Geomorphological Evolution of Estuaries: The Dynamic Basis for Morpho-Sedimentary Units in Selected Estuaries in the Northeastern United States

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Background

The basic concept of an estuary is that it is an aquatic system located at the land-sea interface, and it is a transition feature, extending from freshwater to marine environments. Day (1981) offers a more detailed explanatory description of the estuarine ecotone that allows for intermittent connection to the ocean and adds aspects of freshwater flow. Kennish (2000) amplifies the variety of descriptors to include classifications based on physiography, hydrography, salinity and tidal characteristics, sedimentation, as well as ecosystem energetics.

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ABSTRACT—The coastal geomorphological processes of alongshore transport and tidal currents are interacting with the attendant influences of sea-level rise and sediment supply to generate morpho-sedimentary units in selected estuarine systems. Constrained by the conditions promoted by microtidal situations in barrier island settings, vectors of sediment transport have established spatial sequences of morphologies and sediment types that are components of shellfish habitats. Greater depth and decreasing grain-size toward the mainland are common characteristics in five northeastern U.S. estuarine systems. The patterns are repeated at various scales among the lagoon-type estuaries as well as within the estuarine settings to establish geospatial associations of geomorphology and habitat.

This paper is not an attempt to define and describe all estuaries, but it focuses on five estuaries in the northeastern portion of the United States (Fig. 1). In so doing, it identifies the geomorphological setting of these estuaries and provides context to the sedimentological characteristics of a few types of shellfish habitat. It also establishes spatial associations of sediment types and provides explanatory descriptions of grain-size distributions that are often associated with shellfish abundance (MacKenzie et al., 2006).

Geomorphological Basis

The physical features that occur at the marine margin of the continents and islands are largely the products of the last few thousand years, the Late Holocene, when the rising ocean inundated the margins of the land masses and created the present-day matrix of coastal and estuarine systems. Whereas many of

Figure 1.—The five estuaries presented in this paper.

the estuarine settings are derived from the drowned topography and pre-existing forms (Isla, 1995), some aspects of the estuarine settings are produced by the ambient processes and available sediments following the Late Holocene sea-level position (Perillo, 1995; Roman et al., 2000; FitzGerald and Knight, 2005).

The present sea level position is associated with the most recent and relatively slow rise of several meters (including water rising and land subsiding) during the last several thousand years after millennia of very rapid rise. Although there is local variation, a similar regional pattern of relative sea-level rise in the Northeast is in agreement with the trends reported in coastal Massachusetts and Connecticut by Donnelly (2006), a relative rise of about 2.6 m in the past 3,300 years. The recent inundation includes a rate of 0.8 ±0.25 mm/yr during 3300–1000 YBP, and a rate of 0.52 ±0.62 mm/yr from 1000 YBP to 150–500 years ago. However, it must be pointed out that relative sea-level rise has increased substantially in the past several centuries to 2–4 mm/yr (Bindoff et al., 2007). Importantly, the recent (past 3,300 years) slow rate of sea-level rise was accompanied by sediment accumulation in the form of barrier islands and wetland expansion at the coast that contributed to the geomorphological characteristics of the estuaries (Walker and Coleman, 1987).

Several studies have created geomorphological groupings of estuaries. Kennish (1986) has summarized a wide range of estuarine literature to produce a classification that consists of four broad genetic associations: 1) drowned river valleys; 2) lagoon-type, bar-built; 3) fjord-type; and 4) tectonically produced. That classification includes the major groupings but lacks details of the geomorphological products. Earlier, Davies (1964) approached estuaries as groupings within a climatic and geographical association, describing estuarine form related to glacial processes at one climatic extreme and to coralline processes at the other extreme, creating a primary classification very much like the more recent effort by Kennish. However, Davies further reviewed the active geomorphological processes (waves, tidal range, tidal currents, storms) associated with estuaries and suggested that tidal range was a major variable in the development of morpho-sedimentological characteristics within estuarine settings. He identified the concept of micro-, meso-, and macro-tidal morphologies later amplified by Hayes (1975, 1980) as a basis for discriminating groupings of process-response characteristics (processes acting upon sediments to produce morphologies) in coastal settings.

Essentially, estuarine coastal areas with low tidal ranges will tend to have impressive tidal deltas and considerable sedimentation driven through the functioning inlets to create flood-tide or ebb-tide dominated deltas with a myriad of channels and delta lobes (Knight and FitzGerald, 2005). As tidal range increases, the dominance of the tidally-created landforms tends to decrease and fluvial forms at the inland margin of the estuary become more significant. At the extreme, the macrotidal estuary has a broad mouth open to the sea. Waves and sediment supply are important to the microtidal condition because the coastwise barrier and the tidal deltas are composed of sand delivered along the shore face. However, rather than inland transfers along the entire seaward margin of the estuary (as in the high tidal range coasts), the transfers in the microtidal settings are restricted to the presence of inlets and the growth of tidal deltas at those sites.

Implicit in both Davies (1964) and Hayes (1975) is the availability of sediment to create the morpho-sedimentological units. Sediment becomes an additional variable because the coastal system is transporting material through space across time. Therefore, some aspects of the geomorphological evolution of form may never reach full development because of a sediment limitation, or some aspects may be in an accumulating or eroding mode because of vectors of sediment delivery. In site-specific examples, the products of a process-response association are often constrained by the quantity and quality of sediments available (Cooper, 2001). The variety of input sources determines the size and mineralogy of the sediments delivered to the estuaries, and therefore, it is common to find a wide range of sediment sizes in an estuarine environment. Estuarine sediments may range in size from gravel (>2 mm), to silt (<1/16 mm), but most common grain sizes are found in the sand class ranging in size among very coarse sand (2–1 mm); coarse sand (1–1/2 mm); medium sand (1/2–1/4 mm); fine sand (1/4–1/8 mm); and very fine sand (1/8–1/16 mm).

The following discussion and descriptions apply the concepts of coastal geomorphological associations to the evolution of five specific estuaries in the northeastern portion of the United States and offer some insights to the distribution of physical characteristics within these sites. By extension, the pattern of morphologies and sediment types interfaces with flows, bathymetry, and salinity gradients to influence shellfish distributions (Hunt, 2005; Mann et al., 2005).

