Chapter 2

Geomorphology

Britt Argow

Barrier beaches are found along 18% of North America's coasts, mostly along the Atlantic and Gulf seaboards. These barrier islands and spits create a quiet, sheltered environment in which unique and diverse lagoon, marsh, and tidal flats develop, known collectively as the back-barrier. About 100 km of Maine's roughly 5,600 km coast is protected by barriers (Kelley 1987, Duffy *et al*. 1989). Relatively little research has focused on the ecological, sedimentary and physical processes that shape this coastal environment relative to its southern counterparts. Wells NERR includes perhaps the largest and best studied estuarine and marsh system in Maine, and is an important example of a northern back-barrier system.

Wells NERR is located at 43°19'N and 70°34'W in the Wells Embayment on the Gulf of Maine. The Wells Embayment is defined by its arcuate coastline, and lies offshore between the Kennebunk River and the Ogunquit River inlets. The Embayment has an irregular seafloor dominated by bedrock outcrop and relict deposits of glacial sediments from the last major North American ice sheet. Geophysical technology allows us to visualize the layers below the surface and glimpse the sediments of the seafloor (Kelley *et al*. 1988, Fig. 2-1, Fig. 2-2, Fig. 14-2). Sand is only a thin cover on the nearshore in most places (Miller 1998). The dominant sources of sand for the present coast include reworking of this narrow and thin wedge during sea-level rise, and new sediment introduced from glacial deposits at headlands.

The coast of Maine has been and continues to be shaped by the forces of wind, waves and tides. Maine experiences semidiurnal tides (two high tides and two low tides daily) along its 5,600 km coastline (Dickson 2003). The mean tidal range (the vertical difference between mean high tide and mean low tide) at Wells Inlet is 2.7 m, increasing to 2.9 m around full and new moons each month (Ch. 15, Fig. 15-4). Winds are seasonal, coming from the north and northeast during the colder months and primarily from the south and southwest during the summer (Ch. 3, Fig. 3-4, Fig. 3-5). Waves generated by these winds vary seasonally in their direction of approach to the shoreline (Byrne and Ziegler 1997), and also in their height. The largest waves, which have the highest energy, approach from the northeast and are associated with Northeasters and winter storms. These waves can be 7 meters in height while offshore on the western continental shelf of the Gulf of Maine (GoMOOS), and will increase in height and steepness as they approach the shore. These waves are often responsible for massive erosion during a single storm event, and are a dramatic reminder of the power of the sea. During most of the year, however, wave approach into the Wells Embayment is from the south and

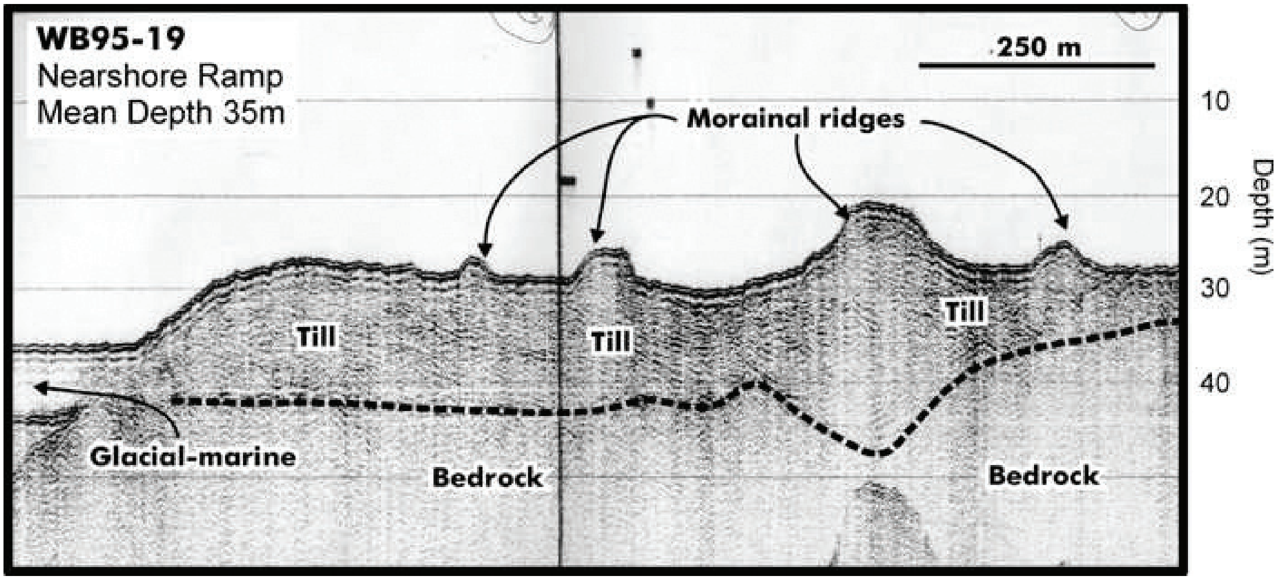


Figure 2-1: Seismic reflection profile. Glacial deposition left morainal ridges on the inner shelf as the ice retrated. Subsequent reworking produced a seafloor composed of sand and gravel with some boulders. The horizontal dotted line traces the border between glacial till and the bedrock below. Source Maine Geological Survey.

southeast, and these calm-weather waves are smaller and less energetic (GoMOOS), yet due to their steady, constant action, they dominate coastal sedimentation processes on the open coast of the Wells NERR barrier and headlands.

Back-barrier environments generally experience reduced wave, storm and wind conditions relative to open coastlines. The resulting lower-energy environment becomes a sediment sink for sands and muds carried into the system via the ocean inlet or from rivers and streams draining the upland. The evolution of this coastal system will be discussed in Chapter 14; here we focus on the physical characteristics and processes of the dominant ecosystems and environments of the back-barrier and surrounding uplands.

Barrier Beaches

The barrier system at Wells NERR comprises two beaches: Wells Beach, south of Wells Inlet, and Drake's Island Beach and Laudholm Beach (a single system) to the north. Wells Beach is a barrier spit, anchored on the till and bedrock outcrops of Moody Point. The Drakes Island / Laudholm Beach, located between Wells Inlet and Little River Inlet, is a barrier island anchored on till. The barrier and inlet complex of Wells NERR is near the northern end of a semi-continuous chain of barrier islands and spits stretching southwest along the coast of Maine, New Hampshire, and Massachusetts to Cape Ann.

The Wells NERR barrier system itself is a long, low coastal feature. Stretching a total of 4.7 km in a gently curving arc from its anchor points on Moody Point to the till that forms Drakes Island (Fig. 2-3), the barrier island stands only 2 - 4 m above mean sea level. Wells Beach barrier is heavily developed, and large sections of the beach have been stabilized by sea walls or revetments. Stabilization protects property in the short term, but alters the natural evolution of the barrier complex and prevents the island from migrating landward in a regime of rising sea level by reducing overwash processes. The three or more rows of houses effectively stop the action of winds moving sediment from the beach into a dune system and onto the back-barrier (Jacobson 1988). The development of Wells Beach has resulted in several changes to the shoreface, discussed in more detail in Chapter 14.

