Coastal Bluffs of New England

By Joseph T. Kelley

Introduction

Although its shoreline differs in many ways from that of the mid-Atlantic and southeastern states, New England is part of the United States East Coast passive continental margin. South of New England, the outer coast of the United States is dominated by barrier islands, but bedrock frames all of the coast north of New York City with the exception of Cape Cod and nearby islands. The rocks of this region are all part of the Appalachian Mountains, which formed primarily during several plate collisions in the early-middle Paleozoic Era. North America grew as a consequence of these collisions, and the rocks of the New England coast are a patchwork of exotic terranes derived from a variety of sources. Following the initial formation of the Appalachians, several basins within them filled with sedimentary rocks in the late Paleozoic. The Atlantic Ocean opened up in the early Mesozoic and failed rift basins, filled with sandstones and basaltic volcanic rocks, remain along the coast and offshore from that time. The last igneous rocks formed in the late Mesozoic, and the region has generally undergone erosion since then.

The weathered products of the erosion of the Appalachian Mountains, the coastal plain sediments of the south, are not exposed on the New England coast, and were presumably eroded themselves. It is not a coincidence that the latest agents of erosion, continental glaciers, covered all of New England, and reached only as far south as Long Island, New York. Although the glaciers removed the Coastal Plain material, they left in its place a heterogeneous assemblage of deposits partly mantling the bedrock. Contemporary reworking of these glacial deposits by coastal processes provides materials for the highly variable modern environments of the New England coastal zone.

The irregular shape of the New England coast is mostly due to the structure and differential erosion of its bedrock skeleton. Rocks that have most resisted erosion by glaciers (igneous rocks, quartzites) tend to form peninsulas, islands, and relatively high headlands. More easily eroded rocks (sedimentary rocks and slates/shists) underlie embayments and estuaries. Because these rock types are associated with numerous exotic terranes, and often separated by ancient fault zones, there is great variation in topography and shoreline orientation throughout New England (fig. 1). Despite this overall heterogeneity, the coast may simply be described as a series of bedrock compartments that are internally relatively homogeneous, but distinct from their neighbors (fig. 1).

Extending southwest from the Bay of Fundy, Canada, the cliffed coastline (fig. 1) is framed by fault zones, and is a relatively high-relief shoreline of igneous rocks with few embayments (Kelley, 1987, 1993; Kelley and others, 1989, 1995, 2003). As a result of the high rock cliffs, bluffs of unconsolidated sediment are relatively rare.
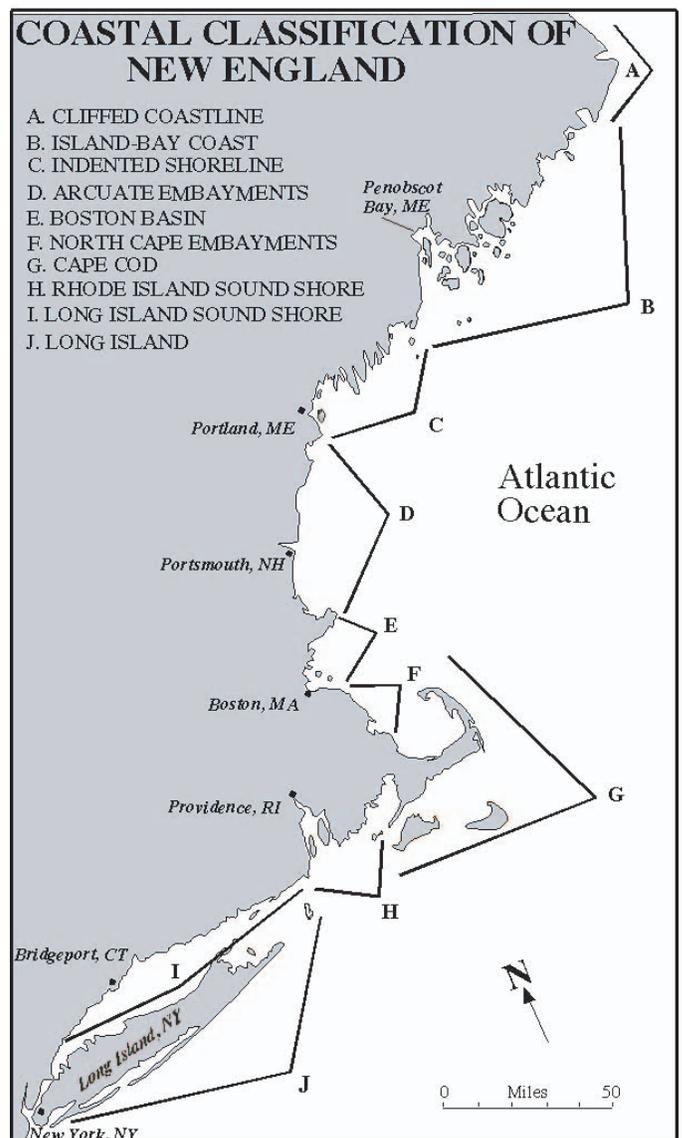
Figure 1. Generalized map of the New England coast, with geomorphic compartments of similar bedrock and glacial materials marked (modified from Kelley, 1987; Kelley and others, 1995).