Barnegat Bay

The Barnegat Bay embayment is a shore parallel estuary with an area of 155 km^2 and one direct inlet. It has a coastal length of about 39 km and a width that varies from less than 1.0 km at its northern portion to about 7 km opposite Barnegat Inlet (Fig. 2). The dominant tides are microtidal, varying from a range of about 0.6 m spring tide to 0.3 neap tide at the inlet and decreasing away from the inlet (Guo et al., 1997). The estuary is shallowest at its eastern margin, adjacent to the barrier, and deepest (maximum of 7 m) toward the contact with the continent (Kennish, 2001). The morpho-sedimentary units within the estuary are related to the geomorphological evolution of the barrier spit as it migrated inland and extended southerly (Psuty, 2004). Availability of sediment has been a constraint. Some of the limitation is related to the source area. According to McMaster (1954), the alongshore transport supplying the barrier island seaward of Barnegat Bay is limited to erosion of the Pleistocene headland north of the bay and a very limited supply of sediment from offshore.

The result of that limitation is a narrow barrier and a very restricted flood-tide delta and overwash contribution as the barrier was extending southward. Further, by the time the barrier equilibrated in position relative to sea-level rise, the inlet was near the southern margin of the estuary.

Independent of the exact causal situation, the present geomorphological association is a variation in the morpho-sedimentary units along the long axis of the Barnegat estuary (Fig. 2, 3). The dominant sedimentary feature is the broad zone of medium sand that forms a 2–3 km wide shelf extending westerly from the barrier spit into the bay. The shelf increases to 4–5 km in width nearer Barnegat inlet and sediment sizes shift toward coarse sand. There are two morpho-sedimentary trends evidenced. One is the increasing width of the medium-sand shelf with a depth of up to 2 m from north to south. The other is the grain size gradient that is coarser on the ocean side of the estuary and finer toward the continent; this characteristic also co-varies with depth in the estuary. This morphological assemblage is consistent with the persistence of a major inlet in the southern portion of the estuary and the accumulation of sediment in a flood-tide delta process-response relationship. It is also in agreement with the importance of tidal currents in the generation of morpho-sedimentary units in microtidal locations (Davies, 1964; Hayes, 1980).

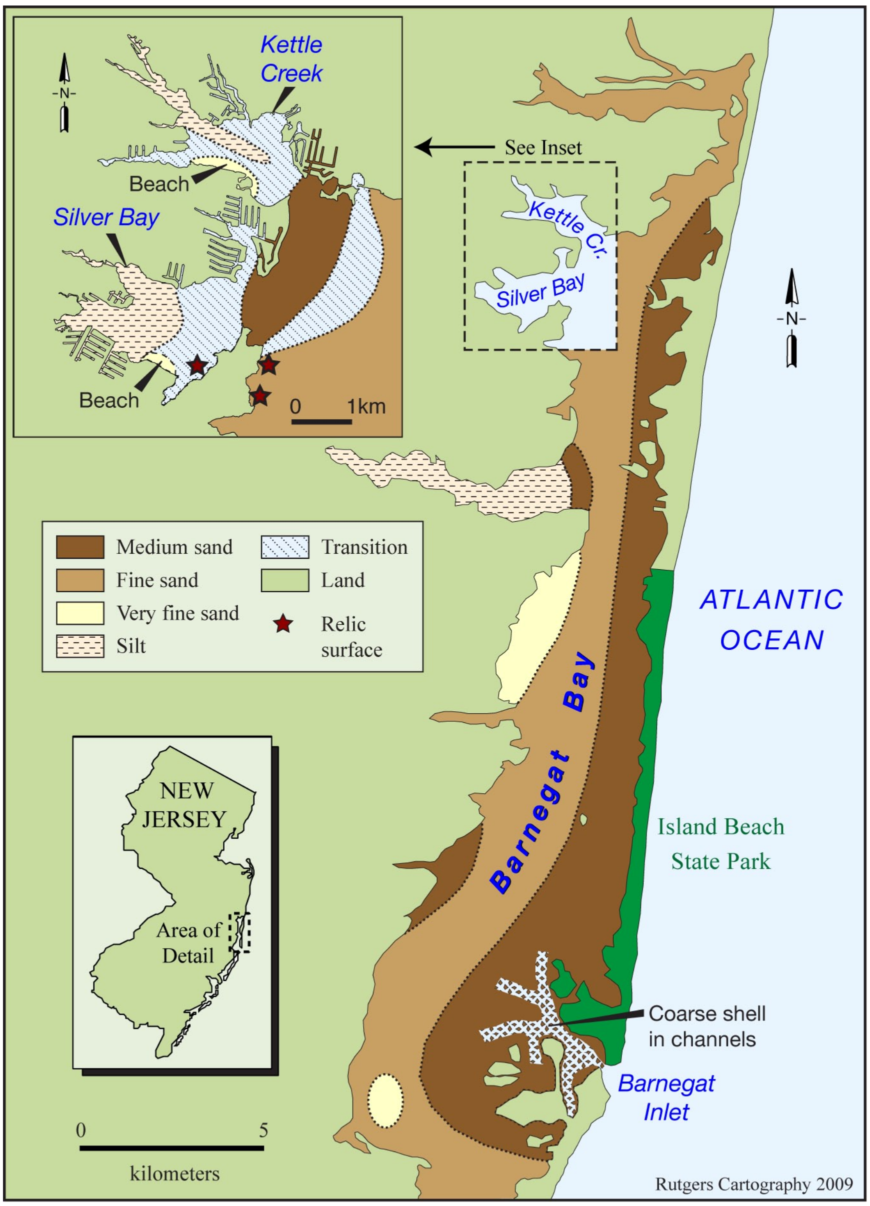

Figure 2.—Distribution of morpho-sedimentary units in Barnegat Bay; detailed distribution of morpho-sedimentary units in the Silver Bay–Kettle Creek micro-estuaries.

