/or dredged. Tidal prisms and tidal currents are insufficient along most of this microtidal shoreline to maintain navigable entrance channels for pleasure craft.

Associated Sand Shoals and Backbarrier Settings

Sand which is dumped into the inlet channel by littoral processes and flood tidal currents is transported seaward by ebb currents to the ebb-tidal delta or moved landward into bays forming flood-tidal deltas. Ebb-tidal deltas are links and short-term repositories in the littoral transport system that allow sand to bypass inlets. Flood-tidal deltas my build vertically to form intertidal sand shoals which subsequently may be colonized by marsh vegetation, resulting in the filling of the bay (Lucke, 1934). Models depicting tidal deltas and inlet settings were first put forth by Hayes et al. (1973) and Hayes (1975), originally based on the tidal range of the region. Later, these geomorphic models were modified to include the influence of wave energy (Hayes, 1979; Nummedal and Fischer, 1978).

Ebb-tidal deltas

In Massachusetts ebb-tidal deltas are well developed along mesotidal shorelines at medium-to-large inlets (Table 2). At these locations, like Essex River Inlet (Fig. 3), the ebb delta has a main ebb channel that incises a broad arcuate accumulation of sand called the swash platform (Hayes, 1975). On top of the swash platform are wave built swash bars which migrate onshore eventually attaching to the beach (Hine, 1975; FitzGerald, 1976). The main channel shoals in a seaward direction and is often bordered by linear bars. In mesotidal settings where sand is abundant, swash bars and channel margin linear bars are often exposed at low tide. At large jettied inlets like Merrimack River Inlet the ebb-tidal delta forms too far offshore for intertidal bars to develop. Likewise, at New Inlet along the South Shore (Fig. 2) the paucity of sand in this region probably prevents bars from building vertically to an intertidal exposure. In contrast, at the structured Pamet River Inlet where an abundant sand supply leaks around the updrift jetty, intertidal bars are well formed (Fig. 2). The small tidal prism and relatively weak tidal currents of this inlet result in the ebb delta forming in shallow water close to the inlet mouth (FitzGerald and Levin, 1981).

Ebb-tidal deltas are much more poorly developed along the microtidal shorelines of Buzzards Bay and Nantucket Sound (Table 2). In these regions the ebb delta is completely subtidal due to relatively small tidal prisms and smaller tidal range to expose the sand shoals. At many inlets, like Westport River Inlet (Fig. 2), the ebb delta is best defined during large wave conditions which serve to outline its extent. At other inlets, such as Slocum River Inlet and several inlets along the southern coast of Cape Cod (Bass River Inlet, Fig. 2), the ebb-tidal delta is moderately well developed and visible in aerial photographs because it has formed on a shallow nearshore platform. Ebb deltas at small tidal inlets along microtidal shores are mostly absent (Table 2).

Flood-tidal deltas

Most tidal inlets in Massachusetts have singular or multiple flood-tidal deltas, provided there is enough space in the backbarrier for them to form (Table 2). Flood deltas develop landward of the inlet throat where tidal current velocities diminish due to an increase in channel dimensions. At inlets where filling of the backbarrier has produced marsh islands and tidal creeks with little open-water area, flood deltas may be absent (e.g., New Inlet, Scituate; Fig. 2). In some instances, deltas become colonized and modified by marsh growth and are no longer discernible as flood-tidal delta landforms (cf., FitzGerald et al., 1990). At jettied inlets and inlets with boat marinas, flood deltas are often removed to provide better navigation or space for boat moorings (e.g., Green Harbor, Scituate, Fig. 2).

Flood-tidal deltas are normally horseshoe-shaped and consist of a flood ramp that bifurcates into flood channels through which sand is transported onto the delta platform (Fig. 3). The ebb shield which defines the landward extent of the delta is the highest part of the delta and is commonly partially vegetated by Spartina grasses. This part of the delta shields the rest of the shoal from effects of the ebb currents. Sand eroded from the ebb shield by ebb tidal currents is carried seaward forming ebb spits which extend toward the inlet throat (Boothroyd and Hubbard, 1975; Hayes, 1975).

On the Massachusetts coast, flood deltas are best developed at large inlets along mesotidal shorelines (Table 2). For instance, flood deltas are well formed with intertidal exposures at Merrimack, Parker, and Essex River Inlets north of Cape Ann and at Plymouth Inlet and Barnstable Harbor Inlet in Cape Cod Bay. There are multiple flood deltas at Nauset Inlet (Fig. 2); their presence influences the flow of water through the inlet and the pattern of inlet migration (Aubrey and Speer, 1984). Multiple flood deltas are still evolving landward of the breach through Nauset Beach and their resulting configuration and location will strongly affect the patterns of flow in Chatham Harbor and Pleasant Bay (FitzGerald and Montello, 1990; see other articles in this volume). A large flood delta on the western side of the Monomoy Breach is presently undergoing modification due to the recent closure of this inlet.

Along the microtidal shorelines of Buzzards Bay and Nantucket Sound, flood-tidal deltas are usually small compared to those found along mesotidal shorelines. Commonly, much of the delta is subtidal and irregularly shaped (e.g., Westport River Inlet and Green Pond Inlet; Fig. 2). Their diminutive nature probably is related to smaller tidal prisms and weaker tidal currents. Storms are a major cause of flood delta development along microtidal coasts resulting from the process of barrier breaching (Pierce, 1976) or increased sediment being delivered to the inlet coupled with elevated flood current strength associated with storm surge development (FitzGerald, 1988).

Backbarrier Systems

There are two major types of backbarrier environments associated with tidal inlets in Massachusetts and these correlate well with tidal range (Hayes 1975, 1979). Tidal inlets along mesotidal coasts have backbarrier areas composed primarily of high tide marsh (Spartina patens) incised by major and minor tidal creeks. At inlets north of Cape Ann and New Inlet in Scituate, rivers form the major tidal channel(s) in the backbarrier (Fig. 12 and 2, respectively; Table 1). In mesotidal settings the percentage of open water area and intertidal flats decreases away from the inlet mouth while the percentage of marsh increases (Fig. 13; Som, 1990).

In microtidal settings tidal inlets connect the ocean to shallow bays or lagoons (e.g., Green Pond and Bass River Inlet; Fig. 2, Table 1). In the case of Westport River Inlet, the bays are drowned river valleys with some intertidal flats and marsh areas. Most of the marsh islands occur behind the middle of Horseneck Beach at the site of an old tidal inlet and probably represent flood-tidal delta shoals that were deposited before the inlet closed (Magee and

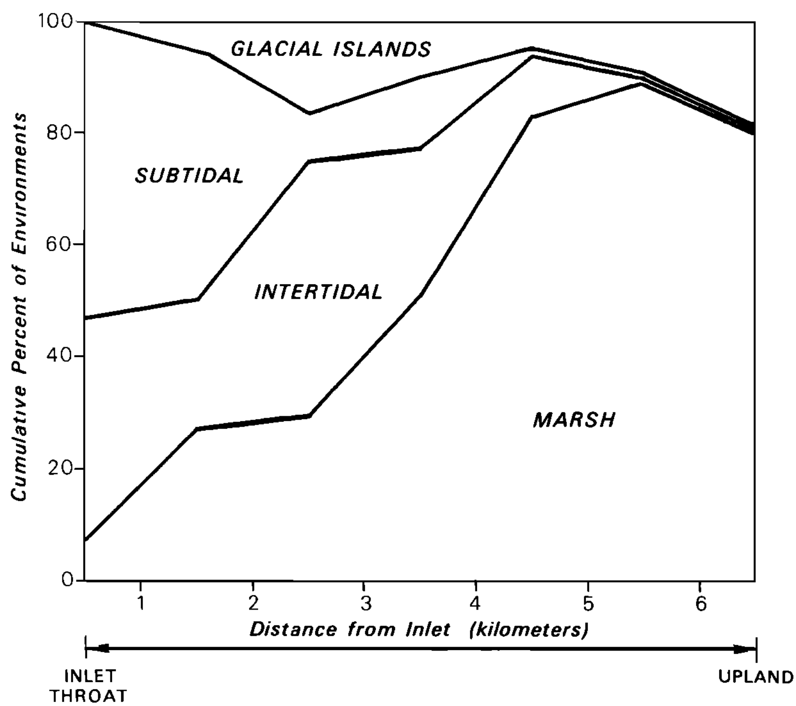

Figure 13. Distribution of backbarrier environments associated with Essex River Inlet. Note that with increasing distance away from the inlet mouth, the percentage of marsh increases while open water areas and intertidal flats decrease (after Som, 1990).

FitzGerald, 1980; Ibrahim, 1986; FitzGerald et al., 1987). The difference between the marsh and tidal creek backbarrier setting of mesotidal inlets versus the open water and fringing marsh of microtidal inlets is probably related to the larger tidal prisms, stronger tidal currents, and greater potential of bringing sediment into the bay at inlets with larger tidal ranges. The greater tidal fluctuation in the bay also produces larger intertidal areas which promote marsh formation and stabilization of fine-grained sediment. One exception to this trend is the mesotidal backbarrier system of Plymouth Inlet (Fig. 1) where the bay is composed principally of intertidal sand and mud flats and open water areas (Fig. 6). A detailed stratigraphic and sediment transport study of this region has revealed that Plymouth Bay has been a sediment sink since its formation during the Mid-to-Late Holocene and that the bay fill consists generally of a fining upward sequence of sands and muds (Hill et al., 1990; Hill and FitzGerald, in press). The presence of intertidal flats and absence of marshes indicate that these environments are not suitable for marsh development. This condition is likely the result of the size of the bay and tidal range which allow tidal and wave-generated currents at high tide and especially during storms to inhibit colonization of the flats by halophytic grasses. Ice gouging of flats during the winter may also be an operative process. The absence of salt marshes despite the presence of expansive tidal flats has been noted along the Friesian Islands in the North Sea and behind the Copper River Delta barrier system in Alaska (FitzGerald and Penland, 1987).

Tidal Inlet Stability

Stable tidal inlets are in dynamic equilibriun with the scouring action of tidal currents and the infilling of sediment delivered by longshore currents (Inman and Frautschy, 1965). However, the equilibrium of the inlet channel does not imply stability in position of the inlet, rather only in its cross-sectional area. The size of an inlet has been shown to be proportional to the volume of water flowing through it during a half tidal cycle (tidal prism). This relationship was quantified by O'Brien (1931, 1965) and later refined by Jarrett (1976) for structured versus unstructured inlets and inlets with varying wave energy (i.e., Pacific, Gulf and Atlantic Coasts).