The beach runs 3.5 km north from Moody Point to Wells Inlet (Wells Beach), and 2.2 km from Wells inlet to the Little River Inlet (Laudholm Beach). Both beaches narrow to the south. Wells Beach is ≈ 250 meters wide at low tide at the inlet, and gradually becomes narrower

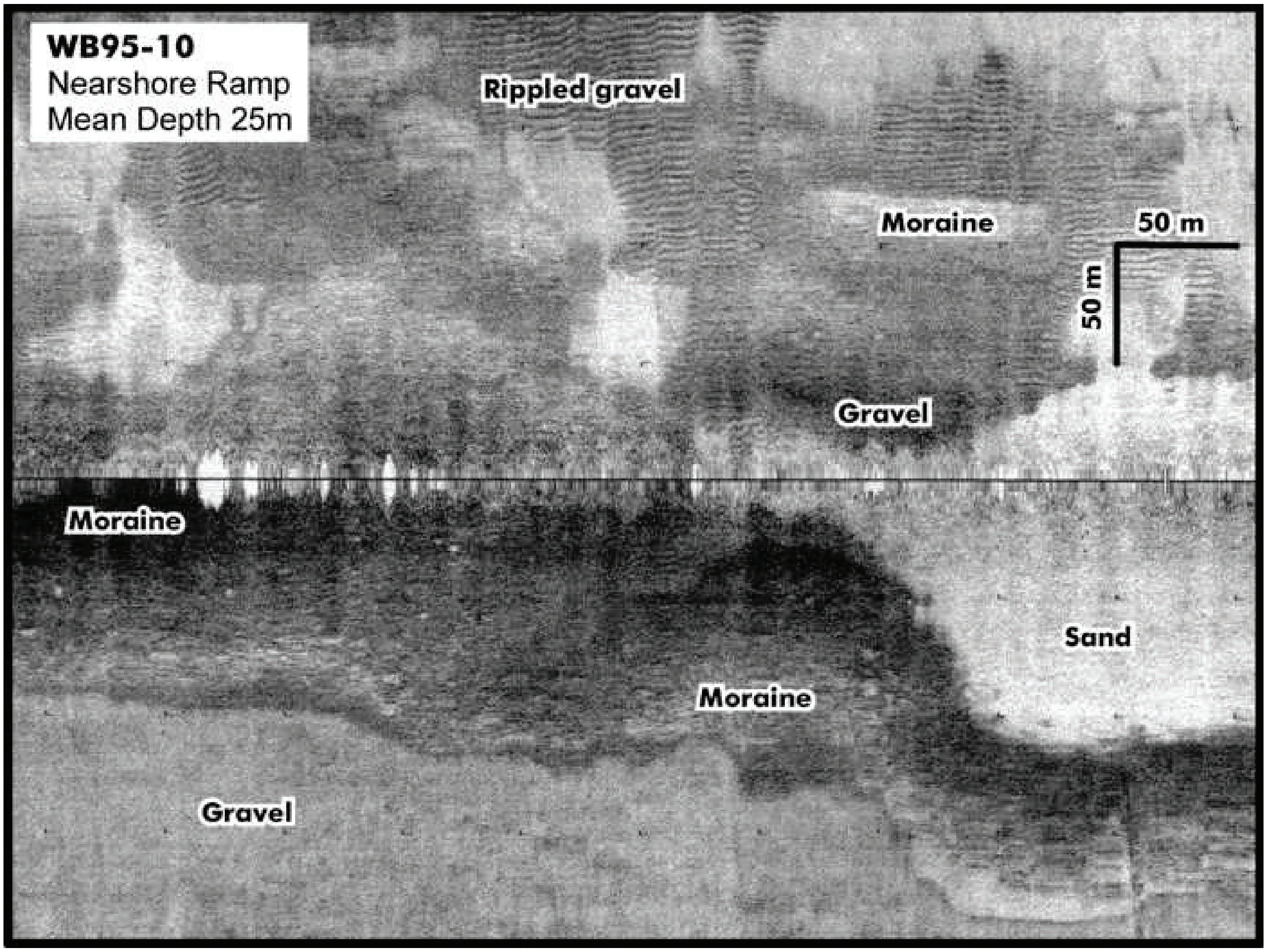


Figure 2-2: Side-scan sonar image of the seafloor, looking down on a 5 – 10 m high moraine in the Wells Embayment. Nearby sand and gravel deposits were once part of the moraine but have been removed by erosion. This technique is used in combination with seismic reflection profiles and bottom sampling to determine substrate type. Source Maine Geological Survey.

until it tapers and disappears at Moody Point. Laudholm Beach is more consistent in width and the narrowing is more subtle, widening again at the northern jetty. Low-tide beach width ranges from 140-200 meters over its length.

The variation of beach width is a function of the dominant direction of wave approach from the southeast and the resulting transport of sediment in a northerly direction along the shoreface. These waves also move sediment onshore, building up and widening the beach over the summer months. The north-south shoreline asymmetry is milder than one might expect, however, because of the influence of Northeaster storms which move large quantities of sediment in a southerly direction along the beach, as well as offshore. Currently there is a near balance of northerly and southerly transport in the long term (Belknap *et al.* 1995), best demonstrated by the symmetry of the deposits that have built up on both sides of the jetties at Wells Inlet (Timson and Kale 1976).

Major winter storms are largely responsible for the seasonal variation in beach width observed at the barrier beach fronting Wells NERR, as the large waves associated with winter storms have so much energy that they do not expend it all crashing on the beach, and therefore carry sediment offshore as well as up the beach face. During especially large storms, overwash may occur in lower (or less-protected) sections of the barrier spit system. In a natural setting this same process moves sediment from the beach onto the barrier island, raising the elevation of the island and helping it to maintain its position with rising sea level. In lower and thinner sections of a barrier, or on barriers that have been stabilized, overwash will deposit sediment in the back-barrier environment when it occurs.

The barrier itself is made up of layers of sand and gravel. These sediments are re-worked deposits first brought to the area by glacial processes during the last major glaciation of North America (Ch. 14). The barrier is anchored in its present position along the coast by till and bedrock outcrops (Fig. 2-3).

Soils on the barrier are derived from the sands that dominate the stratigraphy of this feature, and are characterized as thin, sandy loam.

Salt Marshes

The extensive salt marshes of the Webhannet River and Little River marshes are among the largest in the state. They form a broad, flat, vegetated platform deeply incised by tidal channels and creeks (greens in Figs. 2-3 and 2-7). These intertidal environments cover approximately 526 ha, and are the most obvious recognizable ecosystem in the Reserve for many visitors. They formed over the last 4,000 years or so during a time of relatively slow sea-level rise (approximately 10 centimeters per century), but today face a much higher rate of sea-level rise (about 25 centimeters in the last century). Rates of sea-level rise are expected to keep accelerating, resulting in the inundation and loss of these salt marshes if they are not able to maintain their position relative to rising sea level.