The major geomorphological feature is the extensive flood-tide delta at the present location of Barnegat Inlet and its variety of forms and sediment types. The inlet has been artificially stabilized since 1939 and the flood tide delta had been expanding into the southern bay prior to stabilization (Kennish, 2000). Although the delta is composed largely of medium sand, the deeper tidal channels in the delta are lined with coarse shell debris and some gravel, creating lineations and habitats cutting across the general morpho-sedimentary units. Former flood-tide delta forms compose the broad shelf along the estuarine margin of the barrier spit, and subsequent re-working of the tidal delta deposits has altered most of their channel morphologies. Thus, whereas there may be ancestral lobate sedimentary projections into the bay associated with former inlets or washover features, there is little variation in the deltaic morphology or sediment type at this time, and little variation in shellfish habitat.

The northern and inland part of the Barnegat Bay has a repetitive suite of morpho-sedimentary units that is related to tidal flows in the minor drainage channels emanating from the mainland. Detailed analysis of bottom sediments in the Kettle Creek–Silver Bay area identify the local interaction of tidal currents and wave action that create sandy barriers across the mouths of each of the small drainage channels (Fig. 2, inset). The pattern consists of a well-sorted, medium sand accumulation that extends as a shallow bar across the mouth of the channel. Tidal flows and local wave action have concentrated the coarser sands at these locations, with finer sediments both inland and bayward of the bar. The association of sediment type and morphology is well-displayed in the bivariate plot of grain-size versus a measure of sorting (expressed as standard deviation in phi units) for the complex situation found at the Kettle Creek–Silver Bay site (Fig. 4).

The points on the plot are sediment sample sites and they cluster in the following groups: 1) the sand bar at the mouth of the channels is well-sorted medium sand; 2) the sediments at the inland portions of the micro-estuaries are composed of silts with poorer sorting than the bar; 3) there is a narrow beach at the southern margin of the channels that is well-sorted very fine sand; 4) there is a transition zone to either side of the bar environment that incorporates fluvial silts, the mean grain size is between the two major clusters and has poorer sorting; and 5) some of the bottom in these micro-estuaries (and elsewhere in the larger estuary) lacks any new sediment accumulation and consists of an old oxidized surface with gravels and pebbles (with a large mean grain size and very poor sorting), this is a kind of relic topography that is not related to the modern coastal or estuarine processes or sediment supply.

Portions of the continental margins of the estuary have narrow beach deposits that extend into the adjacent water and create spatially-limited bottom types because of the exposure to ambient wave conditions and available sediments. They form isolated shore-parallel bands of well-sorted medium-to-fine sand bounded by finer sediments.

Importantly, the juxtaposition of sediments and morphologies present in Barnegat Bay represents associations of hydrographies and flows that create shellfish habitats and they may be re-

Figure 3.—Aerial view of Barnegat Bay, showing the extensive flood-tide delta at the Barnegat Inlet and the broad shelf along the estuarine margin of the barrier spit, formed by earlier flood-tide delta and overwash deposits.

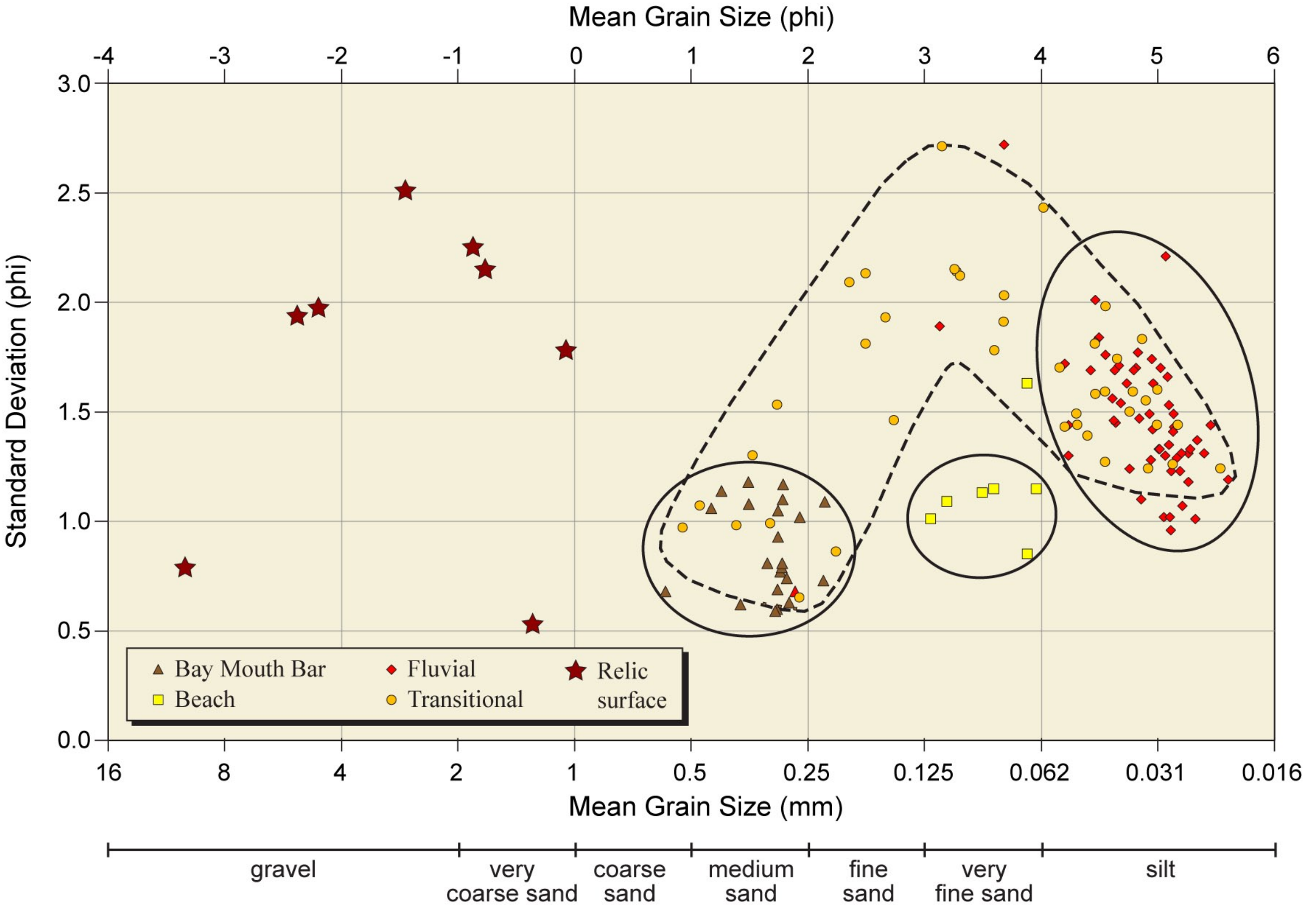

Figure 4.—Bivariate plot of sorting (standard deviation in phi units) and mean grain-size values of sediment samples from Kettle Creek–Silver Bay micro-estuaries, Barnegat Bay (after Psuty, 2004). Samples were collected from a variety of morphological features within and adjacent to the micro-estuaries. The relict surface has no recent sediment accumulation and thus has no relationship to the ambient processes.

peated in other estuarine situations that have similar current flow regimes and sediment availability.