The stability of inlets along the shores of Denmark, Netherlands and United States was examined in detail by Bruun and Gerritsen (1959) and Bruun (1967) and found to be governed by shear stress along the channel bottom. They noted that the magnitude of shear stress and maximum current velocities in the channel necessary to flush the inlet of sediment varied according to inlet geometry, rate of littoral drift delivered to the inlet, and concentration of suspended versus bedload. Later investigators suggested that inlets possess a critical cross-sectional area and if inlet size is reduced below this critical value through the influx of sand, it will close (O'Brien and Dean, 1972). While these various relationships would be useful in interpreting the evolution and closure of certain inlets in Massachusetts, the lack of hydraulic and morphologic data concerning these inlets make these analyses impossible. Therefore, the stability of Massachusetts inlets will be evaluated using historical information and other data sources. Effects of varying tidal prism and wave energy, changes in sediment supply, inlet closures and openings, and jettied inlets will be examined.

Tidal Prim and Wave Energy

The influence of tidal prism and wave energy on the equilibrium cross sectional area of tidal inlets is illustrated well along the northwest coast of Buzzards Bay. This shoreline consists of elongated bays fronted by thin transgressive barriers; the beach ridge barrier of Horseneck Beach at Westport River Inlet is a major exception. As shown in Figure 14, there is a close correspondence between bay size and inlet width, with large bays having wider inlets. This relationship exists because tidal range is fairly constant along this coast and bay area can be taken as a first order approximation of inlet cross-sectional area. The fact that many of the bays have no permanent connection to the sea is a function of a limited sediment supply in a regime of rising sea level (Fig. 4). During the ongoing transgression the lack of sediment along most of this coast has resulted in a landward migration of the barriers, a process which is decreasing bay area at a faster rate than the upland has been inundated by rising sea level. This has reduced the tidal prisms of many of the bays causing the closure of the smaller inlets. This same phenomenon explains the lack of tidal inlets along the elongated pond shorelines of Martha's Vineyard and Nantucket (Fig. 11). If jetties had not been constructed at many of the inlets along the Cape's Nantucket Sound, several of them would have closed.

The relationship depicted in Figure 14 also illustrates the importance of wave energy in influencing the stability of inlets. Note that while tidal inlets exist at Salters Pond and Little River Inlet, the larger bays of Quicksand Pond and Briggs Marsh Pond, which potentially would produce larger tidal prisms than the other two, maintain no permanent inlets. This apparent contradiction in the aforementioned area/inlet width relationship can be explained due to differences in wave energy. The eastern two bays that have tidal inlets (Salters Pond and Little River Inlet) are partially sheltered from wave energy by headlands and the offshore Elizabeth Islands. In contrast, the barriers fronting Quicksand and Briggs Marsh Ponds are directly exposed to the prevailing southerly wave climate (Fig. 4). Thus, for inlets along the Buzzards Bay coast that are close to the condition which produces instability and closure (O'Brien and Dean, 1972), it appears that slight differences in

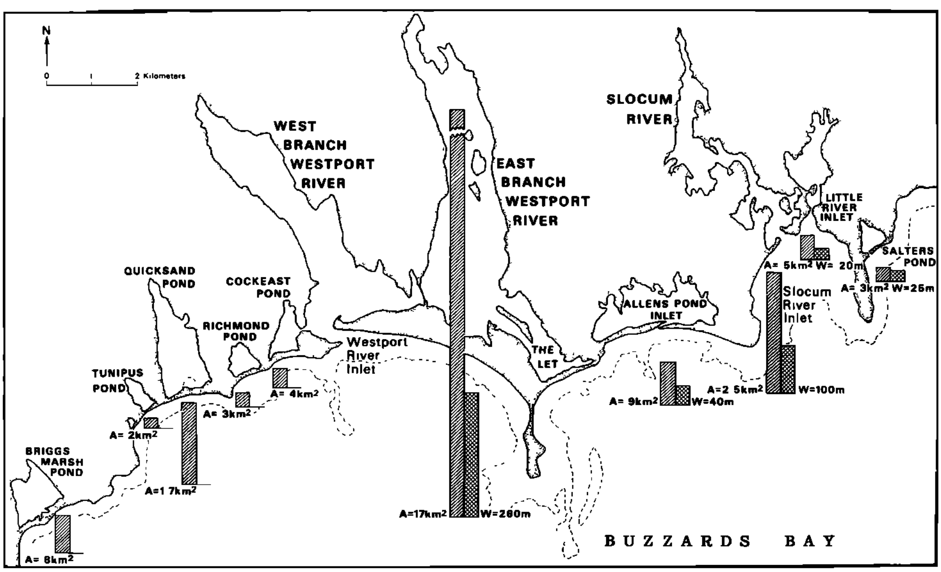

Figure 14. Plot of bay area versus tidal inlet width for the northwest Buzzards Bay coast. This diagram illustrates the relationship between tidal prism and inlet cross sectional area. Larger bay areas produce larger tidal prisms which require larger tidal inlet openings and conversely (from FitzGerald, 1988).

wave energy and longshore sediment transport rates can control the fate of the inlet (FitzGerald et al., 1987).

Changes In Sediment Supply

Along barrier island coasts a decrease in sediment supply leads to beach erosion and a thinning of the barrier. Usually, this condition makes the barrier more susceptible to storm breaching and tidal inlet formation. As speculated earlier, such a situation may have facilitated the recent breaching of Monomoy Island in 1978 and Nauset Beach in 1987.

Along the Buzzards Bay coast in Slocum River Embayment a spit with associated tidal inlet was formed and subsequently destroyed in a period of less than 50 years. The construction of the spit system that formed the inlet and its later destruction were a consequence of a period of sand abundance followed by sediment starvation (FitzGerald et al., 1986; Fig. 15). Before 1941 the inner embayment was open and a channel existed along Deepwater

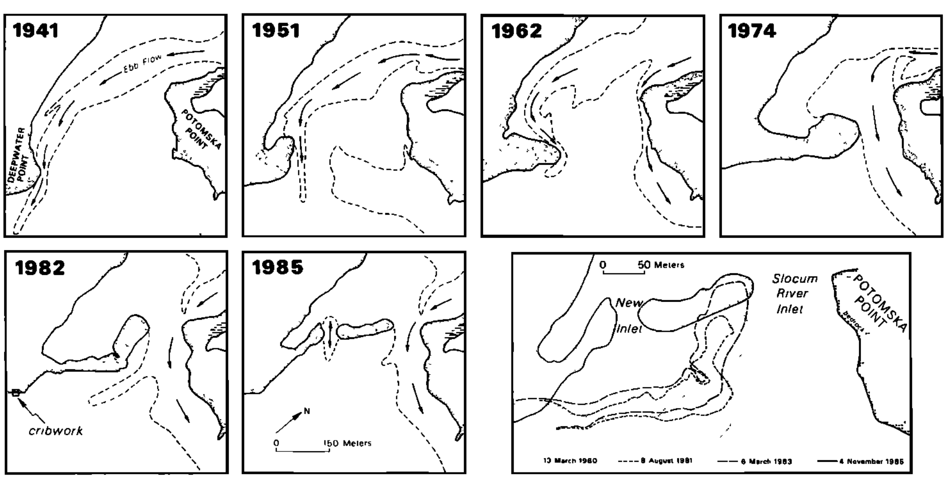

Figure 15. The construction and destruction of Slocum Spit as determined from vertical aerial photographs and field studies (from FitzGerald et al., 1986).

Point. Between 1941 and 1951 a spit began forming at Deepwater Point and accreted eastward across the bay. By 1974 the spit had deflected the main channel to a position along Potomska Point producing an inlet approximately 100 m wide. After the mid-1970's the spit began to erode and storm overwashing caused a landward migration of the barrier and onshore displacement of the inlet throat. The spit was breached in November 1984 during a spring tide and second inlet was formed adjacent to Deepwater point (Fig. 16). Since that time, the barrier continued to migrate onshore until it was transformed into an intertidal bar 50 m landward of its 1985 position (Mello, pers. comm.). As this process proceeds, the inner bay will return to an open water embayment and the tidal inlet will disappear.

The sedimentation history within Slocum River embayment suggests that a discrete supply of sand was responsible for forming the spit system and Slocum River Inlet. FitzGerald et al. (1987) speculate that the 1938 Hurricane transported sand from the Allens Pond barriers into the embayment (Fig. 14). Once the sediment was inside the bay, low wave energy gradually moved the sand toward Deepwater Point. A series of partially buried beach ridges in the marsh system landward of the shoreward migrating bar suggests that spit and tidal inlet formation process has occurred several times in the past in this embayment.

Closure And Openings of Tidal Inlets

Numerous tidal inlets have opened and closed along the Massachusetts coast in historic times and more would have closed if dredging projects had not been undertaken and engineering structures had not been constructed. A partial list of inlet openings and closures is given in Tables 1 and 3, respectively. To illustrate the conditions that led to inlet openings and closure several case studies are presented below.

Shirley Gut

Prior to the mid 1930's, Shirley Gut was a tidal inlet that separated Deer Island and Point Shirley along the northeast shore of Boston Harbor (Fig. 17A). The earliest surveys and charts of this region indicate that the inlet was 146 m wide

Figure 16. Oblique aerial photographs of Slocum River Inlet in: A. 1983 and B. 1985.

Table 3. Inlets which have closed along the Massachusetts coast (partial list). Location shown in Figure 1.

INLET	LOCATION	HISTORY
Shirley Cut	Winthrop	Closed in 1934-36
South River	Marshfield	Closed During a Northeast Storm in 1898
Scusset Mills	Sagamore	Closed when the Cape Cod Canal was Built
East Harbor	Provincetown	Closed in 1869 Forming Pilgrim Lake
Katama Bay	Martha's Vineyard	Closed in 1869, 1915, 1934, 1969

at the inlet throat in 1860 and 10.7 m deep in 1847, shoaling to 7.2 m by 1861 (Nichols, 1949; Figs. 17B and D). During the next 70 to 75 years, the inlet narrowed and shoaled and by 1934 the inlet channel was barely subtidal and only 25 m wide at mean high water. A narrow isthmus (30 m wide) joined Point Shirley and Deer Island in 1936 (Nichols, 1949). Eventually the isthmus was broadened and filled to provide better access to facilities on Deer Island.