Low marsh colonizing sandy tidal flat in Webhannet Estuary. An established low marsh ramp is visible to the west (right), and the cliffed leading edge of the high marsh platform can be observed above the ramp. Photo Britt Argow.

There are two major classifications of salt marsh ecosystems found in Wells NERR. Low marsh systems form between mean tide level and mean high-water (generally from 0.8 to 1.3 meters above sea level at Wells NERR), and are commonly defined in the field by their vegetation. They appear to be a near-monoculture, comprised almost exclusively of the halophyte (salt-tolerant) grass species Smooth cordgrass (*Spartina alterniflora*). At Wells NERR, low marsh ecosystems are restricted to narrow ribbons along tidal creeks and to slumped ramps along the main tidal channels. The high marsh, in contrast, inhabits broad, fairly level fields, and makes up the majority of the marsh system in the Webhannet estuary (Fig. 2-3). High marsh is formed at elevations around and above mean high tide level (1.39 meters above mean sea level at Wells Inlet), up to the upland margin ecosystem that begins at the limit of highest spring tidal inundation (around 2 m above mean sea level). The high marsh community is fairly diverse, but at Wells is dominated by salt marsh hay (*Spartina patens*).

Salt marshes at Wells NERR, like most New England marshes, formed in a regime of slow, steady sea-level rise. But what will happen if rates of sea-level rise increase, as has been predicted (Church *et al*. 2001)? Coastal wetlands respond to changes in local sea level by migrating seaward as sea level falls, and by accreting vertically and migrating landward (where local topography allows) as sea level rises. Vertical accretion is the result of both mineral sediment influx and the production of organic matter, and is therefore also dependent on suspended sediment concentrations, nutrient abundance, and storm frequency and intensity (Leonard, 1997; Leonard and Luther, 1995; Leonard *et al*. 1995; Reed 2002). The hypsometry of the marsh, type and abundance of vegetation and resulting patterns of hydrologic flow can also impact marsh accretion (Boon and Byrne, 1981; Leonard and Luther, 1995). Past studies indicate that there may be a limit to annual accretion rates in salt marshes, making this environment extremely vulnerable to acceleration of rising sea level (e.g. Redfield 1972; Bricker-Urso *et* al. 1989; Reed 1995; Callaway et al. 1997; Reed 2002; Rybczyk and Cahoon 2002).

Marshes throughout the world have been investigated to quantify rates of vertical accretion[1]. Methods used include direct measurement of vertical accretion on the surface of the marsh, measurements of sedimentation rates using known marker horizons (Fig. 2-4), and historical measurements calculated by linear regression from radiometric dates. The total range of accretion rates reported is 0 -14 millimeters per year, with a mean of 5.0 millimeters per year (FitzGerald *et al.* 2006). If the upper end of this range reflects the maximum rate at which coastal wetlands can vertically accrete, then all marshes should potentially be able to keep up the average projections of sea-level rise rates. A closer look at the data, however, reveals that low marsh can accrete much more rapidly than can high marsh (a mean of 6.1 mm yr^{-1} versus 2.6 mm yr^{-1}; FitzGerald *et al.* 2006, Fig. 2-5). This difference reflects the larger contribution of inorganic sediment to the low marsh as a function of more frequent tidal inundation, as well as the greater bioproductivity of low marsh plants relative to high marsh plants (Bagwell and Lovell 2000; Foote and Reynolds 1997; Gabrey and Afton 2001). High marshes may be more vulnerable to accelerated sea-level rise, as they accrete more slowly, with a higher proportion of organic matter, being distant from sources of inorganic sediment. Many high marshes may not be able to keep up with the projected acceleration in the rate of sea-level rise. In back-barrier environments, this may trigger dramatic coastal evolution (Ch. 14). The back-barrier marshes of New England form a unique ecosystem that is currently

Figure 2-3: Geomorphic provinces of the back-barrier and barrier island complex at Wells NERR (Argow 2006).

1 For a list of world-wide accretion research locations and scientists, see the USGS Patuxent Wildlife Research Center's directory, available at http://www.pwrc.usgs.gov/set/ (Accessed 13 November 2006).

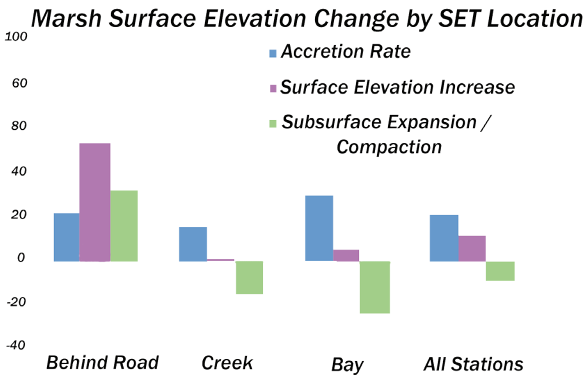


Figure 2-4: SET (sediment elevation table) data from the Webhannet marsh. Data David Burdick, University of New Hampshire.

threatened by projected increases in sea level (Kelley *et al.* 1988, Kennish 2001, Donnelly and Bertness 2001).

In Wells NERR there is a distinct change in slope between the flat lowlands along the coast and the relatively steep uplands, and this landscape is characteristic of much of New England's coastal zone. Because of this topography, New England marshes may not be able to maintain their current area by landward migration as sea-level rises; these marshes must accrete at a rate comparable to rising sea level in order to survive.

Current research at Wells NERR shows that the Webhannet marshes are accreting at an annual rate comparable to local rates of rising sea level (Gehrels 1994, 1999, 2000; Gehrels *et al.* 1996, 2002; Goodman *et al.* 2006). However, changes in vegetation on the high marsh may be an early warning of a marsh in distress. Through processes associated with formation of pannes (ephemeral waterlogged areas) and pools (small, persistently water-filled depressions), it may be possible to evaluate whether or not Maine's marshes (and nearby areas) may be profoundly changing or eroding. These changes in pannes and pools may be harbingers of overall marsh health, help identify stresses on marshes including anthropogenic influences, and help predict future responses to climate and sea-level change (Belknap and Kelley 2006; Wilson 2006). See chapter 18 for details on emergent vegetation monitoring at Wells NERR.