Where large granitic bodies crop out in central Maine, the island-bay compartment consists of many broad embayments underlain by metamorphic rocks that are protected by granitic islands (figs. 1, 2). South of Penobscot Bay, Maine, layered metamorphic rocks of varying resistance to erosion form a closely spaced series of narrow peninsulas and estuaries (figs. 1, 3). Bluffs of glacial materials are extremely common in the many sheltered coves of these two compartments. Because of the highly irregular nature of this stretch of shoreline, it is approximately as long (4,098 km; Kelley, 1987) as the coastlines of all of the other New England states combined (Ringold and Clark, 1980).

Figure 2. The island-bay coastline at Mount Desert Island, Maine.
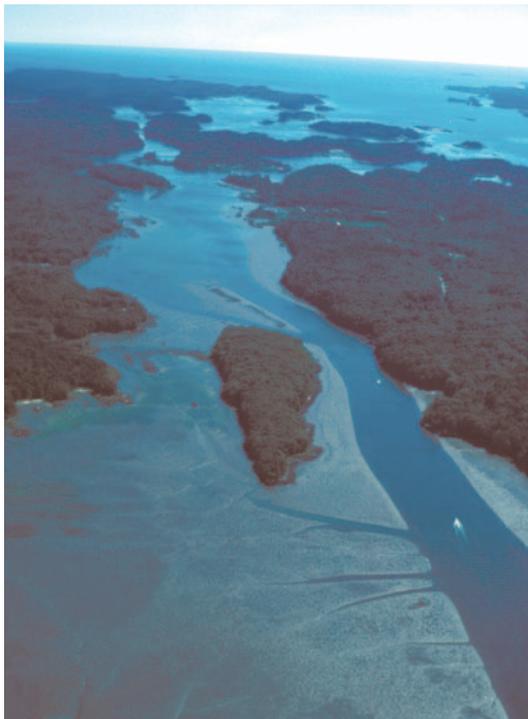
Figure 3. The indented-shoreline coast near Wiscasset, Maine.

South of Portland, Maine, these rocks abruptly change. With the exception of Cape Cod, the rocks from here to Connecticut consist of headlands of low-relief igneous rocks and embayments of more deeply eroded sedimentary and metamorphic rocks. Sand beaches are common in the embayments of this stretch of coast, and straighten the bedrock outline. The Connecticut coast consists of low-lying metamorphic rocks of similar resistance to erosion that, as a consequence, provide a relatively straight shoreline with few large embayments. Cape Cod, Long Island, Block Island, Nantucket, and Marthas Vineyard (and numerous nearby smaller islands) are entirely composed of glacial deposits with no exposed bedrock.

New England has experienced many glaciations during the Pleistocene, but deposits from the last event, the Wisconsinan, dominate the coastline. Long Island (New York), Block Island (Rhode Island), and Nantucket, Marthas Vineyard and Cape Cod (Mass.), along with many smaller nearby islands, are large moraines with outwash plains on their southern sides (Stone and Borns, 1986; Uchupi and others, 2001; fig. 4). The moraines contain boulder- to clay-size sediment and were thrust, or "bulldozed" into place about 21,000 years ago. Some older glacial and nonglacial sediment is included in the moraines (Uchupi and others, 1996; Oldale, 1992). The associated outwash deposits are of low relief except on the eastern and northern shores of Cape Cod. Here, bluffs of fluvial sand and gravel are as great as 50 m high as a result of flow from a glacier into an ice and moraine-dammed lake in present-day Cape Cod Bay (Uchupi and others, 1996, 2001; Oldale, 1992; fig. 5).

Drumlins are common near the coast north of Cape Cod to southern Maine. These features are composed of till of heterogeneous sediment textures and lithologies. In Boston Harbor, a large field of drumlins forms many islands and headlands commonly up to 10 m in height. Erosion of these drumlins has formed many of the large tombolos and spits in this area (fig. 6).