The inlet closed sometime between 1934 and 1936 and it has been suggested that storm processes contributed greatly to filling the inlet (FitzGerald, 1980). The short-term stability of the channel cross section during various periods of the inlet's history (1861 to 1869, Fig. 17B) suggests that under normal wave conditions the inlet was probably stable and tidal scour was sufficient to remove sediment dumped into the channel by longshore sediment transport. However, during storms stronger wave energies would have substantially increased the transport of sand and gravel from along Deer Island and Point Shirley toward the inlet. During the Blizzard of 1978 this region was the site of considerable deposition, including large gravel washovers greater than 1 m thick (FitzGerald, 1981). Although some of the sediment dumped into the inlet during storms would have been removed by increased currents caused by the accompanying storm surge, much of the sediment probably remained. The reason for this is that during storms most of the increased flow into and cut of northern Boston Harbor was accommodated through President Roads channel. Thus, at Shirley Gut a disequilibrium was established during storms between the volume of sediment delivered to the inlet and the quantity of sediment scoured by tidal currents; this condition led to closure of the inlet.

Katama Bay Inlet

Katama Bay Inlet on the southeastern shore of Martha's Vineyard (Fig. 11) has opened and closed numerous times during the past 150 years (Ogden, 1974). As seen in Figure 18, breaching of Norton Point spit normally occurs in the middle of the barrier and is commonly associated with major storms

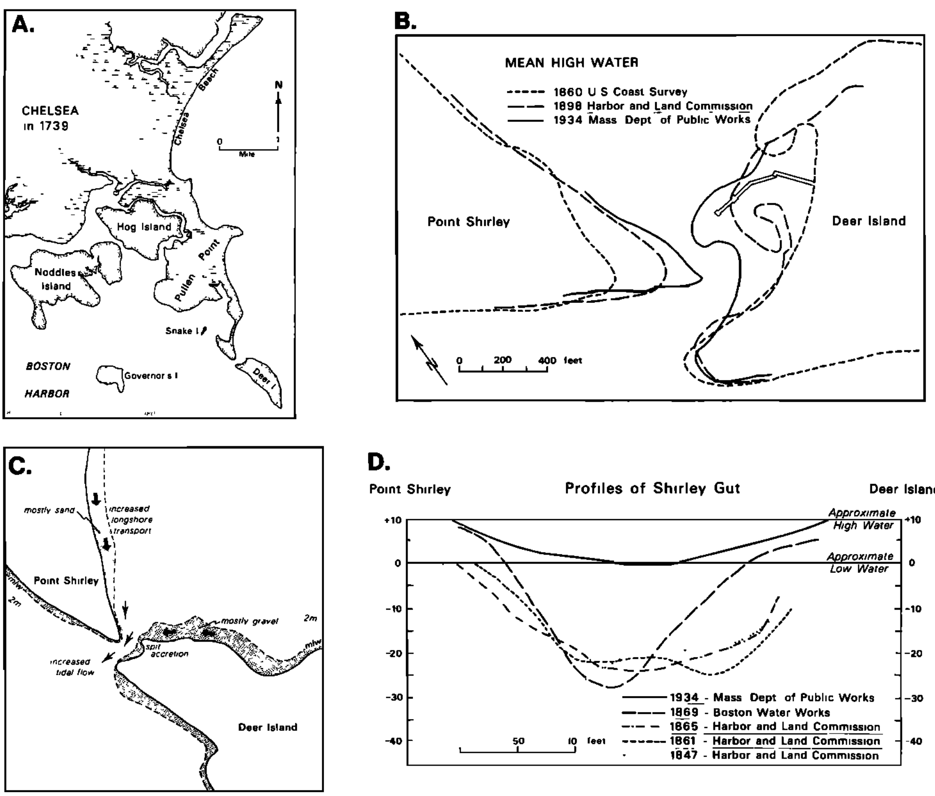

Figure 17. Historical account of the closure of Shirley Gut at Boston Harbor: A. early map of the region in 1739, B. and D. morphological changes of the inlet channel (from Nichols, 1949), and C. storm processes responsible for closing the inlet (from FitzGerald, 1980).

(Ogden, 1974). The opening which formed in 1886 was caused by a severe January northeast storm (Whiting, 1887). Breachings of the barrier, in approximately the same location, were produced by the 1938 Hurricane and Hurricane Carol in 1954. The February Blizzard of 1978 opened a small breach along the western part of the barrier, but this incipient breach immediately closed (Hanson and Forrester, 1978). Man-made cuts through the barrier were attempted in 1871, 1873, 1919 and 1921; only the last of these was successful (Ogden, 1974). After an inlet is cut, it migrates to the east and eventually closes as the spit attaches to Wasque Point. Inlet closure occurred in this manner in 1869, 1915, 1934 and 1969; since 1969 it has remained closed.

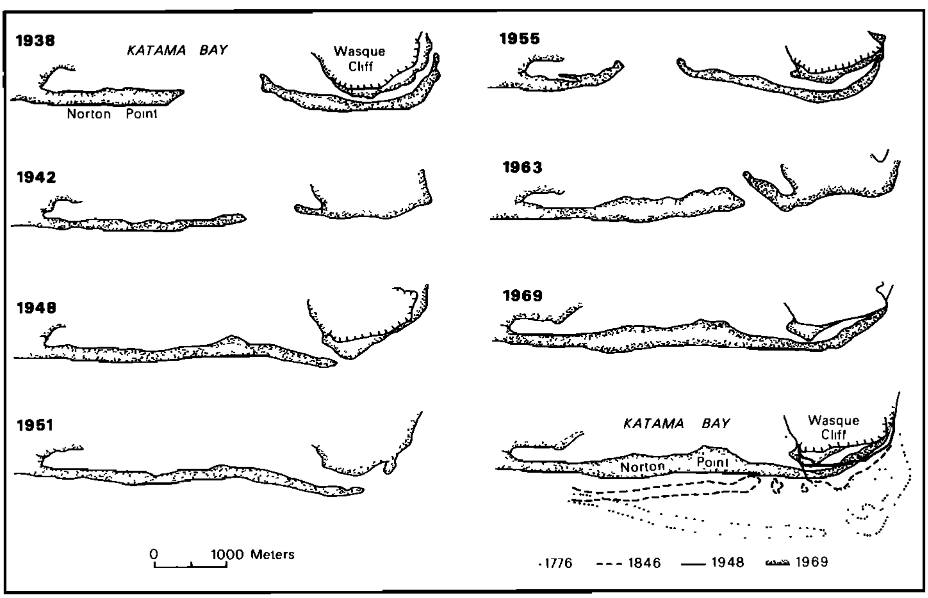

Figure 18. Shoreline changes at Katama Bay, Martha's Vineyard (from Ogden, 1974).

The instability of Katama Bay Inlet is related to a number of factors including: a strong easterly longshore transport system, a small tidal range (TR = .8 m), the shallowness of the southern end of Katama Bay that includes numerous intertidal shoals, and a northern deep channel opening to Katama Bay at Chappaquiddick Point (Fig. 11). The easterly movement of sand along the southern shoreline of Martha's Vineyard produces an eastward extension of the Norton Point spit and an easterly migration of Katama Bay Inlet. As the inlet moves farther to the east, the main tidal channel in the bay elongates and flow at the inlet becomes less efficient (cf., Keulegan, 1967). Also, repeated historical migrations of the inlet have produced numerous flood-tidal delta deposits which obstruct flow and provide an intertidal east-west barrier between the northern and southern portions of the bay. The most important factor which has led to the historical instability of the Katama Bay Inlet is the presence of the relatively deep inlet channel within Edgartown Harbor (Fig. 11). Most of the Katama Bay tidal prism is exchanged through this passage. If this opening did not exist, the ephemeral Katama Bay Inlet would be much larger and would probably remain open.

Allens Pond Inlet

The history of Allens Pond Inlet on the northwestern coast of Buzzards Bay is depicted over a 46-year period in Figure 19. During this time the inlet repeatedly migrated westward at an average rate of 100 m/yr, slowing considerably when it reached a far westerly position. The westward migration of the inlet is in opposition to the dominant easterly longshore transport direction and is caused by the configuration of the backbarrier main channel, which runs parallel to the eastern spit before turning southward at the inlet mouth (Fig. 19). Ebb flow in this channel is directed at the western inlet shoreline, causing erosion of the western channel bank in a manner similar to that of the cut bank side of a river meander. The westerly accreting spit is the point bar side of the meander bend and receives its sediment from sand that has been eroded at the inlet mouth and transported seaward to the eastward longshore transport system (FitzGerald et al., 1987). This mode of updrift inlet migration has been desoribed by Aubrey and Speer (1984) as one of the mechanisms reponsible for the northerly updrift migration of Nauset Inlet.

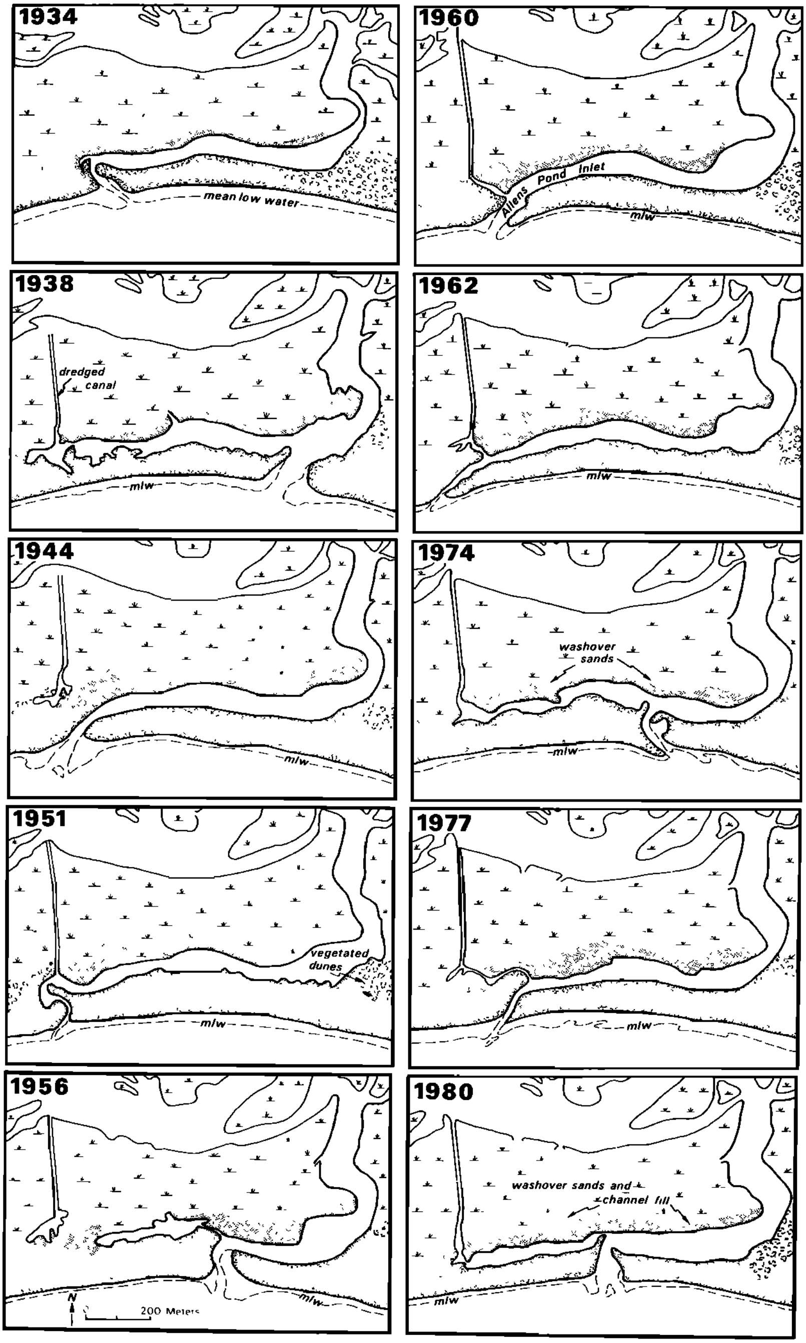

Figure 19. Historical shoreline changes at Allens Pond Inlet. This inlet migrates updrift and periodically closes until a channel is cut at the eastern end of the spit (from FitzGerald et al., 1987).