Great Egg Harbor Estuary

The Great Egg Harbor embayment is a complex estuary that incorporates a lagoon-type form along with a drowned river valley. It has one active inlet. At present, it encompasses an area of 22 km^2, has a coastal length of about 8 km, and a width that varies from about 1.0 km near its inlet to about 4.5 km inland from Ocean City, NJ (Fig. 5). The dominant tides are microtidal, with a range varying from about 1.52 m spring tide to 0.7 m neap tide at the inlet.[1]

There is an abundant coastal sediment supply being delivered from the erosion of a drowned delta to the north as well as sediment arriving from the south, transported from the Delaware River (McMaster, 1954; Dobday, 1981). The estuary has a large flood tide delta that occupies 3 km^2. There are deep channels along the margins of the tidal delta through which there is a counter-clockwise tidal current circulation (Psuty et al.[2]). The morpho-sedimentary units within the estuary are related to the geomorphological evolution of the barrier island and the flood tide delta building into Great Egg Harbor Inlet.

The present morpho-sedimentary pattern consists of a series of subaerial marsh islands atop a complex of very-fine sand shoals extending inland toward the drowned river channel (Fig. 5, 6). The major channels and their distributaries dissecting the flood-tide delta are sites of coarser sediments, usually with fine sand and shell lining the channel.

The channels near the inlet have high concentrations of shell debris covering the bottoms and coarser sediments. In places of very high tidal currents, the bottom sediments are composed of relic materials, the old Pleistocene surface which has no modern sediment accu-

[1]Mean tide conditions are available for Great Egg Harbor on the NOAA Tides and Currents website located at: http://tidesandcurrents.noaa.gov/tides09/tab2ec2b.html#32

[2]Psuty, N. P., Q. Guo, and N. S. Suk, 1993. Sediments and sedimentation in the proposed ICWW Channels, Great Egg Harbor, NJ. Report submitted to O'Dea, Pavlo & Associates, 107 p.

mulation. These sites tend to be deeper and near the contact with the margin of the continent. All of the sand is derived from the marine side of the estuary and shallow cores demonstrate that the marine sand covers former bay habitats consisting of silty open-water deposits, and that habitats shifted from oyster beds at the base of the cores to hard clam environments at the core surface as sea level rose and salinity gradients changed (Psuty et al.[2]).

The Great Egg Harbor is a relatively small site, and it is dominated by the flood-tide delta composed of fine and very fine sand. There are deep channels that flank either side of the delta and one shallower channel that bisects the delta. The channels are the avenues of tidal flow and relatively coarser sediments in transport. The shoals extend through most of Great Egg Harbor and lie between the major channels. They form a shallow zone that connects with the mainland to the west of Great Egg Harbor. There is a grain-size gradient that has coarser material nearer the inlet and finer material inland. Sorting decreases inland as fluvial silts mix with the coastal sands, creating a softer bottom with modest changes in morphology, leading to good shellfish habitat. The deep channels at the margins of the flood tide delta tend to have a consistent depth and bottom type.

The quantity of sand entering the Great Egg Harbor estuary is apparently insufficient to maintain the complete flood-tide delta system. An analysis of the areal extent of the islands and the shoals from aerial photos covering the period of 1940 to 1991 (Guo and Psuty, 1997) reveals that the islands and shoals are diminishing in areal extent, a loss of 5% over this 51-year period, and shifting inland. Cores and grab samples also suggest that the islands and shoals are eroding on their inlet margin and extending inland. A few C^{137} dates from the island indicate that the combined rate of sea-level rise and compaction in the very recent accumulations is on the order of 7 mm/yr (Psuty et al.[2]). That is a very large demand on the ambient sediment transport mechanisms to maintain the characteristics of the surface area of the flood-tide delta, leading to a shift in the morpho-sedimentary units and a migration of the sites of shellfish abundance.

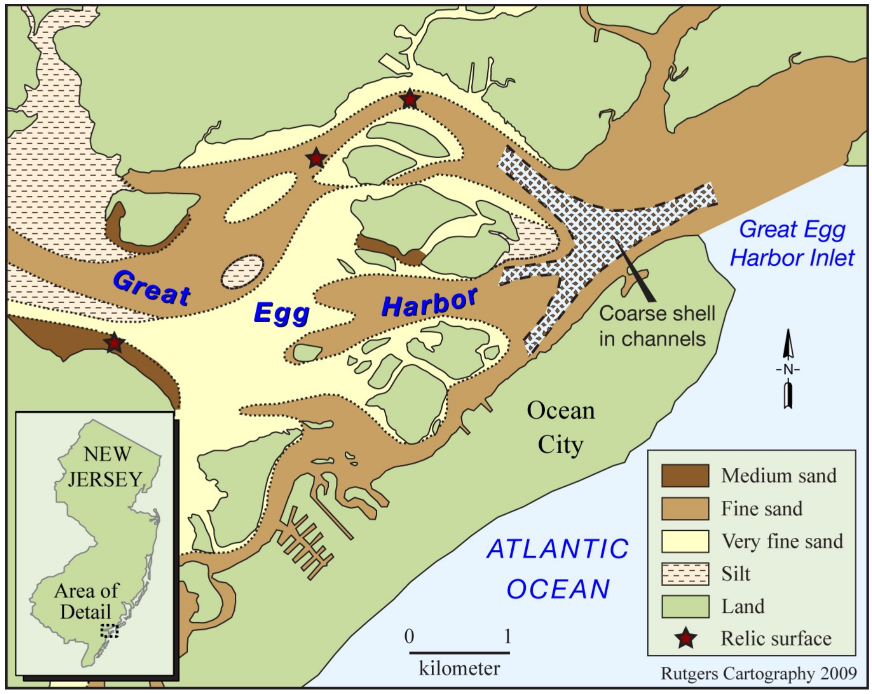

Figure 5.—Distribution of morpho-sedimentary units in Great Egg Harbor.