The coastal lowlands north of Boston experienced a marine inundation during deglaciation between about 14,000 and 11,000 years ago (Belknap and others, 1987; Dorion and others, 2001; Stone and Borns, 1986). This resulted from isostatic depression of the land by thick glacial ice. Because of the late-glacial flooding, moraines in this region are often stratified combinations of subaqueous outwash (underwater fans of sand and gravel) and till (fig. 7) (Ashley and others, 1991). Most of the coastal till deposits are relatively low-relief features, less than 5 m in height above sea level (though often extending well below the sea surface). In a few places, large moraines partly block embayments and have significantly controlled the Holocene evolution of the shoreline (fig. 8). Bluffs of glacial-marine muddy sediment occur in association with moraines and are extremely common in the coastal zone north of Portland (fig. 9). These bluffs range up to 15 m high and are most abundant in the protected, inner reaches of embayments (Kelley and Dickson, 2000).

Northern and southern New England experienced differing sea-level histories as a consequence of the differing thick-

Figure 4. Bluff cut into a glacial moraine on Block Island, Rhode Island (photograph by Jon Boothroyd, University of Rhode Island).

Figure 7. Stratified coastal moraine in Kennebunk, Maine.

Figure 5. Highland Light on outer Cape Cod. Eroding bluff is mostly composed of outwash sand and gravel. The lighthouse was moved back from the bluff shortly after this photo was taken (photograph from James Allen, U. S. Geological Survey).

Figure 8. Sprague Neck moraine has eroded for a long time, but still blocks a large part of the entrance of Machias Bay, Maine. Note the 2-km-long beach (left) derived from erosion of the till.

Figure 9. Eroding bluff of glacial-marine sediment, Brunswick, Maine.

Figure 6. Drumlin islands in Boston harbor. Erosion of these till deposits leads to the formation of the associated spits and tombolos.

ness of ice in the two areas. Because Maine was covered by relatively thick ice, it was isostatically depressed and drowned in late glacial times (Dorion and others, 2001). Once the load of the ice was removed, the land rebounded and sea level fell to a lowstand around 60 m below present sea level (Kelley and others, 1992, 2003; Barnhardt and others, 1995, 1997). Sea

level has risen to the present day at an uneven rate, possibly because of delayed isostatic responses (Barnhardt and others, 1995; Balco and others, 1998). Present sea-level rise ranges from 2 to 3 mm/yr in the Gulf of Maine.
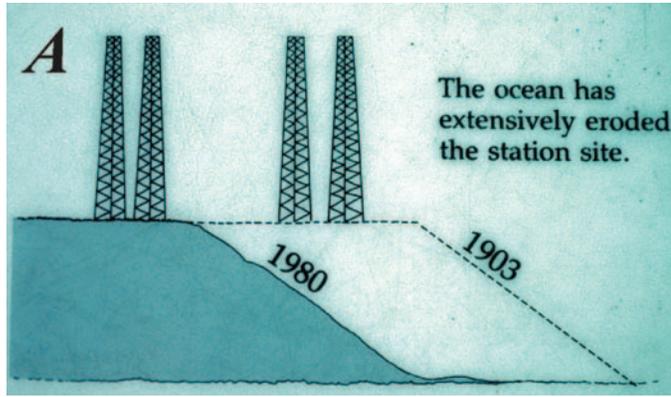
Figure 10. Marconi Station, outer Cape Cod. **A**, A representation of the original Marconi apparatus and its disappearance is shown in this National Park Service diagram. **B**, Eroding bluff of glacial-fluvial sand and gravel at Marconi Station. The most landward part of Marconi's wireless transmitter's foundation (arrow) disappeared in 1993.

In southern New England, the thin ice load did not depress the crust significantly, and the region was isostatically uplifted by the peripheral bulge of material squeezed from beneath areas to the north. Thus, the late-glacial coastal environments were terrestrial, and sea-level rise has occurred more or less continuously since glacial times. Sea-level rise today ranges from 3.0 to 4.0 mm/yr in southern New England, as peripheral bulge collapse augments the worldwide rise of sea level (Emery and Aubrey, 1991; Peltier, 2002).

Bluff Erosion and Failure

Because of its highly irregular outline, varying orientation, differing rates of sea-level rise and heterogeneous collection of glacial materials, New England's bluffed coast erodes at spatially variable rates and through many mechanisms. The most rapid and persistent bluff retreat is caused by high wave energy on the outer coast in the Cape Cod (and nearby islands) region (figs. 5, 10). During storms, waves directly strike the base of the sandy bluffs, and undermine them. The collapsed material forms a beach, but strong longshore currents continuously transport sand away, exposing the bluff to further erosion (fig. 11).

Wave erosion of till deposits is usually a slower process because boulders eroded from the till remain nearby, acting as a seawall and inhibiting further wave impact. Finer constituents of the till are winnowed away, however, and a lag deposit of gravel often marks the retreat of till bluffs (fig. 12). Where sand and fine gravel is abundant within till deposits, large beaches may grow and protect the coast. This is the case in Boston Harbor, where drumlin till is the source of sediment (fig. 6). During thousands of years of sea-level rise, the coast retreats in a stepwise fashion from one glacial sediment source to another (Boyd and others, 1987). For a time, beaches may protect bluffs from wave attack, but when one source of beach material is gone, the next bluff begins to erode.