As the inlet migrates to the west, flow in the elongating inlet channel becomes increasingly inefficient (Keulegan, 1967). When it reaches a far westerly position as it did in 1934, 1951, 1962, and 1977 (Fig. 19), the inlet narrows and eventually closes. Because the bay behind the inlet, Allens Pond, is a productive shellfishing area, the Town of South Dartmouth dredges a new inlet at the eastern end of the spit whenever this happens. Since 1980, an inlet has been cut through the spit in 1985 and again in 1989. When the inlet closed most recently, a rainy autumn resulted in the marsh being flooded by approximately 30 cm of water and salinity in the bay dropping to 7‰ (Mello, pers. comm.). Thus, to maintain an opening at Allens Pond Inlet, a new inlet must be cut every 5 to 10 years.

Briggs Marsh Pond and Quicksand Pond

Briggs Marsh and Quicksand Ponds are elongated bays situated on the northwestern shore of Buzzards Bay (Fig. 14). Although the ponds are actually located on the Rhode Island coast, the inlets that open and close along their shores are similar to the behavior of some inlets on the southern coasts of Cape Cod, Martha's Vineyard and Nantucket (Fig. 11) and thus, they are included in the discussion here. As explained earlier, the small potential tidal prisms of these ponds and the exposure of this coast to wave energy prohibit permanent inlets along their barrier shores. However, significant inflow of freshwater during late winter and early spring, which is derived from precipitation and melting snow and ice, produces outlets at these sites and other ponds along this coast (FitzGerald et al., 1987). The discharge channels are narrow (< 20 m) and form when the pond overtops the height of the barrier, usually at the site of a previous inlet. The depth of the outlet channel, which seldom exceeds mean low water, and overall dimensions of the cut through the barrier are dependent on the volume of water discharged and hydraulic head between the pond and ocean level. Because the barriers that front these ponds are composed of sand and gravel and are commonly porous, some water is continually discharged through the barriers themselves.

As the outlets become fully developed, tidal exchange between the ocean and bay establishes tidal inlet processes including the formation of recured spits, inlet migration, and the development of flood-tidal deltas (Greacen et al., 1983; Fig. 20). Similar processes have been described at other tidal ponds on the Rhode Island coast (Boothroyd et al., 1985). Tidal inlets also develop at these ponds during intense storms such as the 1938 Hurricane and the Blizzard of 1978. Regardless of how the inlets formed, they are ephemeral features which close soon after they open, usually within several months. As seen in the maps of Quicksand and Briggs Marsh Ponds, the construction of flood-tidal deltas is an important process in impeding flow through the inlets and causing their closure (Fig. 20).

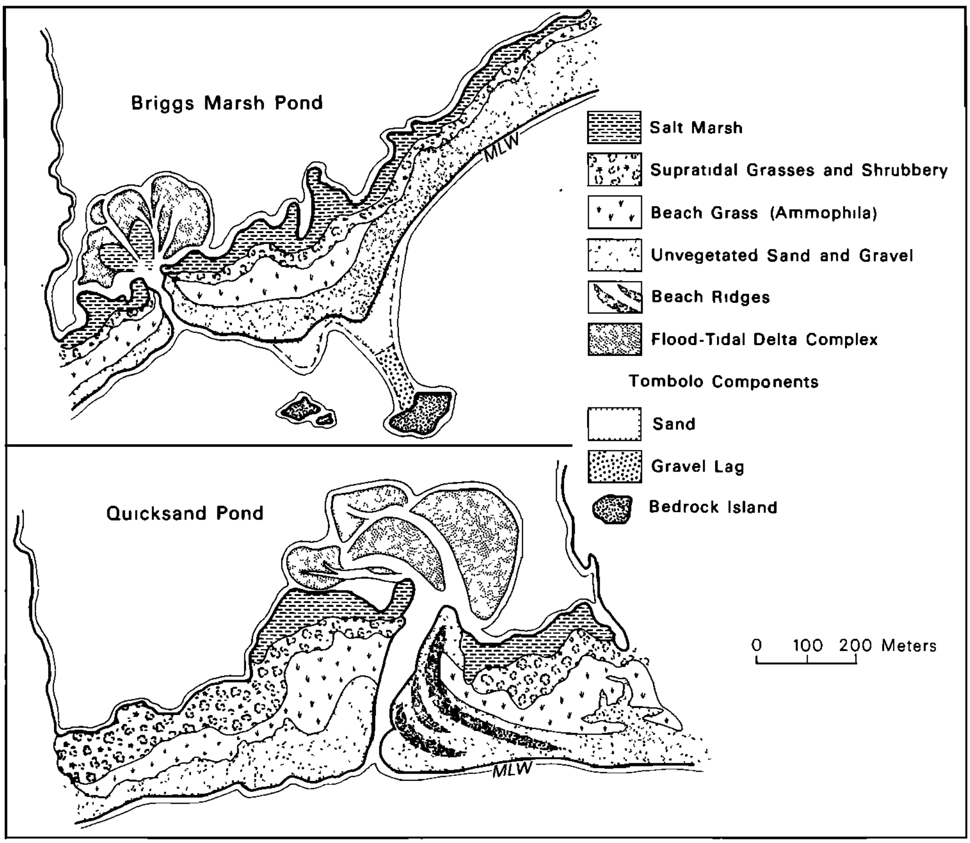

Figure 20. Sedimentary environments of the barriers fronting Briggs Marsh and Quicksand Ponds. Emphemeral inlets form along these shores due to storms and the discharge of freshwater. Note the development of flood-tidal deltas which restrict flow through the inlets (from FitzGerald et al., 1987 and modified after Greacen et al., 1983).

Scusset Mill Creek Inlet

Prior to the construction of the Cape Cod Canal in the early 1900's, Scusset Mill Creek emptied into Cape Cod Bay through Scusset Beach (Fig. 1). However, after the canal was completed and jetties were constructed to stabilize the entrance channel, the inlet closed. In digging the canal the headward portion of Scusset Mill Creek was connected to the waterway and thus its tidal prism was simply diverted to the canal. The accumulation of sand updrift of the north jetty caused a 200 m progradation of Scusset Beach and all traces of Scusset Mill Creek Inlet disappeared.

New Inlet, Scituate

New Inlet is located at the confluence of the North and South Rivers along the Massachusetts south shore (Fig. 21). The present inlet is anchored next to Fourth Cliff, one of several drumlins along this section of shoreline. In its early history North River was known for its shipbuilding and an American pirate who preyed on unsuspecting merchant ships journeying to and from Boston during the 1700's. At that time the entrance to the South and North rivers was 5.5 km south of Fourth Cliff along the southern end of Humarock Beach (Fig. 21). The inlet remained in that location until 1898, when a winter storm breached the sandy barrier that joined Third and Fourth Cliffs and New Inlet was formed. After the original breach, the inlet migrated slightly to the south and stabilized against Fourth Cliff. Much of the sand that originally comprised the barrier beach between Third and Fourth Cliffs has been reworked onshore in the form of two transgressive spits that extend southwest from Third Cliff and northeast from Fourth Cliff (Fig. 21). New Inlet is presently bordered on the north by a wide, low beach and intertidal shoal complex (Fig. 2). The stability of New Inlet will depend on the longevity of Fourth Cliff and the future of Humarock Beach. The thin parts of Humarock Beach and its overall erosional history have left this barrier highly susceptible to breaching, especially the neck region where South River impinges along the backside of the barrier (Fig. 21).