Great South Bay

Great South Bay is a shore-parallel, lagoon-type estuary with one major inlet (Fire Island Inlet) and a secondary inlet (Moriches Inlet) that is connected to the ocean via the next embayment to the east (Moriches Bay). Great South Bay has an area of 217 km^2, a coastal length of about 37 km, and a width that varies from about 300 m at its eastern end to nearly 9 km at its western portion (Fig. 7). The dominant tides are microtidal, attaining a range of about 1.3 m at spring tide at the ocean side near the stabilized Fire Island Inlet.[3] Tidal range decreases greatly into the bay, with an average spring range from 0.21 to 0.62 m, lower ranges at greater distances from the inlet. Although there are some deep channels in portions of Fire Island Inlet, the estuary tends to have a broad gently-sloping shelf extending and deepening inland from the southern margin (ocean side). The deepest portion of the estuary is 3–4 m and it is nearer the inland margin of the bay. As with other lagoon-type estuaries, the distribution and makeup of the morpho-sedimentary units within the embayment are related to the geomorphological evolution of the ancestral barrier spit as it migrated inland and extended westerly (Bokuniewicz and Schubel, 1991).

In the past, there was a very abundant sediment supply available to construct the barrier island system along Long Island. Glacial outwash at and near the eastern end of Long Island provided great quantities of sand that was eroded and transported westerly (Taney, 1961; Williams, 1976; Rosati et al., 1999). The geomorphological features on Fire Island indicate that the island is composed of several smaller islands that have coalesced to form the present lengthy barrier (Psuty et al., 2005).

The presence of former inlets associated with the multi-island configuration of Fire Island is seen in the existence of broad flood-delta morpho-sedimen-

[3]Mean tide conditions are available for Great South Bay on the NOAA Tides and Currents website located at: http://tidesandcurrents.noaa.gov/tides09/tab2ec2a.html#20

Figure 6.—Aerial view of Great Egg Harbor, portraying the submarine and subaerial morphological features of the flood-tide delta and the shoals and channels associated with the riverine system.

tological units extending northerly into the bay that consist of medium sand near the barrier and grade to fine and very fine sand with silt toward the north (Bruderer, 1970; Rockwell, 1974; Jones and Schubel, 1980; Bokuniewicz and Schubel, 1991). The largest flood-delta deposit with a myriad of channels, shoals, and marsh islands extends inland from Fire Island Inlet (Fig. 7, 8). The sediments are well-sorted medium sands, coarsening with gravels and shell fragments lining the bottoms of the channels. Ali et al. (1976) distinguished components of the tidal deltas based on current flow regimes and noted that whereas the tidal channels had a distinctive high energy sediment-size distribution, the deeper embayment was often modified by the energy-absorbing eelgrass to create fine grain size accumulations. The very large flood-tide delta at Fire Island Inlet is probably related to the persistence of that inlet compared to other sites discharging into Great South Bay as well as the extensive migration of the inlet at the western margin of the barrier, more than 8 km from 1825 to 1941 (Smith et al., 1999; Allen et al., 2002).

A large flood-delta deposit is also found at the eastern end of Great South Bay, emanating from the aptly-named "Old Inlet" portion of Fire Island (Fig. 7, 8). Another major flood-delta extends from the Watch Hill region of the barrier island. The deepest areas near the mainland are sites of silt accumulations (Greene et al., 1978). They also tend to be associated with stream valleys cut into the mainland topography, and thus the morpho-sedimentary units at these sites are related to the pre-existing fluvial topography and to the fluvial sources of fine-grained sediments. In a few locations, beach deposits occur on the inland margin of the estuaries where exposure to waves and the presence of sand create the opportunity for sorting and transport of the sand at the water contact and for some distance offshore.

To the north of the barrier island and its flood delta extension, there is a considerable admixture of silt in the surface sands, increasing the silt content into deeper water. Vast seagrass beds occur in these portions of Great South Bay

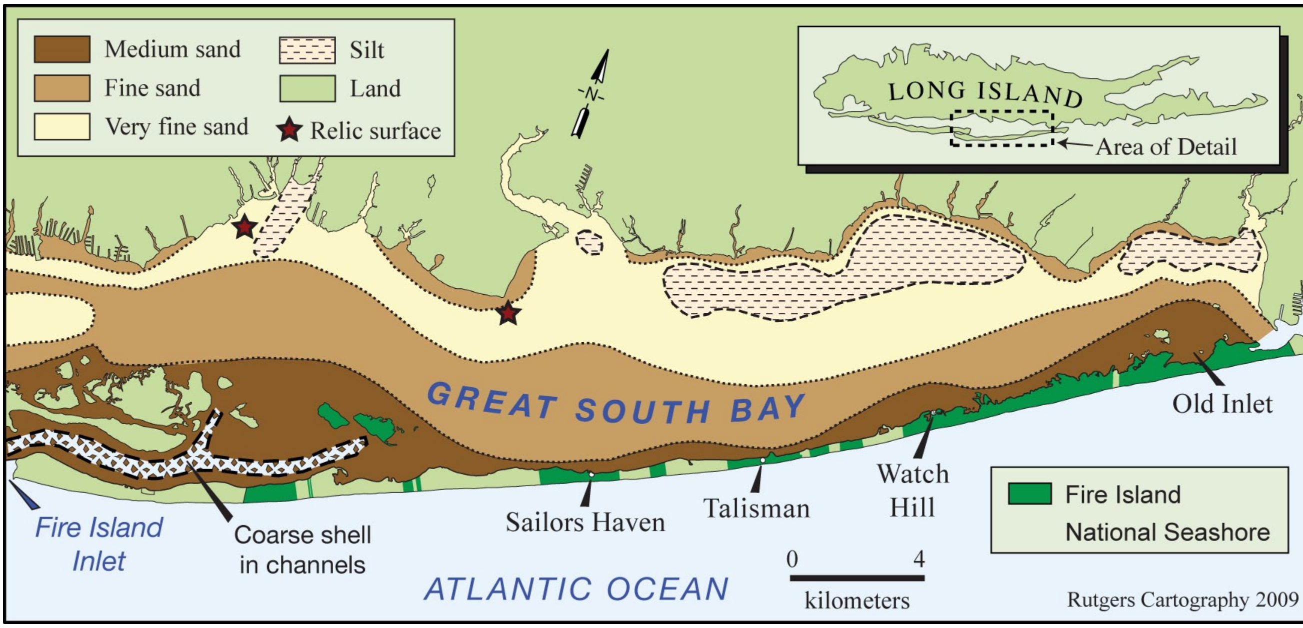

Figure 7.—Distribution of morpho-sedimentary units in Great South Bay.