The average rate of high marsh accretion is 2.6 mm yr^{-1}, which is comparable to modern rates of sea-level rise in New England (Kelley *et al.* 1988, van de Plassche 1998). This would seem to indicate that these marshes are at present stable coastal systems, but that they may not be able to keep up with accelerated sea-level rise. However,

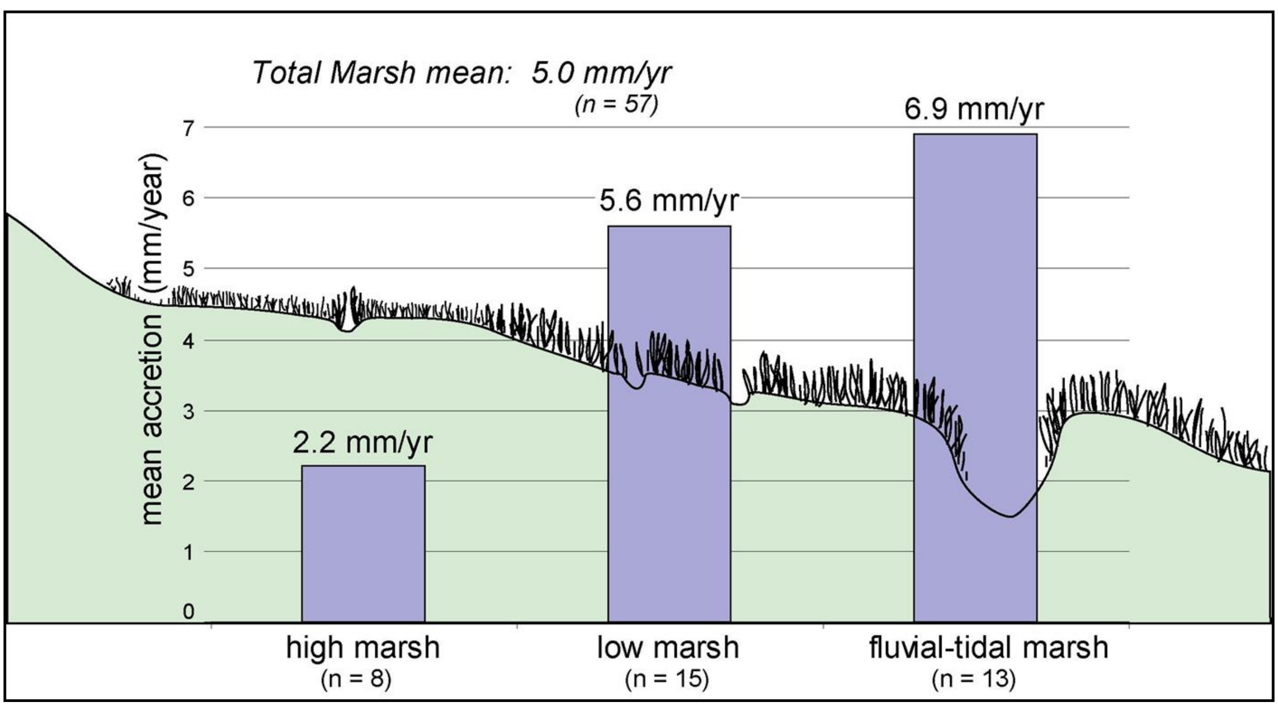


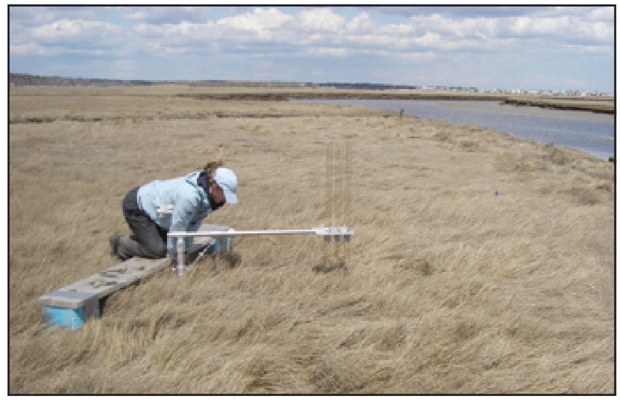
Figure 2-5: Summary of literature values for sediment accretion by marsh zone (Argow 2006).

scientists are still working to untangle the complex biological, sedimentological, and hydrodynamic factors that control the elevation of the marsh (Fig. 2-4). Climate and morphological differences may be the key, as these may turn out to be critical controls on vertical accretion.

Morphologically, northern marshes are dominated by high (supratidal) marsh, while southern marshes are primarily low (intertidal) marsh. These factors may impact vertical accretion by affecting sediment influx and bioproductivity, and will control the pattern and threshold of flooding should the marsh be unable to keep up with rates of rising sea level (Fig. 2-6) (Argow and FitzGerald, 2006). In addition, Northern marshes experience colder average temperatures, more days with temperatures below freezing, and longer duration and thickness of snow and ice cover than do their southern counterparts.

Relatively little research has focused on marsh winter processes. Previous work indicates that ice rafting may have a measurable impact on vertical accretion in northern marshes (e.g. Dionne 1989, Wood *et al*. 1989, Kelley *et al*. 1995, Ollerhead *et al*. 1999, Goodman *et al*. 2006). Work has been limited by the difficulty of quantifying ice rafting and the total volume of sediment redistributed across the marsh surface, but careful field study can yield useful approximations. Ongoing research at Wells NERR indicates that a measurable and significant volume of sediment is indeed deposited on the marsh surface via ice rafting. This sediment influx accounts for as much as 50% of the inorganic material contributed to peat development each year, and may be critical to vertical accretion on the marsh surface. Raising the surface elevation of the marsh is critical if the marsh is to survive in a regime of rising sea level (Argow and FitzGerald 2006).

Wetlands loss is a serious problem facing the global community (Gornitz 1995, Church *et al*. 2001, Kennish 2001, Adam 2002). Coastal wetlands are among the most productive ecosystems on earth, serving as nursery grounds for many marine species and supplying a substantial amount of detritus and living biomass to the waters offshore, supporting secondary oceanic productivity. Marshes are sinks for pollutants, and filter surface waters before they reach the oceans. Wetlands are also important buffer zones, absorbing storm energies and



Preparing the SET (sediment elevation table) for measurement of change in the elevation of the marsh surface on the high marsh north of Mile Road, early spring, 2005. Photo Britt Argow.

storing flood waters. The loss of this protection presents an unmistakable hazard to inland areas. More than half of the world's population lives within 50 km of the coast (Titus 1990), and this environment is already under intense pressure from anthropogenic effects. If accelerating rates of sea-level rise cause marshes to be inundated, the conversion of marsh to open water in the back-barrier environment could initiate a cycle leading ultimately to coastal transgression, ie. inland movement of the coast. Today, evidence suggests the rate of sea-level rise is increasing, threatening the survival of coastal wetlands.

Tidal Flats

Tidal flats make up a relatively small percentage of the total intertidal area of Wells NERR. This sedimentary environment is characterized by gentle slopes and sandy or muddy substrate, and is home to a diverse population of benthos. Tidal flats may form at elevations from spring low tide (1.45 m below sea level) to spring high water (1.45 m above sea level), depending on the amount of energy along the shore from waves and tidal currents.