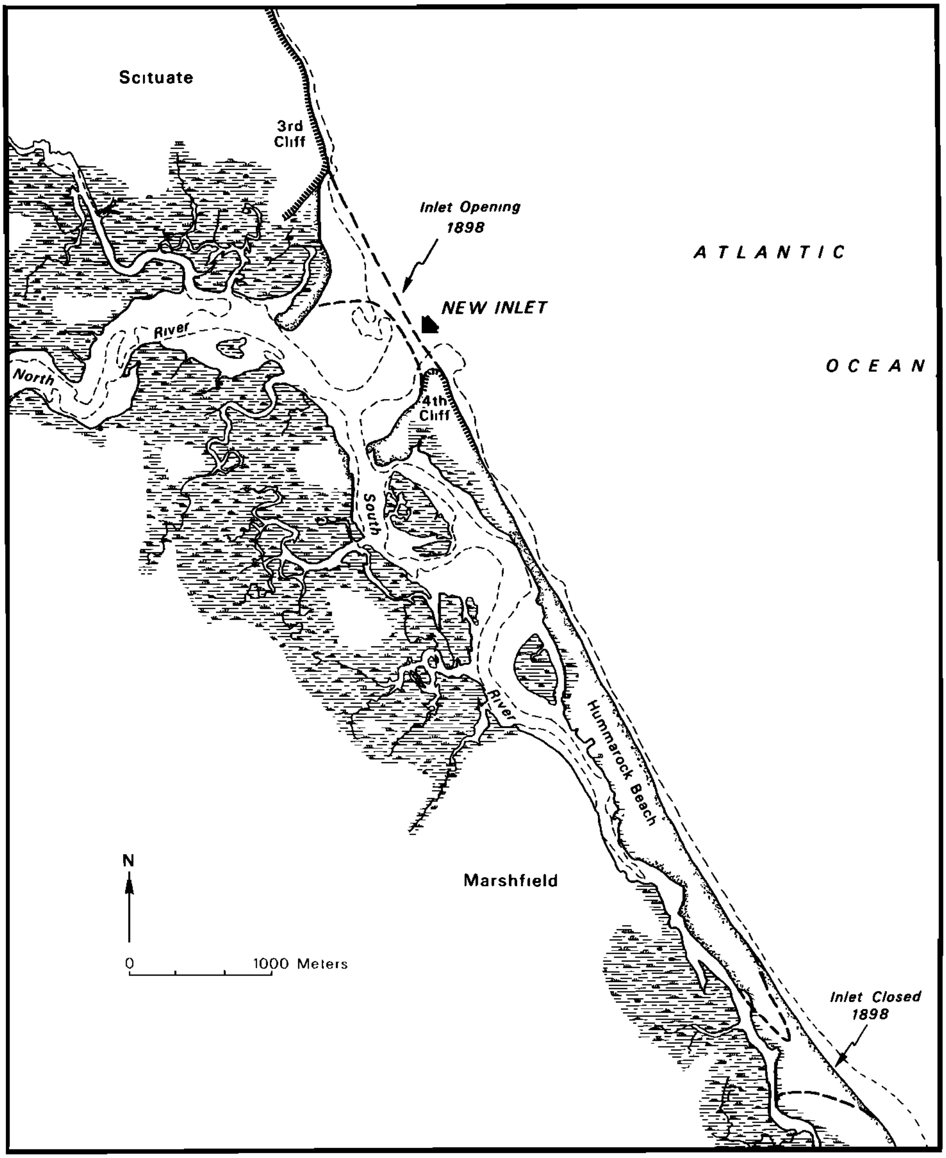

Figure 21. The northeast storm of 1898 caused the breaching of the barrier beach between Third and Fourth Cliffs. As New Inlet became established, the old inlet at the southern end of Hummarock Beach closed due to its greatly reduced tidal prism.

Jettied Inlets

There are more than 20 jettied inlets in Massachusetts, most of them concentrated along the microtidal shorelines of Nantucket Sound, Vineyard Sound, and Buzzards Bay (Table 1). Jetties are constructed to improve navigation through tidal inlets and depending upon their engineering design, they may stabilize a migrating inlet or its main channel, prevent or restrict the longshore transport of sand from entering the inlet channel, provide protection from wave action, and constrict or direct the ebb flow of an inlet to scour a deeper entrance channel. Jetty projects in Massachusetts have had mixed results, but in few instances have they provided the ultimate solution to navigation problems and in many cases they have created additional sedimentation and erosional problems. The effects of jetties along the Massachusetts shoreline are discussed using several inlet case histories.

Merrimack River Inlet

Tidal inlets situated along coasts where the longshore transport rate is comparable or greater than the potential sediment discharge in the inlet channel, often migrate or have main ebb channels that are deflected in a downdrift direction (Bruun and Gerritsen, 1959; Oertel, 1975). This condition was prevalent at the mouth of the Merrimack where the inlet had a history of southerly migration followed by a breaching back to the north prior to being stabilized by jetties in 1881 (Fig. 22; Hubbard, 1975; U.S. Army Corps of Engr., 1976). Since 1881, the jetties have been gradually extended so that now the north jetty is 1,250 m long and the south jetty is 745 m long. The shoreline has prograded on both sides of the inlet due to trapping of littoral drift moving south along Salisbury Beach during northeast storms and moving north along Plum Island by waves that refract around the ebb-tidal delta (Hubbard, 1975). After the initial progradation of the beach, the northern shoreline stabilized as further sand accumulation against the jetty was removed by storm waves and transported over the jetty into the inlet channel (Hubbard, 1973).

The northern end of Plum Island has a peculiar shape, in that a basin exists in the middle of the barrier (Fig. 22). Bathymetric surveys indicate that the basin

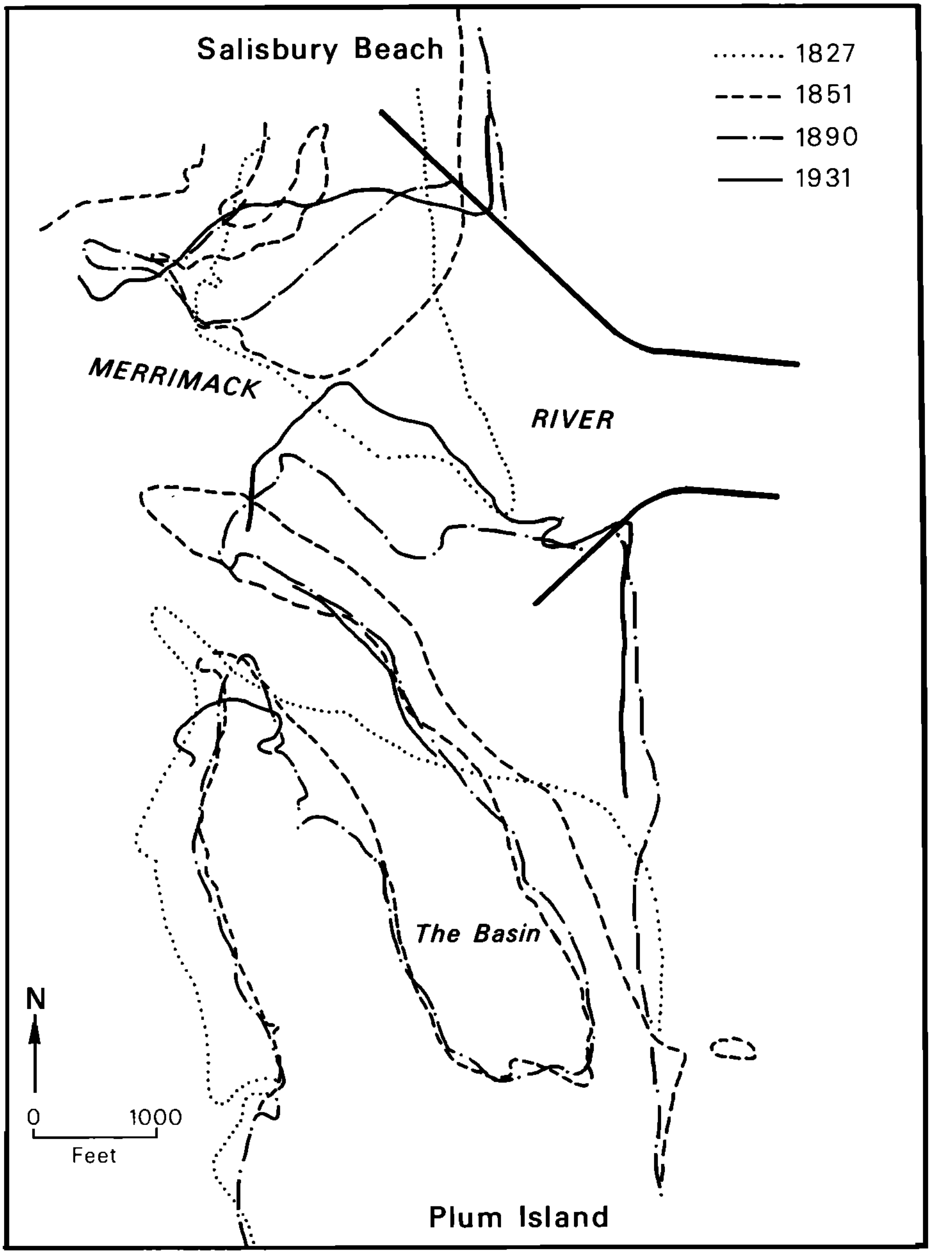

Figure 22. Shoreline changes at Merrimack River Inlet (from Nichols, 1941).

is almost 9 m deep (at mean low water). Although some of the depth may be attributed to dredging, it appears as though the basin represents a former position of the Merrimack River Inlet channel that existed sometime between 1827 and 1851. Nichols (1964) suggested that the basin formed due to a retrogration of northern Plum Island, followed by development of a spit along northern Plum Island which built northward. This scenario seems unlikely because the dominant longshore transport direction is to the south in this area (Hubbard, 1975), and thus the spit would have been accreting in opposition to this.

It appears more likely that ebb-tidal delta breaching took place at this inlet (Fig. 23) (cf., FitzGerald, 1988). In this model, the southerly longshore transport of sediment caused a preferential addition of sand to the northern, updrift side of the ebb-tidal delta (Fig. 23, Stage 1). In turn, this accumulation produced a southerly deflection of the main ebb channel and erosion of the northeast end of Plum Island (Fig. 23, Stage 2). In this configuration the circuitous pathway of the main channel produces inefficient flow through the inlet, resulting in a new channel being breached through the ebb-tidal delta sometime before 1851 (Fig. 23, Stage 3). The sand that had been on the updrift side of the ebb delta migrated onshore forming a large arcuate bar (U.S. Army Corps of Engr., 1976). In time the bar attached to Plum Island at its southern end and further sand supply from the ebb delta built the bar above mean high water (Fig. 23, Stage 4). This mechanism of inlet sediment bypassing and basin development along the downdrift inlet shoreline also has been identified on the South Carolina coast at Price and Capers Inlets (FitzGerald, 1982). The major effects of the Merrimack River Inlet jetty project have been a stabilization of the inlet channel and initial accretion of the shoreline on both sides of the inlet. However, subsequent shoaling at the inlet has required several emergency dredging projects by the U.S. Army Corps of Engineers. Erosion of the shoreline south of the jetties has resulted in beach nourishment projects and the construction of seven groins by the Commonwealth of Massachusetts.