(Greene et al., 1978). They modify the local tidal currents and ambient wave action and, together with the siltier sedimentary units, offer suitable habitat for shellfish.

Shinnecock Bay

The Shinnecock Bay embayment incorporates an area of 33 km^2 and is a complex lagoon-type estuary with one active inlet. It has a coastal length of about 15 km and a width that varies from 0.6 km to about 4.5 km, with a general maximum depth of 3 m (Fig. 9). The semi-diurnal tides are microtidal, varying from about 1.01 m mean tide range at the inlet, to 0.86 at Ponquogue Point (2 km distance) and 0.74 m in the bay at a distance of about 4 km (Militello and Kraus, 2001). The estuary is shallowest at its southern margin, adjacent to the barrier, and has a general depth of about 3 m throughout much of the inner portion of the estuary. The morpho-sedimentary units within the estuary are related to the geomorphological evolution of the barrier spit as it migrated inland and extended westerly, and as it was breached by inlets at several locations, primarily in the eastern portion of the barrier (Morang, 1999).

Figure 8.—Aerial view of Great South Bay, portraying the submarine and subaerial morphological features of the extensive flood-tide delta associated with the Fire Island Inlet and the flood-delta deposits from earlier inlets.

The Great Hurricane of September 1938 (Long Island Express) produced several sites of large washover across the barrier and into the estuary. This major storm also created the present Shinnecock Inlet, occupying a former inlet location, that migrated westerly until stabilized with jetties in 1952–55 (Rosati et al., 1999). The modern flood-tide delta is the most recent addition to the broad sandy shelf that is extending inland along the entire length of the barrier (Fig. 9, 10). The inlet margin of the delta is composed of the coarsest sediment (Pratt and Stauble, 2001); the dredged channels incorporate some gravel as well as shell debris and coarse sand that extend through and at the margins of the flood-tide delta (Dooley, 1974). Most of the shoal surface of the tidal delta as well as the shallow shelf along the inland margin of the barrier is medium sand. Toward the inland margin of the shelf and shoal, and at greater depths, sediment is largely fine sand in and among seagrass beds.

The inland margin of the estuary is often the site of glacial-fluvial sediments that are worked by the ambient waves and currents to create narrow sandy beaches and sandy offshore zones. The variable glacial topography produces a patchwork of sediment types that continue into the estuary and contributes to a mix of morpho-sedimentary units at the inland portion of the estuary.

Shellfish habitat is limited near the barrier island because of planar morphology, shallow depths, and exposure to predators (MacKenzie et al., 2006). However, the deeper bay has greater morpho-sedimentological variety and a greater range of habitat characteristics.

Pleasant Bay Estuary

The Pleasant Bay embayment is a complex estuary with an area of 29 km^2 and two active inlets toward its southern margin. The bay has a coastal length of about 11 km and a width that varies from less than 1 km at its northern portion to a maximum of about 5 km in the central portion (Fig. 11). The ocean tidal range is about 2 m at the inlet, at the limit of the microtidal classification. However, the tides decrease in range in the estuary, varying from about 1.58 m spring tide inside the inlet, to 1.13 m in Pleasant Bay, and to 0.4 m at the northern limits of the estuary.[4] The estuary is shallowest at its eastern margin, adjacent to the barrier, and deepest (maximum of 7 m) toward the northern contact with the continent. The morpho-sedimentary units within the estuary are related to the geomorphological evolution of the barrier spit as it migrated inland and extended southerly (Goldsmith, 1972).

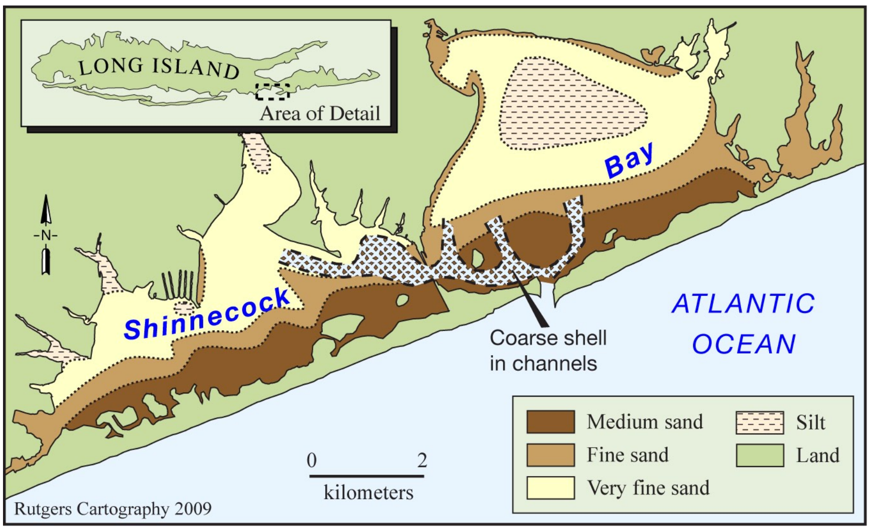

Figure 9.—Distribution of morpho-sedimentary units in Shinnecock Bay.