The sand and mud that make up a tidal flat are brought to the estuary from two sources: rivers and streams, or the ocean via the tidal inlet. Muds more commonly are sourced in the uplands; a greater percentage of sand is derived from the nearshore and littoral regime and is moved into the inlet by waves and tidal currents. Tidal flats build up in areas of relatively low energy and little wave action and slower tidal currents in the estuarine environment. If the energy of the environment is too great, then sand and mud will not be able to settle and form a tidal flat. In environments with moderate to low energy, sand flats may form as sand can settle out while clays will still be suspended in the water column and will wash back out with the tide; in low-energy conditions mud will be deposited and mud flats will form.

Estuarine processes act to concentrate fine cohesive sediments (clays) as well, enhancing the deposition of muddy tidal flats. Flocculation is a process in which tiny particles of clay in the water column are attracted to one another and aggregate to form larger particles, which can then settle to the bottom during slack high water when tidal current velocities are low. Tidal pumping occurs when the incoming tidal waves shoals on the rising bottom of the estuary as it moves from the inlet towards the estuary's head. This process moves sediment-laden water into the estuary more effectively than back out to sea, due to the difference in velocity and the relative channelization of flood and ebb currents. Finally, estuarine circulation itself has a tendency to move fine sediment up into the estuary, as relatively dense saline sea water moves into the estuary along the bottom, while fresher lighter water moves outward at the top of the water column. Hence, as sediments drift down through the water column, they are likely to be moved farther into the estuary by density-driven currents before they settle on the bottom. This explains why the tidal flats and channels of the estuary get progressively muddier towards the head of the estuary, and are sandy near the inlet.

In the upper intertidal zone above mean sea level, tidal flats may be colonized by *Spartina* grasses and converted to tidal wetlands. This process has reduced the total area of tidal flat at Wells NERR significantly over the past 4,000 years (Fig. 2-6).

Tidal Channels

Tidal channels incise the salt marshes and tidal flats of the Wells NERR estuarine systems. This system of creeks and larger channels drains the intertidal region during ebb tides. The tidal network is also the conduit for rising flood tidal waters, until the water level reaches the height of the banks and floods the marsh surface, after which tidal flow in the back-barrier is driven by estuary-wide circulation patterns.

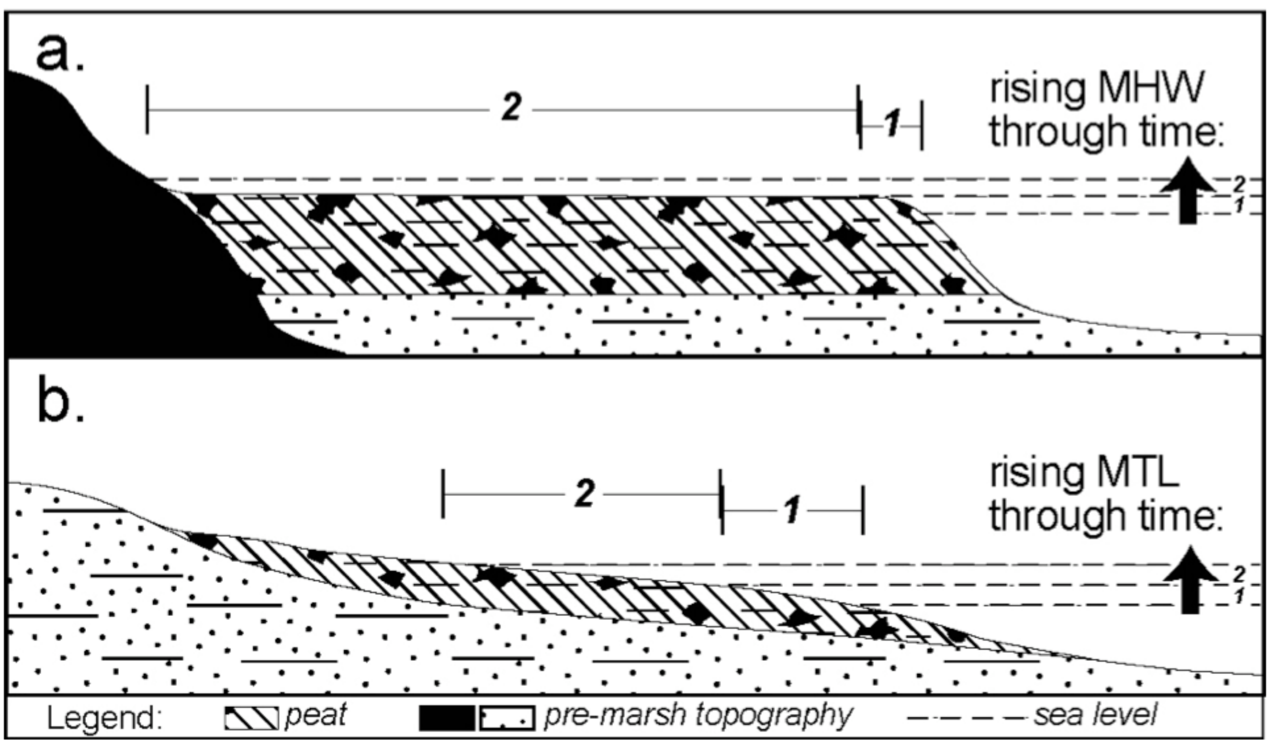


Figure 2-6: Salt marsh cross-sections: a) Platform marsh morphology, b) Ramped marsh morphology (Argow 2006; similar figure appears in Argow and Fitzgerald 2006).