Bass River Inlet

Jetties interrupt the natural mechanisms whereby tidal inlets bypass sand and in doing so, cause a progradation of the updrift shoreline while the sand-

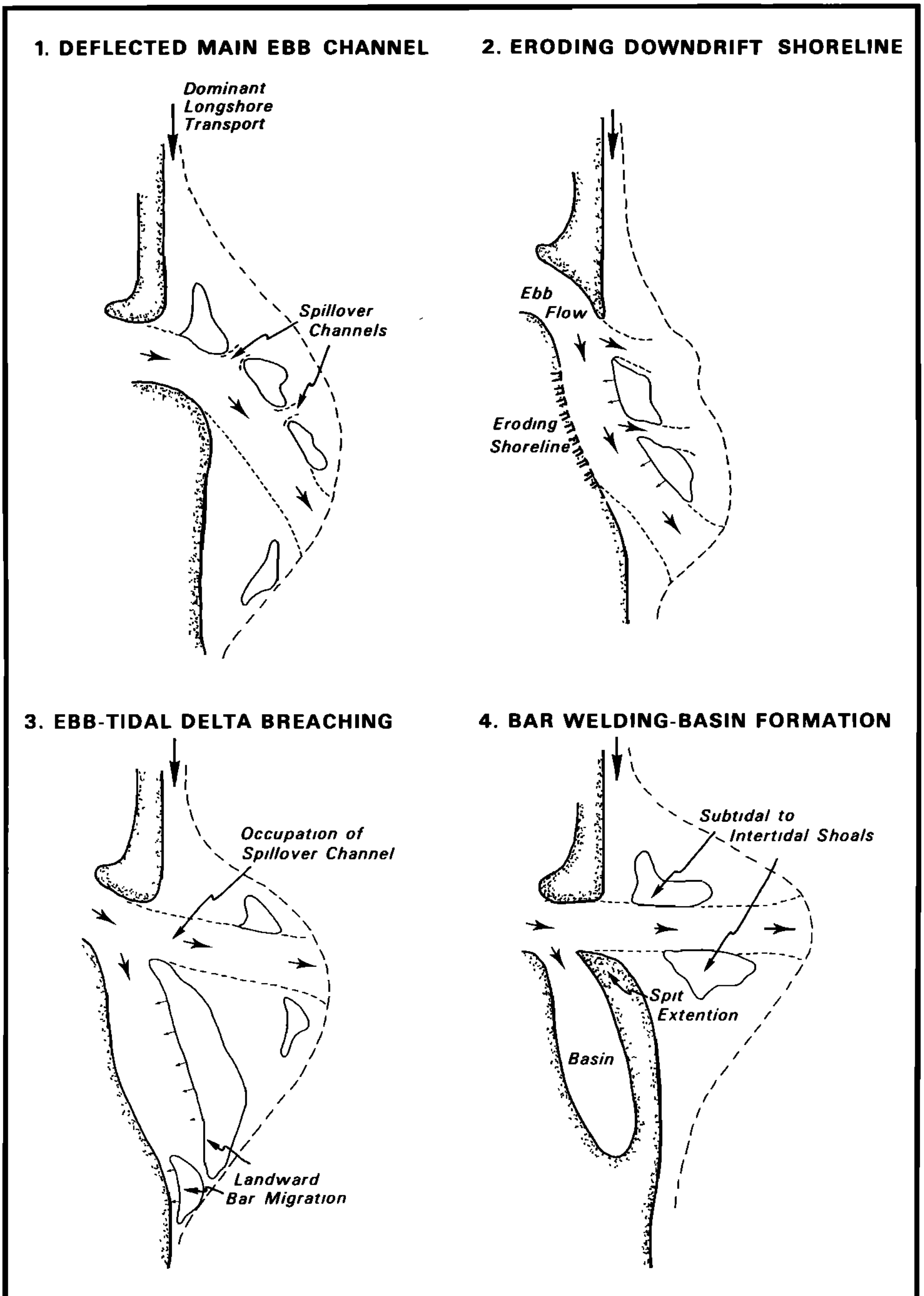

Figure 23. Conceptualized four stage model of basin development at northern Plum Island.

starved downdrift shoreline retreats. Bass River Inlet, located along the southern Cape Cod shoreline, is a good example of this condition (Figs. 2 and 24). A double jetty system, which was constructed at the inlet between 1866 and 1889, interrupts the easterly longshore transport system that dominates this coast. A net longshore transport rate of 4,400 m^3/yr was calculated for this shoreline from the volume of sand that was trapped by the west jetty (177,000 m^3) during a 40-year period from 1938 to 1978 (Slechta and FitzGerald, 1982). This is a minimum estimate because it does not account for the sand that bypassed the jetty during this time. Even at this relatively low transport rate, sand deposition along the Yarmouth shoreline necessitated a 30 m extension of the west jetty in the early 1950's (Fig. 24).

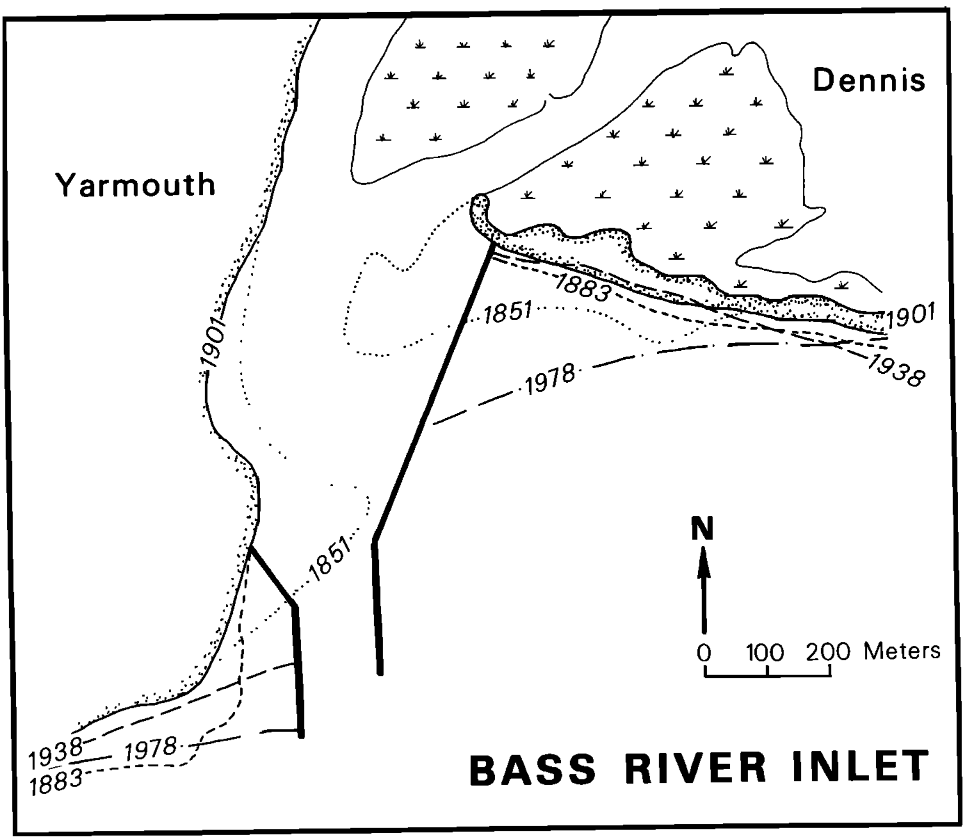

Figure. 24. Shoreline changes at Bass River Inlet as the result of jetty construction (from Slechta and FitzGerald, 1982).

In conjunction with the construction of the jetties in the 1800's, the interior of Bass River Inlet was dredged to provide a straight seaward path for the main channel. The jetties were designed to stabilize the entrance channel and alleviate shoaling problems. However, the small tidal prism of the inlet, coupled with periodic leakage of sand around the west jetty and transport of sand over the east jetty, have caused continuous shoaling problems. The shallowness of the offshore in this region, which is less than 2 m deep (mlw) at a distance of 1.5 km from the shoreline, exacerbates the shoaling problems seaward of the jetties (Slechta and FitzGerald, 1982).

Green Harbor Inlet

One consideration when constructing jetties is their orientation with respect to the approach of storm waves and the dominant wave swell of the region. For instance, at Wells Inlet along the coast of southern Maine the double jetty system is oriented into the direction of dominant wave approach (Byrne and Zeigler, 1977) making navigation through the jettied channel during storms and even periods of large swell extremely treacherous. In addition, wave action in the channel has been shown to contribute to the landward transport of sand through the inlet which has caused shoaling problems in the harborage area (Mariano and FitzGerald, 1991).

Green Harbor Inlet, located along the Massachusetts South Shore (Figs. 1 and 2), has double jetties oriented to the southeast away from the dominant northeast storm waves (Weishar and Aubrey, 1988). Current measurements taken at three sites across the channel at the mouth of the jetties on 31 August and 2 September 1981 indicate that the tidal currents are weak (max. vel. < 40 cm/sec), and that ebb velocities are consistently stronger than flood currents (FitzGerald, unpub. data). Based on tidal current measurements alone, the data suggest that the inlet should not import sediment. However, the entrance channel has had a long history of shoaling problems and has been dredged on several occasions. Interestingly, the material that accumulates in the entrance channel consists of sand and gravel. Some of this sediment is transported over the northern jetty during major storms and evidence of this process can be seen in Figure 2. However, most of the sediment moves landward into the inlet through the mouth of the jetties (Weishar and Aubrey, 1988). It would appear that the situation at Green Harbor Inlet is comparable to Wells Inlet, whereby shoaling waves in the main channel generate instantaneous, landward-directed currents that augment flood currents while retarding ebb currents. This process, especially during storms, would account for sediment transport into the inlet.

Construction of dikes, roadways, and retaining walls in the backbarrier region of Green Harbor have contributed to weak currents in the inlet channel. These structures cordoned off portions of the bay, marsh system, and tidal flats, thereby decreasing the volume of water entering and leaving the inlet. The tidal prism was reduced as a consequence of these modifications, so the size of the equilibrium entrance channel decreased.

Pamet River Inlet

Prior to stabilization, Pamet River Inlet in northern Cape Cod Bay had a history of northerly migration with periodic breachings of the spit to the south (Figs. 2 and 25). A new inlet was cut through the spit in 1919 and stabilized

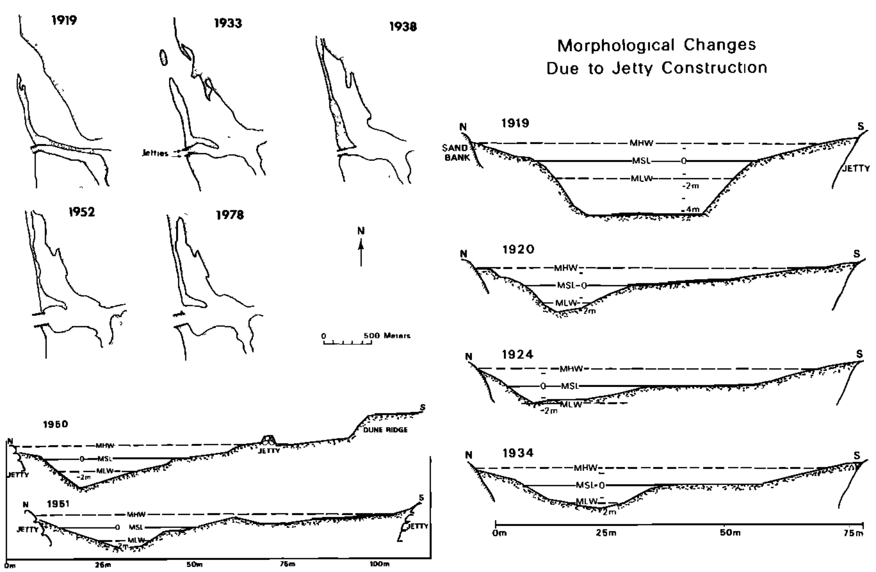

Figure 25. Morphological changes at Pamet River Inlet due to jetty construction (from FitzGerald and Levin, 1981)

with two stone jetties. The new inlet was 70 m wide and dredged to a depth of 4 m below mean low water. When the inlet was dredged, the spoil was placed landward of the inlet in the form of a dike which partitioned the backbarrier into two bays (Fig. 25, Year 1919). The jettied inlet quickly shoaled and it was not until the old inlet was closed and the dike severed that the combined tidal prisms of the two bays deepened the channel to 3.1 m by 1950 (FitzGerald and Levin, 1981).