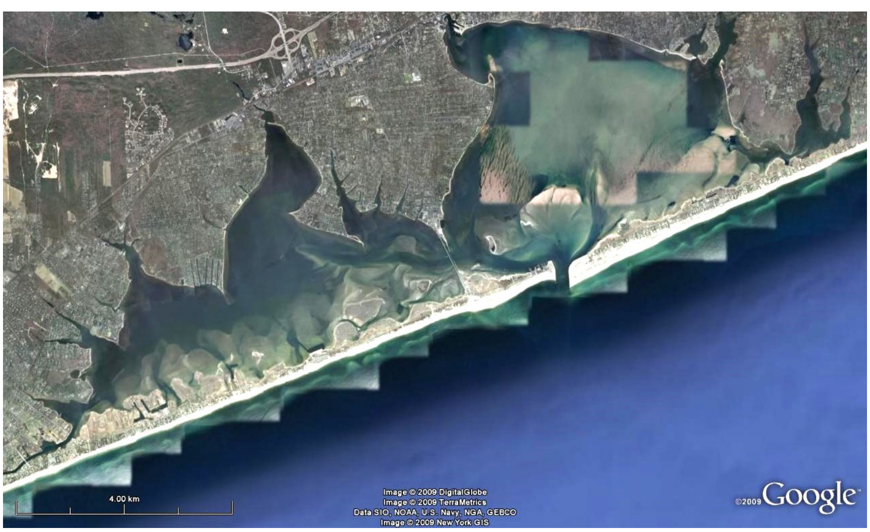

Figure 10.—Aerial view of Shinnecock Bay, portraying the submarine and subaerial morphological features of the flood-tide delta and the sandy shelf extending inland along the barrier.

Sediment supply consists largely of medium sand derived from erosion of the glacial deposits north of Chatham and the alongshore transport creating the Nauset Spit barrier. As the spit extended southward, considerable sand accumulated on the flood-tide-delta side of the barrier. Goldsmith (1972) suggested that the spit was periodically breached at an updrift location and a new inlet migrated southerly at some multi-decadal to centurial time scale. Recent inlet breaches, in 1958 (Hine, 1972), in 1987 (Borrelli, 2008), and 2007 have contributed to the morpho-sedimentological development. As a result, the flood-tide delta was rejuvenated at this temporal interval and repeatedly extended into the estuary.

The existing flood-tide delta is continuing to evolve and has a very complex pattern of channels (Fig. 11, 12). Some are inherited from the tidal flows associated with the 1987 inlet, and others are related to the 2007 inlet. Whereas most of the shoals in the flood-tide delta consist of medium sand, the channels are lined with coarse sand and shell debris. The estuary deepens quickly beyond the limits of the tidal delta and the sediments also grade quickly to fine and very fine sand. The central portion of Pleasant

[4]Mean tide conditions are available for Pleasant Bay on the NOAA Tides and Currents website located at: http://tidesandcurrents.noaa.gov/tides09/tab2ec1b.html#8

Bay has silt deposits. At a number of locations along the margin of the bay, erosion of the glacial deposits provides fine sand to accumulate as a localized beach feature and an associated sandy offshore slope.

The complex geomorphological history leads to a wide variety of shellfish habitats, ranging from deep abandoned channels lined with shell debris to moderately-deep silty pockets with seagrass beds. The 2007 inlet in Nauset Spit is causing a migration of shoals and channels and is redefining sites of shellfish abundance.

Conclusions

The geomorphological characteristics of the selected microtidal estuaries in the northeastern U.S. are largely related to the dynamic evolution of the barrier island system over the past 3,000 years or so (young in a geological sense) and the concomitant transfers of sediment through inlets as well as overwash into the estuaries. The vectors of sediment transport in barrier island systems dictate that the greatest thickness of sediment and the coarsest sizes of sediment are at the seaward margin of the estuaries. Each of the estuaries is flood-tide dominant and, in general, each is shallowest at the seaward margin, except for the inlet channels, and deepens toward the mainland. The flood-tide deltas are the most dynamic component of the geomorphological system, accumulating great masses of sediment and extending into the estuaries.

In the natural progression of barrier island development and inlet migration, the flood-tide delta has shifted downdrift as the inlet migrated. The result was a continual expansion of the shallow shelf on the inland margin of the barrier island. As a consequence, the water depths tend to increase inland away from the barrier island and toward the mainland as a function of distance from the source of sediment input

Also, the deeper areas near the mainland are zones of accumulation of fine sediment, very-fine sand, and silts, derived from the fluvial sources draining the upland. Bottom types are therefore coarser toward the mouths of