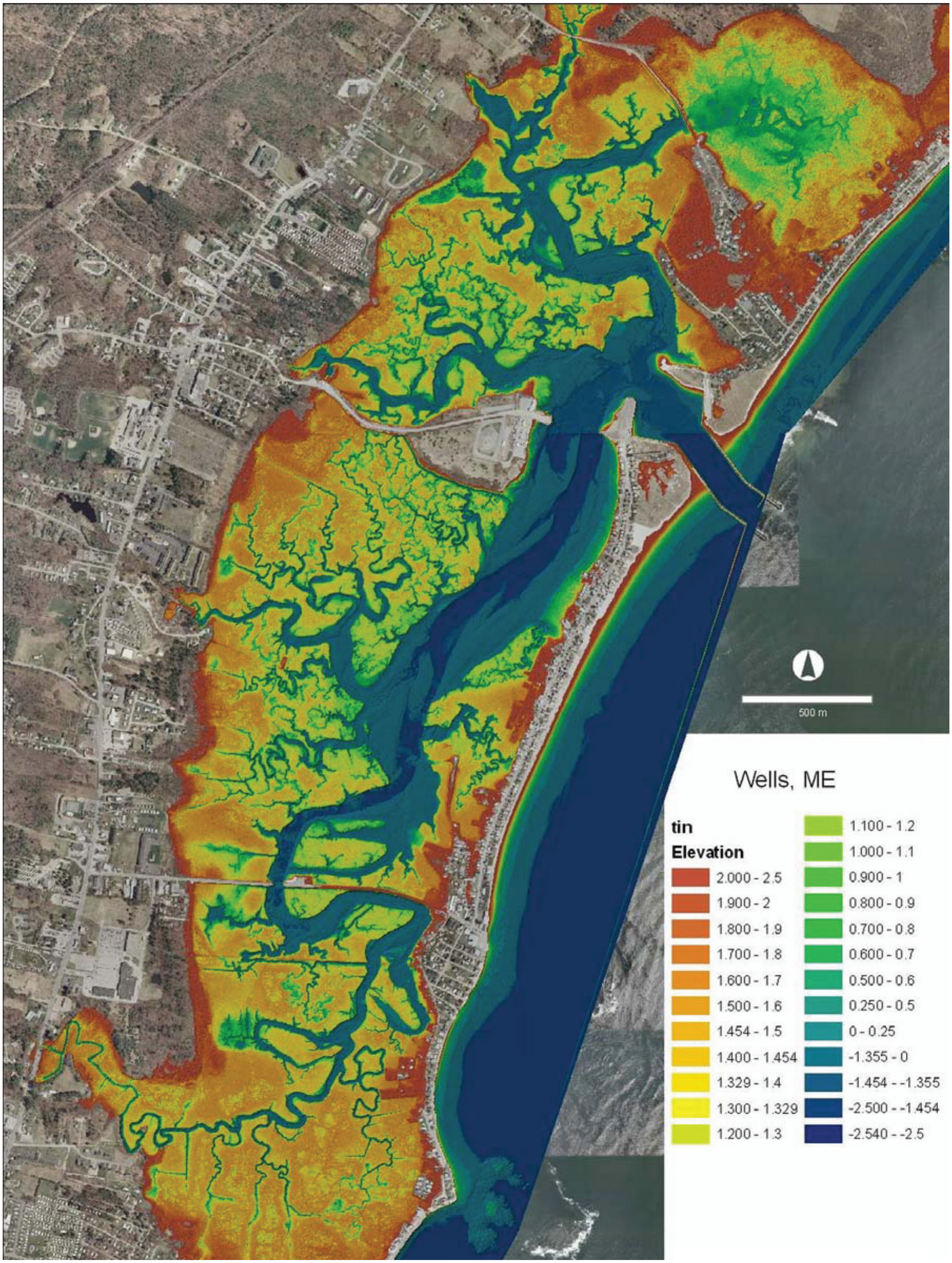


Figure 2-7: Triangulated Irregular Network image of Webhannet marsh elevations made with NOAA LIDAR data (Argow 2006).

Tide channel development on mud and sand flats is primarily controlled by ebb drainage patterns in the major channels, because the current velocities are greater during ebb tide in tidal channels, although flood tidal currents do affect the morphology of the drainage network as well. Tidal channels may meander across sand and mud flats in response to changes in tidal current flow and sedimentation rates. After tidal flats become colonized by vegetation, however, the tidal creeks become more stable and tend to migrate much more slowly through time. Sediment in the tidal creeks and channels of the Webhannet estuary is transported into the back-barrier through the tidal inlet from the Gulf of Maine, and probably represents re-suspended coastal shelf deposits that are in turn re-worked glacial sediments.

Sand (and during storms, gravel) tends to shift back and forth with the tides in sand ripples or waves that resemble low underwater sand dunes, pushed along the channel bed by tidal currents. Smaller particles are moved as suspended sediment with the water. The net movement of sediment, both as suspended flow and as bedload, is towards the estuary head, gradually filling the estuary with sediment over hundreds or thousands of years. This infilling is caused by a phenomena known as 'tidal asymmetry.'

Highest flood-tide velocities occur 3—4 hours after low tide. As the salty, dense ocean water moves into the tidal channels, the fastest velocities occur at the bottom of the water column, scouring sediments from the channel bed and re-suspending fine-grained material, which is then carried farther into the marsh with the rising tide. The imbalance in ebb and flood velocities results in a longer period of low-velocity "slack water" around high tide, and is a function of the time lag between high and low tide at the head of the estuary versus at the inlet. As the flood current begins to propagate through the inlet and back into the far reaches of the estuary through tidal channels, water from the last high tide is still draining off the vegetated marsh surface, and slows the progress of the rising tide.

During the hours of low-velocity currents surrounding high tide, fine sediment can be deposited. The water also mixes with the freshwater influx from rivers, overland flow or groundwater discharge, and becomes less dense.

Figure 2-8: Freshwater streams feed into Wells NERR estuaries. Drawing Robert Shetterly.

As it begins to drain back out of the marsh system, the highest-velocity currents are found at the top of the water column, and flow rapidly becomes concentrated in tidal creeks. It takes between 4—6 hours for maximum ebb-tidal velocities to be reached, and by this time the water level has lowered so that most intertidal areas are already exposed. That means that only the deepest channels are scoured by the outgoing tide, despite the higher velocities and greater net flow (due to freshwater influx). This is why the Little River and Webhannet marsh surfaces are flood-dominated and are an inorganic sediment sink, while larger tidal channels and the inlets are ebb-dominated. Lighter organic matter particles (detritus), however, can be easily moved by even the low-velocity currents of high tide, so the marshes experience net export of organic matter to the adjacent coastal area even though they import sediment.

Rivers and Streams

Each estuary at Wells NERR is fed by freshwater rivers and streams. The Webhannet River enters the Webhannet estuary towards the south end of the Reserve, and the Blacksmith and Depot Brooks enter the estuary north and south of Wells Inlet, respectively. The Little River meanders to the sea from the northwest and ends in the Little River estuary and inlet (rivers and streams are generally the darkest blue channels on Fig. 2-7).

The Little River is formed from the confluence of the Merriland River and Branch Brook. The drainage area of the Little River estuary is the larger of the two, at 30.4 mi^2 (84 km^2), despite the fact that it is a much smaller estuary and has a smaller tidal inlet with the Atlantic

Ocean (27 meters wide). The Webhannet estuary is fed by three rivers, but their combined drainage area, including very small streams entering the estuary, is only 14.1 mi^2 (36.5 km^2). Nevertheless the Webhannet estuary's inlet to the Atlantic, Wells Inlet, is 122 meters wide, over 5 times as wide as the Little River Inlet. This is because the size of an inlet is not a function of the watershed, but rather a function of how large and how open the estuary itself is. The cross-sectional area of a tidal inlet is controlled by the volume of water (known as the tidal prism) that must move in and out of the inlet with each tidal cycle . This is why changes in the morphology of the estuary due to human development or natural vegetative succession can lead to changes in the stability, size and position of a tidal inlet, and to erosion or deposition on the barrier shore around the inlet.

Not all precipitation falling on the uplands is channeled into streams or rivers, and instead travels to the estuary as overland flow (runoff), or infiltrates into the porous glacial sediments and flows to the estuary as groundwater. All surface water, including steams, ponds, freshwater marshes or bogs, is an expression of the intersection of the water table with the surface of the ground, and in Wells NERR it all ultimately flows in response to gravity towards the lowlands and the estuary. The amount of runoff that empties into the estuaries of Wells NERR has been estimated as the equivalent of 51 cm (20 inches) of additional rainfall per year.