In 1951 the jetties and channel were widened to 100 m to accomodate increased traffic through the inlet. The equilibrium channel cross section responded by shoaling more than a meter (Fig. 25, Years 1950 and 1951). At the same time the jetties were widened, they were also lengthened 50 m. In this configuration the south jetty was an efficient sediment trap of the northerly longshore transport, resulting in a 50 m progradation of its shoreline and a retreat of the downdrift northern shoreline. This retreat continued such that the north jetty was separated from the dune system and presently 10 to 20% of the tidal prism leaks between the north jetty and the adjacent beach. On the south side of the inlet, the beach has built to the end of the jetty and sand is readily transported into the inlet. Shoaling waves combined with flood currents move lobes of sand into the backbarrier region. Little of this sediment is removed by ebb tidal currents as evidenced by the beach ridges that are forming inside the inlet on the southern side of the bay (Fig. 2). Presently, access through the jettied channel can only be accomplished near high tide (FitzGerald and Levin, 1981).

The shoaling problems at Pamet River Inlet have resulted from poor jetty design and construction projects in the backbarrier. During the period from the mid-1800's to the early 1900's, the building of roads and railroad trestles has required portions of the marsh and bay to be diked. These dikes have isolated parts of the marsh in some areas and restricted tidal flow in others. As tidal strength was diminished, sedimentation in the backbarrier proceeded at a faster rate. These processes combined with the landward transport of sand into the bay have reduced the tidal prism and decreased the inlet equilibrium cross sectional area (FitzGerald and Levin, 1981).

Summary

Tidal inlets occur along the entire Massachusetts coast but are most common where the sand supply is most abundant, including the barrier coast north of Cape Ann and the sandy coasts of Cape Cod. Inlets are less common along the sand-starved coasts of Cape Ann and Buzzards Bay. Development of tidal inlets is closely related to barrier formation and constriction of an embayment. In Massachusetts, the constriction of embayments has occurred most commonly through spit accretion due to the presence of irregular coastlines (e.g., Sandy Neck and Nauset Spit), however, the formation of beach ridge barriers in front of bays (e.g., Horseneck Beach) is also an important process. Bays associated with Massachusetts inlets have developed in a variety of different settings. Drowned river valleys, groundwater sapping channels, kettles, and the enclosure of rocky and sandy irregular coasts are examples.

Tidal inlets in Massachusetts exhibit highly variable morphologies and sedimentation processes as a result of varying physical parameters including wave and tidal energies, sediment supply, and size of the backbarrier. Generally, inlets along mesotidal shorelines have well-developed ebb- and flood-tidal deltas and their backbarrier areas usually consist of marsh and tidal creeks with some open water areas near the inlet mouth. Plymouth Bay Inlet is an exception in that its backbarrier is dominated by intertidal flats. Inlets on microtidal shores commonly have poorly developed ebb-tidal deltas, poor-to-well developed flood-tidal deltas and backbarrier areas consisting of open bays with peripheral marshes (Hayes, 1975). The size of inlets is governed by bay area and tidal range.

Stability of unstructured tidal inlets along the Massachusetts shore is dependent on bay size, physical setting, and the erosional-depositional history of the associated barriers. Tidal inlets that have closed during the past 100 yrs generally are those along microtidal shores that had small bay areas or those where the tidal prism was rerouted through another inlet. Several barriers along the Buzzards Bay coast and the shores of Martha's Vineyard and Nantucket have ephemeral inlets which open during storms or when snow melt and precipitation cause the pond level to exceed the height of the barrier. Draining of the pond produces a cut through the barrier leading to inlet formation. Inlets that originate in this manner typically exist for a period of less than six months. Breaching of barriers and formation of semi-permanent tidal inlets have occurred predominantly along the outer coast of Cape Cod.

There are numerous jettied inlets on the Massachusetts coast; they are particularly prevalent along microtidal coasts where small bays and small ocean tidal ranges generate small tidal prisms. Jetties constructed at these sites disrupt the littoral transport system causing updrift accretion and downdrift erosion. In most cases, periodic dredging of the inlet channel is required to provide adequate navigation.

Acknowledgments

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References

Aubrey, D.G., and A.G. Gaines, 1982. Recent evolution of an active barrier beach complex: Popponesset Beach, Cape Cod, MA. Technical Report # WHOI-82-3, Woods Hole, MA, 75 pp.

Aubrey, D.G. and P.E. Speer, 1984. Updrift migration of tidal inlets. *J. Geology*, v. 92, p. 531-546.

Aubrey, Twichell, D.C., and S.L. Pfirman, 1982. Holocene sedimentation in the shallow nearshore zone off Nauset Inlet, Cape Cod, MA. *Mar. Geology*, v. 47, p. 243-259.

Belknap, D.F., B.G. Andersen, R.S. Anderson, W.A. Anderson, H.W. Borns, Jr., G.L. Jacobson, J.T. Kelley, R.C. Shipp, D.C. Smith, R. Stuckenrath, Jr., W.B. Thompson and D.A. Tyler, 1987. Late Quaternary sea-level changes in Maine. In: Nummedal, D., O.H. Pilkey and J.D. Howard, (eds.), *Sea-level Fluctuations and Coastal Evolution*, SEPM Spec. Pub. #41, p. 71-85.

Boothroyd, D.F., 1985. Tidal Inlets and Tidal Deltas. In: Davis, R.A. (ed.), *Coastal Sedimentary Environments*, Springer-Verlag, New York, p. 445-532.

Boothroyd, J.C., N.E. Friedrich and S.R. McGinn, 1985. Geology of microtidal lagoons, RI. *Mar. Geology*, v. 63, p. 35-76.

Boothroyd, J.C. and D.K. Hubbard, 1975. Genesis of bedforms in mesotidal estuaries. In: Cronin, L.E. (ed.), *Estuarine Research*, Academic Press, New York, v. 2, p. 217-234.

Bruun, P., 1967. Tidal inlet housekeeping. *J. of Hydraulic Divisions*, v. 93, p. 167-184.

Bruun, P., and F. Gerritsen, 1960. Natural bypassing of sand at coastal inlets. *J. of the Waterways and Harbors Div., Amer. Assoc. of Civ. Eng.*, v. 85, p. 75-107.

Byrne, P. and J.M. Zeigler, 1977. Coastal engineering study, Wells Harbor, ME. U.S. Army Corps of Engr., NE Division, Waltham, MA, 88 pp.

D'Amore, D.W., 1983. Hydrogeology and geomorphology of Great Sandford outwash plain, York County, ME with particular emphasis on the Branch Brook Watershed. Ph.D. Diss., Geology Dept., Boston Univ., Boston, MA, 147 pp.

Davis, R.A. and M.O. Hayes, 1984. What is a wave-dominated coast? *Mar. Geology*, v. 60, p. 313-329.

Davis, W.M., 1896. The outline of Cape Cod. American Academy of Arts and Sciences, Proceedings, v. 31, p. 303-332.

Edwards, G.B., 1988. Late Quaternary geology of northeastern Massachusetts and the Merrimack Embayment, western Gulf of Maine. Unpub. Masters Thesis, Geology Dept., Boston University, Boston, MA, 213 pp.

Fisher, J.J., 1987. Shoreline development of the glacial Cape Cod Coastline. In: FitzGerald, D.M., and P.S. Rosen, (eds.), *Glaciated Coasts*, Academic Press, New York, p. 280-307.

FitzGerald, D.M., 1976. Ebb-tidal delta of Price Inlet, SC: geomorphology, physical processes and associated inlet shoreline changes. In: Hayes, M.O. and T.W. Kana, (eds.), *Terr. Clastics Depos. Envir.*, Coastal Research Division, Dept. of Geol., Univ. of South Carolina, Columbia, SC, p. 158-171.

FitzGerald, D.M., 1981. Storm-generated sediment transport patterns along Winthrop and Yirrell Beaches, Winthrop, MA. *Northeast Geology*, v. 3, p. 202-211.

FitzGerald, D.M., 1980. Yirrell Beach Dynamics and Managgnent Guidelines. Tech. Rpt. # 2, Coastal Envir. Res. Group, Geology Dept., Boston University, Boston, MA, 42 pp.

FitzGerald, D.M., 1982. Sediment bypassing at mixed energy inlets. *Amer. Soc. of Civil Engr.*, Proc. 18th Coastal Eng. Conf., p. 1094-1118.

FitzGerald, D.M., 1988. Shoreline erosional-depositional processes associated with tidal inlets. In: Aubrey, D.G. and L. Weishar, (eds.), *Hydrodynamics and Sediment Dynamics of Tidal Inlets*, Springer-Verlag, New York, p. 186-225.

FitzGerald, D.M., C.T. Baldwin, N.A. Ibrahim and D.R. Sands, 1987. Development of the northwestern Buzzards Bay Shoreline, MA. In: FitzGerald, D.M. and P.S. Rosen, (eds.), *Glaciated Coasts*, Academic Press, New York, p. 327-357.

FitzGerald, D.M. and D.R. Levin, 1981. Hydraulics morphology and sediment transport patterns at Pamet River Inlet, Truro, MA. *Northeastern Geology*, v. 3, p. 216-224.

FitzGerald, D.M., J.M. Lincoln, L.K. Fink and D. Caldwell, 1990. Morphodynamics of tidal inlet systems in Maine. In: *Maine Geological Survey Studies in Maine Geology*, Augusta, ME, v. 5, p. 1-30.

FitzGerald, D.M., A. Saiz, C.T. Baldwin and D.M. Bands, 1986. Spit breaching at Slocum River Inlet, Buzzards Bay, MA. *Shore and Beach*, v. 54, p. 11-17.

Friedrichs, C.T., D.G. Aubrey, G.S. Giese and P.E. Speer. Hydrodynamical modeling of a multiple-inlet estuary/barrier system: Insight into tidal inlet formation and stability. In: D.G. Aubrey and G.S. Giese (eds.), *Formation and Evolution of Multiple Inlet Systems, Coastal and Estuarine Studies*, (this volume).

Gatto, L.W., 1978. Shoreline changes along the outer shore of Cape Cod from Long Point to Monomoy Point. CRREL Rpt. #78-17, U.S. Army Corps of Engr., Hanover, NH, 49 pp.