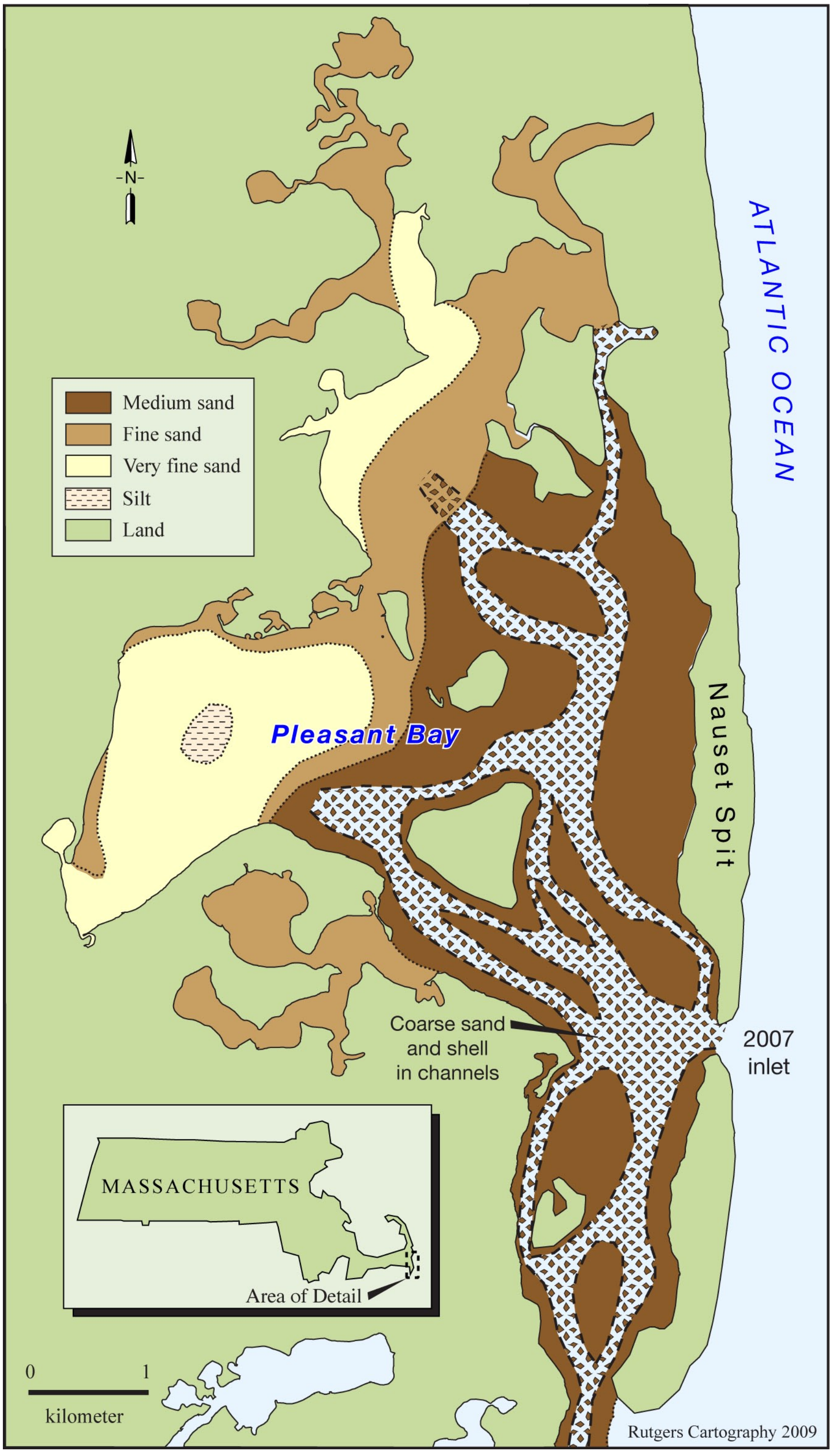

Figure 11.—Distribution of morpho-sedimentary units in Pleasant Bay.

the estuaries and fine along an inland gradient. Sand is predominant in all of the estuaries. Silt is in isolated pockets near the mainland, often associated with some fluvial input. Shellfish habitat, therefore, improves away from the barrier islands as sediment types get finer, topographical variety ensues, and depths increase. Some of the estuaries, Shinnecock and Pleasant Bay, have a more dynamic morpho-sedimentary evolution because of the recent inlet development. The others are more stable and represent an end product of the evolutionary trend of microtidal barrier island estuarine environments. Overall, the pattern of bottom sediments is a product of a geomorphological process interacting with available sediment in a system of barrier island development under a sea-level rise scenario.

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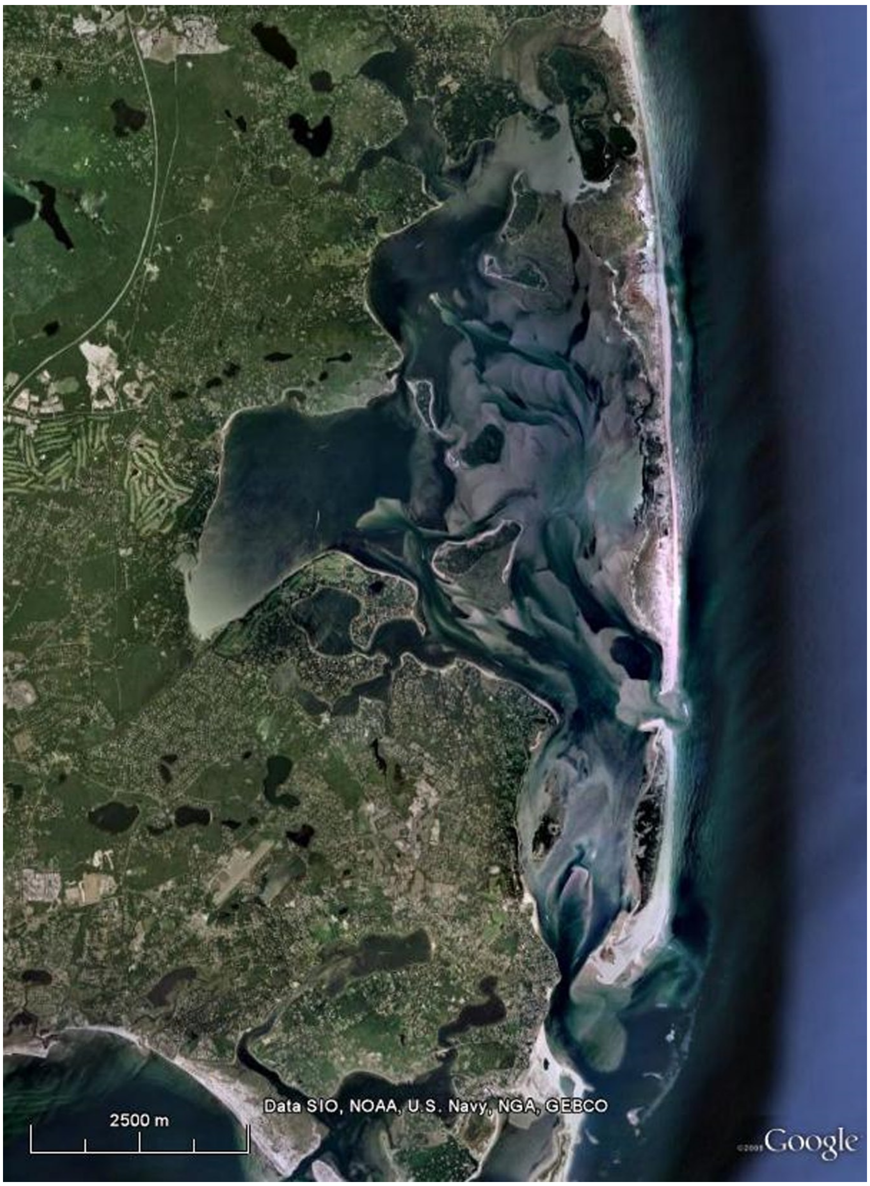

Figure 12.—Aerial view of Pleasant Bay, portraying the submarine and subaerial morphological features of the flood-tide delta, the complex pattern of channels and shoals, and the recently-formed 2007 inlet.

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