Even when we add up all of the freshwater inputs to the Webhannet and Little River estuaries, the volume of freshwater is dwarfed by the amount of salt water moving in and out of the estuaries with each tidal cycle. For example, the annual average discharge of the Webhannet River is 0.6 m per second, or about 1.9 x 10^7 m^3 of freshwater per year. By comparison, the amount of salt water that flows in through Wells Inlet each year is equivalent to 3.5 x 10^9 m^3 of water, which is two orders of magnitude greater than the freshwater input (both fresh and salt water moves out through the inlet with each tidal cycle, of course). The Little River estuary also receives significantly more salt than fresh water. This means that the sedimentary and chemical processes acting in the Webhannet and Little River estuaries are dominated by marine sediment, seawater, and by tidal currents (Mariano and FitzGerald 1989).

Salinity in the Webhannet estuary varies with tide level. At Wells Inlet during 2005, salinity varied between 33.5 psu (practical salinity units) at high tide, a common value for the salinity of seawater in coastal waters along the Gulf of Maine, and ≈ 28 psu at low tide. Near the head of the estuary at Mile Road, salinity is lower (≈ 18 psu) during low tide. This minimum salinity is far greater than the salinity of freshwater. During storms and spring freshets salinity in the estuary drops as freshwater influx increases, then rapidly returns to normal levels. Salinity measurements at the inlet over 2005 had a mean of 30.7 and a mode of 31.7 (Ch. 15, Table 15-1).

Upland

The uplands of Wells NERR are underlain by the metamorphosed siltstones and mudstones of the Kittery Formation, rock that formed from fine-grained sediments laid down in an ancient sea in a region called the Merrimack Trough around 500 million years ago. These sediments were later folded and fused together during a series of continental collisions. Devonian (about 360 million years ago) granites and Triassic (about 65 million years ago) granites also outcrop near the southern end of the Reserve, at Moody Point (Hussey 1989; Ch. 14, Fig. 14-1).

Elevations in the uplands range from the upland / estuarine margin ecosystem found at ≈ 2.2 meters above sea level to open fields and wooded areas at almost 40 meters elevation (orange and red areas on Fig. 2-7). The modern topography of the uplands was shaped by the last glaciation (which ended regionally about 13,500 years ago) littoral erosion during sea-level fall, and fluvial incision to lowstand. The glaciers exposed and shaped the bedrock in some areas of the coast, while depositing large masses of gravel, boulders, sands and clays called "till" in other areas. Drakes Island is an example of such a till deposit. The steep slope backing much of the Webhannet marsh system is a relict feature called an escarpment, carved out during the last glaciation during a short period of slowing in the drop of sea-level around 13,000 years ago. Shorelines created at that time are prominent near the Wells NERR campus.

Upland soils in Wells NERR are developed on the glacial and glaciomarine material that was deposited during and after the last glaciation. These sediments blanketed the pre-existing landscape with a layer of clay and large, often linear mounds of till. This material has developed into a relatively deep, well-drained soil layer rich in mineral material, called a sandy loam. The Reserve uplands exhibit variations of these soil types, but are generally sandy and well-drained, with low water tables. The extremely good hydraulic conductivity of the soils enhances infiltration of rainwater, resulting in less freshwater runoff and fewer streams draining to the lowlands. In relatively low-lying areas near the salt marsh, waterlogged wooded areas have a lacustrine (lake) soil type or are covered by freshwater peats (often found in the yellow regions on Fig. 2-7).

Advances in Geomorphic Research

Modern technology continues to create new opportunities to investigate the complex systems and geomorphic evolution of Wells NERR. Side-scan sonar, single-beam sonar and interferometric sonar are all used to map the bathymetry and reveal the characteristics of the seafloor. SONAR (Sound Navigation And Ranging) works by releasing a pulse of energy which is then reflected back to a receiver by the bottom, a form of echolocation. By measuring the travel time of the pulse, scientists are able to calculate the distance to the bottom at that point. Changes in the energetic qualities of the pulse reflect different properties of the seafloor that can be interpreted as sand, gravel, mud or bedrock. This technology allows us to "see" large sections of the seafloor in great detail.

A similar technology is now used to create very high-resolution maps of topography on land. LIDAR (LIght Detection And Ranging) works on much the same principle as does SONAR. A beam of energy (light) is released from an airplane, which is equipped with sophisticated sensors to detect the reflected energy. The travel time is used to determine distance, while changes in the physics of the light can be used to interpret a number of different properties, such as vegetation type. Currently, LIDAR surveys are being utilized to enhance studies ranging from investigations in vegetative succession to the distribution of sediment from winter storms and ice rafts. The use of LIDAR has facilitated a new level of detail in geomorphologic studies, and will be increasingly useful to scientists working at Wells NERR.

References

Adam, P. 2002. Saltmarshes in a time of change. Environmental Conservation, 29(1): 39-61.

Argow, B.A. 2006. Winter processes of New England salt marshes. Dissertation, Boston University, Boston, MA.

Argow, B.A., and D.M. FitzGerald. 2006. Winter processes on northern salt marshes: evaluating the impact of in-situ peat compaction due to ice loading, Wells, ME. Estuarine Coastal and Shelf Science. 69 (3-4): 360-369.

Bagwell, C.E., and C.R. Lovell. 2000. Persistence of selected *Spartina alterniflora* rhizoplane diazotrophs exposed to natural and manipulated environmental variability. Applied and Environmental Microbiology 66(11): 4625-4633.

Belknap, D.F., Kelley, J.T. and FitzGerald, D.M. 1995. Barriers and inlets of southern Maine - evaluation of sediment budgets and human influences. New England intercollegiate geological conference guidebook to field trips in north-central Maine, 86th Annual Meeting.

Boon, J.D., III, and R.J. Byrne. 1981. On basin hypsometry and the morphodynamic response of coastal inlet systems. Marine Geology 40: 27-48.

Bricker-Urso, S., S.W. Nixon, J.K. Cochran, D.J. Hirschberg, and C. Hunt. 1989. Accretion rates and sediment accumulation in Rhode Island salt marshes. Estuaries 12(4): 300-317.

Byrne, R.J., and J. Zeigler. 1977. Coastal engineering study, Wells Harbor, Maine. U.S. Army Corps of Engineers, New England Division, Waltham, MA. 89 pp.

Callaway, J.C., R.D. DeLaune, and W.H. Patrick. 1997. Sediment accretion rates from four coastal wetlands along the Gulf of Mexico. Journal of Coastal Research 13(1): 181-191.