Giese, G.S., 1988. Cyclic behavior of the tidal inlet at Nauset Beach, Chatham, Massachusetts. In: Aubrey, D.G. and L. Weishar, (eds.), *Hydrodynamics and Sediment Dynamics of Tidal Inlets*, Springer-Verlag, New York, p. 269-283.

Greacen, J., J. Rahilly and C. Tomlinson, 1983. An examination of coastal variation, Sakonnet Point, RI to New Bedford, MA. Unpub. Rpt. Coastal Environmental Research Group, Dept. of Geology, Boston Univ., Boston, MA, 17 pp.

Halsey, S.D., 1979. New model of barrier island formation. In: Leatherman, S.P. (ed.), *Barrier Islands from the Gulf of St. Lawrence to the Gulf of Mexico*, New York, Academic Press, p. 185-210.

Hanson, L.S. and V.S. Forrester, 1978. Coastal Guide to Martha's Vineyard. Geology Dept., Boston University, Boston, MA, 84 pp.

Hayes, M.O., 1975. Morphology of sand accumulation in estuaries: an introduction to the symposium. In: Cronin, L.E. (ed.), *Estuarine Research*, New York, Academic Press, v. 2, p. 1-22.

Hayes, M.O., 1979. Barrier island morphology as a function of tidal and wave regime. In: Leatherman, S.P. (ed.,), *Barrier Islands from the Gulf of St. Lawrence to the Gulf of Mexico*, New York, Academic Press, p. 1-28.

Hayes, M.O., E.H. Owens, D.K. Hubbard and R.W. Abele, 1973. The investigation of forms and processes in the coastal zone. In: Coates, D.R. (ed.), *Coastal Geomorphology*, Publications in Geomorphology, Binghampton, NY, p. 11-41.

Hill, M.C., D.M. FitzGerald and C.T. Baldwin, 1990. Development and assessment of sand resources in Plymouth Bay. U.S. Minerals Management Service Proc., Austin, TX, p. 182-193.

Hill, M.C. and D.M. FitzGerald. Evolution and Holocene stratigraphy of Plymouth Bay, MA. In: Fletcher, C.H. and J.F. Wehmiller (eds.), *Quaternary Coastal Systems of the United States*, SEPM Spec. Pub., (in press).

Hine, A.C., 1975. Bedform distribution and migration patterns on tidal deltas in the Chatham Harbor Estuary, Cape Cod, MA. In: Cronin, L.E. (ed.), *Estuarine Research*, New York, Academic Press, p. 235-252.

Hine, A.C., S.S. Snyder and A.C. Neumann, 1979. Coastal plain and inner shelf structure, stratigraphy and geologic history: Bougue Banks area, NC. Tech. Rpt. North Carolina Sci. Technology Comm., Chapel Hill.

Hubbard, D.K., 1973. Morphology and hydrodynamics of Merrimack Inlet, Massachusetts, Part I. Final Rpt. for Contract # 72-72-C-0032, Coastal Engr. Res. Center, 154 pp.

Hubbard, D.K., 1975. Morphology and hydrodynamics of the Merrimack River ebb-tidal delta. In: Cronin, L.E. (ed.), *Estuarine Research*, New York, Academic Press, v. 2, p. 253-266.

Ibrahim, N.A., 1986. Sedimentological and morphological evolution of a coarse-grained regressive barrier beach, Horseneck Beach, MA. Unpub. Masters Thesis, Dept. of Geology, Boston University, Boston, MA, 196 pp.

Inman, D.L. and J.D. Frautschy, 1965. Littoral processes and the development of shorelines. Coastal Engr. Spec. Conf., Santa Barbara, CA, p. 511-536.

Jarrett, J.T., 1976. Tidal prism-inlet area relationships. GITI Rpt. 33, U.S. Army Corps of Engr. Res. Center, Waterways Exp. Station, Vicksburg, MS, 55 pp.

Jensen, R.E., 1983. Atlantic coast hindcasting shallow water significant wave information. Waterways Experiment Station, Vicksburg, MS, 75 pp.

Keulegan, G.H., 1967. Tidal flow in entrances: water level fluctuations of basins in communications with seas. Tech. Bull. #14, Comm. on Tidal Hydraulics, U.S. Army Corps of Engr., Vicksburg, MS, 100 pp.

Larson, G.J., 1982. Nonsynchronous retreat of ice lobes from southeastern Massachusetts. In: Larson, G.J. and B.D. Stone, (eds.), *Late Wisconsinan of New England*, Kendall/ Hunt, Dubuque, Iowa, p. 101-115.

Lucke, J.B., 1934. A theory of the evolution of lagoon deposits on shorelines of emergence. *J. Geology*, v. 42, p. 561-584.

Magee, A.D. and D.M. FitzGerald, 1980. Investigation of the shoaling problems at Westport River Inlet and sedimentation processes at Horseneck and East Horseneck Beaches. Tech. Rpt. # 3, Coastal Envir. Res. Group, Dept. of Geology, Boston University, Boston, MA, 118 pp.

Mariano, C.G. and D.M. FitzGerald, 1989. Sediment transport patterns and hydraulics at Wells Inlet, Maine. Tech, Rpt. #12, Coastal Envir. Res. Group, Dept. of Geology, Boston University, Boston, MA, 143 pp.

McIntire, G.W. and J.P. Morgan, 1964. Recent geomorphic history of Plum Island, MA and adjacent coasts. Coastal Series #8, Louisiana State Univ. Press, Baton Rouge, LA, 44 pp.

Morton, R.A. and A.C. Donaldson, 1973. Sediment distribution and evolution of tidal deltas along a tide-dominated shoreline, Wachapreague, Virginia. *Sed. Geol.*, v. 10, p. 285-299.

Nichols, R.L., 1941. The geology of Plum Island, Castle Neck, and Great Neck. In: Chute, N.E. and R.L. Nichols, (eds.), *The Geology of the Coast of Northeastern Massachusetts*, Mass. Dept. of Public Works, U.S. Geol. Surv. Coop. Proj., Bull #7, 48 pp.

Nichols, R.L., 1949. Recent shoreline changes at Shirley Gut, Boston Harbor. *J. Geology*, v. 57, p. 84-89.

Nichols, R.L., 1964. Northeastern Massachusetts geomorphology - Trip A. In: Skehan, S.J., (ed.), *Guidebook to Fieldtrips in the Boston Area*, NEIGC, p. 3-40.

National Oceanic and Atmospheric Administration, 1989. *Tide Tables, East Coast of North and South America.* Rockville, MD, 287 pp.

Nummedal, D. and I. Fischer, 1978. Process-response models for depositional shorelines: the German and Georgia Bights. *Amer. Soc. of Civil Eng.*, Proc. 16th Coastal Eng. Conf., p. 1215-1231.

O'Brien, M.P., 1931. Estuary tidal prisms related to entrance areas. *Civil Engr.*, v. 1, p. 738-739.

O'Brien, M.P., 1969. Equilibrium flow areas of inlets on sandy coasts. *Jour. of Waterways, Harbors, and Coastal Engrs.*, ASCE, v. 95, p. 43-55.

O'Brien, M.P. and R.G. Dean, 1972. Hydraulics and sedimentary stability of coastal inlets. Proc. of the 13th Annual Coastal Engr. Conf., Vancouver, BC, Canada, p. 761-780.

Oertel, G.F., 1975. Ebb-tidal deltas of Georgia estuaries. In: Cronin, L.E. (ed.), *Estuarine Research*, New York, Academic Press, p. 267-276.

Oertel, G.F., 1979. Barrier island development during the Holocene recession Southeastern United States. In: Leatherman, S.P. (ed.), *Barrier Islands from the Gulf of St. lawrence to the Gulf of Mexico*, New York, Academic Press, p. 273-290.

Ogden, J.G., 1974. Shoreline changes along the southeastern coast of Martha's Vineyard, MA for the past 200 years. *Quaternary Res.*, v. 4, p. 496-508.

Oldale, R.N. and R.A. Barlow, 1986. Geologic map of Cape Cod and the Islands, Massachusetts. U.S. Geological Survey, Woods Hole, MA.

Oldale, R.N. and C.J. O'Hara, 1980. New radiocarbon dates from the inner continental shelf of southeastern Massachusetts and a local sea-level curve for the past 12,000 years. *Geology*, v. 8, p. 102-106.

Penland, S., R. Boyd and J.R. Suter, 1988. Transgressive depositional systems of the Mississippi Delta plain: a model for barrier shoreline and shelf sand development. *J. Sed. Petrology*, v. 58, p. 932-949.

Pierce, J.W., 1976. Tidal inlets and washover fans. *J. Geology*, v. 78, p. 230-234.

Redfield, A.C., 1967. Ontogeny of a salt marsh. In: Lauff, G.H., (ed.), *Estuaries*, AAAS, Washington, DC, p. 108-114.

Rhodes, E.G., 1973. Pleistocene-Holocene sediments interpreted by seismic refraction and wash-bore sampling, Plum Island-Castle Neck, MA. Tech. Mem. #40, 75 pp.

Slechta, M.W. and D.M. FitzGerald, 1982. Sedimentation patterns and processes at Bass River Inlet. Tech. Rpt. #6, Coastal Envir. Res. Group, Dept. of Geology, Boston University, Boston, MA, 154 pp.

Som, R.M., 1990. Stratigraphy of the Castle Neck-Essex Bay marsh system. Masters Thesis, Geology Dept., Boston Univ., Boston, MA.

Stone, B.D. and J.D. Peper, 1982. Topographic control of the deglaciation of eastern Massachusetts: ice lobation and the marine incursion. In: Larson, G.J. and B.D. Stone, (eds.). *Late Wisconsinian of New England*, Kendall/Hunt, Dubuque, Iowa, p. 145-166.

Thompson, E.F., 1977. Wave climate at selected locations along U.S. coasts. Tech. Rpt. No. 77-1, C.E.R.C., U.S. Army Corps of Engr., Washington, D.C., 364 pp.

U.S. Army Corps of Engineers, 1957. Saco Maine beach erosion control study. House Document #32, 85th Congress, 37 pp.

U.S. Amy Corps of Engineers, 1976. Plum Island feasibilty report. Waltham, MA District Office, 25 pp.

Weishar, L.L. and D.G. Aubrey, 1988. Inlet hydraulics at Green Harbor, Marshfield, MA. U.S. Amy Corps of Engr. Misc. Paper CERC-88-10, Vicksburg, MS, 104 pp.
Whiting, H.L., 1887. Recent coastal changes at Martha's Vineyard, MA, Appendix 9, U.S. Coast and Geodetic Survey, Annual Report.