Church, J.A., J.M. Gregory, P. Huybrechts, M. Kuhn, K. Lambeck, M.T. Nhuan, D. Qin, and P.L. Woodworth. 2001. Changes in Sea Level. *In* Climate Change 2001: The scientific basis, contribution of working group I to the third assessment report of the intergovernmental panel on climate change. *Edited by* Houghton, Y.D.J.T., D.J. Griggs, M. Noguer, P.J. van der Linden and D. Xiaosu. Cambridge University Press. pp. 638-689.

Dickson, S.H. 2003. Coastal Geology. *In* Geological Society of Maine 2004 Short Course: Geology of Maine. Available at http://www.gsmmaine.org/abstracts.html. Acessed 5 January 2006.

Dionne, J.C. 1989. An estimate of shore ice action in a Spartina tidal marsh, St. Lawrence Estuary, Quebec, Canada. Journal of Coastal Research 5(2): 281-293.

Donnelly, J.P., and M.D. Bertness. 2001. Rapid shoreward encroachment of salt marsh cordgrass in response to accelerated sea-level rise. Proceedings of the National Academy of Sciences 98(25): 14218-14223.

Duffy, W., D.F. Belknap, and J.T. Kelley. 1989. Morphology and stratigraphy of small barrier-lagoon systems in Maine. Marine Geology 88: 243-252.

FitzGerald, D.M., and I.V. Buynevich. 2006. Model of tidal inlet and barrier island dynamics in a regime of accelerated sea-level rise. Journal of Coastal Research (Special Issue 39): 789-795.

Foote, A.L., and K.A. Reynolds. 1997. Decomposition of saltmeadow cordgrass (Spartina patens) in Louisiana coastal marshes. Estuaries 20(3): 579-588.

Gabrey, S.W., and A.D. Afton. 2001. Plant community composition and biomass in Gulf Coast chenier plain marshes: responses to winter burning and structural marsh management. Environmental Management 27(2): 281-293.

Gehrels, W.R. 1994. Determining relative sea-level change from salt-marsh foraminifera and plant zones on the coast of Maine, USA. Journal of Coastal Research 10: 990-1009.

Gehrels, W.R. 1999. Middle and late Holocene sea-level changes in eastern Maine reconstructed from foraminiferal saltmarsh stratigraphy and AMS 14C dates on basal peat. Quaternary Research 52: 350-359.

Gehrels, W.R. 2000. Using foraminiferal transfer functions to produce high-resolution sea-level records from salt-marsh deposits, Maine, USA. The Holocene 10: 367-376.

Gehrels, W.R., D.F. Belknap, and J.T. Kelley. 1996. Integrated high-precision analyses of Holocene relative sea-level changes: lessons from the coast of Maine. Geological Society of America Bulletin 108: 1073-1088.

Goodman, J.E., M.E. Wood, and W.R. Gehrels. 2006. A 17-year record of sediment accumulation in the salt marshes of Maine (USA). Marine Geology: *In* press.

Gornitz, V., 1995. Sea-Level Rise - a Review of Recent Past and near-Future Trends. Earth Surface Processes and Landforms, 20(1): 7-20.

Gulf of Maine Ocean Observing System (GoMOOS). Available http://www.gomoos.org. Accessed 15 December 2006.

Hussey, Arthur M., II, 1989 , Geology of southwestern coastal Maine, in Anderson, Walter A., and Borns, Harold W., Jr., *editors*. Neotectonics of Maine: studies in seismicity, crustal warping, and sea level change: Maine Geological Survey (Department of Conservation), Bulletin 40, p. 25-42

Jacobson, H.A. 1988. Historical development of the saltmarsh at Wells, Maine. Earth Surface Processes and Landforms 13: 475-486.

Kelley, J.T. 1987. An inventory of coastal environments and classification of Maine's glaciated shoreline. *In* Glaciated Coasts. *Edited by* FitzGerald, D.M. and P.S. Rosen. Academic Press, San Diego, CA. pp. 151-176.

Kelley, J.T., W.A. Barnhardt, D.F. Belknap, S.M. Dickson, and A.R. Kelley. 1988. The seafloor revealed: the geology of the northwestern Gulf of Maine inner continental shelf. Open File Report 96-6. Maine Geological Survey, Augusta, ME. 55 pp.

Kelley, J.T., W.R. Gehrels, and D.F. Belknap. 1995. Late Holocene relative sea-level rise and the geological development of tidal marshes at Wells, Maine, USA. Journal of Coastal Research 11(1): 136-153.

Kennish, M.J. 2001. Coastal salt marsh systems in the US: A review of anthropogenic impacts. Journal of Coastal Research 17(3): 731-748.

Leonard, L.A. 1997. Controls of sediment transport and deposition in an incised mainland marsh basin, southeastern North Carolina. Wetlands 17(2): 263-274.

Leonard, L.A., A.C. Hine, and M.E. Luther. 1995. Surficial sediment transport and deposition processes in a Juncus roemerianus marsh, west-central Florida. Journal of Coastal Research 11(2): 322-336.

Leonard, L.A., and M.E. Luther. 1995. Flow hydrodynamics in tidal marsh canopies. Limnology and Oceanography 40(8): 1474-1484.

Mariano, C.G., and D.M. FitzGerald. 1989. Sediment transport patterns and hydraulics at Wells inlet, Maine. Boston University, Boston, MA. 143 pp.

Miller, G.T. 1998. Deglaciation of Wells Embayment, Maine: interpretation from seismic and side-scan sonar data. Masters Thesis, University of Maine, Orono, ME. 231 pp.

Ollerhead, J., D. van Proosdij, and R.G.D. Davidson-Arnott. 1999. Ice as a mechanism for contributing sediments to the surface of a macro-tidal saltmarsh, Bay of Fundy. Canadian Coastal Conference: 345-358.

Redfield, A.C. 1972. Development of a New England salt marsh. Ecological Monographs 42: 201-237.

Reed, D.J. 1995. The response of coastal marshes to sea-level rise; survival or submergence. Earth Surface Processes and Landforms 20(1): 39-48.

Reed, D.J. 2002. Sea-level rise and coastal marsh sustainability: geological and ecological factors in the Mississippi delta plain. Geomorphology 48(1-3): 233-243.

Rybczyk, J.M., and D.R. Cahoon. 2002. Estimating the potential for submergence for two wetlands in the Mississippi River Delta. Estuaries 25(5): 985-998.

Timson, B.S., and D. Kale. 1976. Historical changes of the Webhannet River inlet. U.S. Army Corps of Engineers, New England Division.

Titus, J.G. 1990. Greenhouse effect, sea level rise, and barrier islands; case study of Long Beach Island, New Jersey. Coastal Management 18(1): 65-90.

van de Plassche, O., K. van der Borg, and A.F.M. Jong. 1988. Sea level-climate correlation during the past 1400 years. Geology 26(4): 319-322.

Wood, M.E., J.T. Kelley, and D.F. Belknap. 1989. Pattern of sediment accumulation in the tidal marshes of Maine. Estuaries 12: 237-246.