In sheltered areas bluffs do not experience significant wave energy. Gravity acts on all exposed cliff edges, however,

Figure 11.   Landslide on Block Island, Rhode Island. The large volume of eroded material disappeared soon after the bluff collapse (photograph from Jon Boothroyd, Univ. Rhode Island).
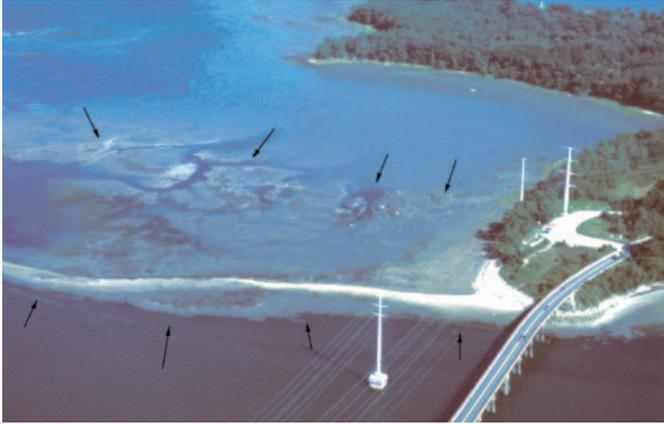
Figure 12. Aerial photo of eroded moraine (surrounded by arrows) in Casco Bay, Maine.

Figure 14. Small gullies on bluff of moraine in Cutler, Maine. This moraine is protected from direct wave attack by a beach of gravel eroded from the till.

and creep of bluff materials leads to slow bluff erosion (fig. 13). Creep is a complex process aided by wetting and drying, as well as freezing and thawing of ground water, in coastal bluffs. Creep is too slow to be observed directly, but the bending of tree trunks as they slide down a slope is a distinct symptom of creep (fig. 13).

Erosion of surface materials by rain or snowmelt is another mechanism causing bluff retreat. When it is the dominant process, rill marks cover a slope (fig. 14). Runoff-induced erosion is abetted by a lack of vegetation. Plants impede downslope water movement and help to dry soils by removing water from the ground. People cut trees and brush to improve views, however, and hiking and bike trails on bluff slopes also aid in the erosion of bluffs by inhibiting plant growth and loosening soil materials.

Ground water is the most important agent influencing bluff erosion where wave action is weak. Seepage of ground water from bluffs occurs through coarse-grained units and at contacts between different materials, especially at the bluff-bedrock contact. Seepage may remove sediment and allow

it to flow down the bluff slope. This is especially important in northern areas where the frozen ground water thaws in the spring and large amounts of water and sediment are released in a brief period of time (fig. 15). Ultimately, ground water reduces sediment strength and is always associated with large-scale mass movements like landslides.

Landslides occur in all glacial materials (figs. 5, 11), but are most common in bluffs of glacial-marine sediment (fig. 16; Kelley and Dickson, 2000). Gravity is the force causing landslides, and they occur largely in materials with at least 5 m of relief (Berry and others, 1996). Gravity is resisted only by friction within the sediment of bluffs. Water reduces the shear strength of sediment and allows gravity to overcome sediment friction, and snow melt during spring or winter thaws has often been implicated as a cause of landslides in Maine's glacial-marine sediment. This material is generally muddy and relatively impermeable, but fractures or sandy beds must exist to allow water to enter the muddy sediment (Berry and others, 1996).

Figure 13. Large block of glacial sand and gravel creeping down the slope of an esker in Prospect, Maine.

Figure 15. Frozen ground water in bluff of glacial-marine mud is thawing and flowing down the face of the bluff in Lubec, Maine.

Figure 16. Landslide in glacial-marine sediment, Rockland, Maine. Two houses were lost when erosion due to the event reached more than 100 m landward from the edge of the bluff in April 1996.

Documenting Coastal Bluff Erosion Rates

The rate of erosion of bluffs in New England is controlled to a large degree by the rate of removal of eroded materials (Sunamura, 1983). These materials may be slump blocks from a large mass movement or sand formed by waves onto a beach. In sheltered areas, salt marshes colonize intertidal mud deposits and landslide debris above mean tide level and inhibit further erosion (fig. 17; Kelley and others, 1989). Thus, the long-term rate of bluff retreat is often the average of short bursts of erosion and long intervals of stability (Sunamura, 1983). Although there are no published studies that have evaluated bluff retreat and storm occurrence, it is reasonable to believe that once a bluff has lost the protection of a salt marsh or beach, retreat occurs during a large storm event.

The best-documented rates of bluff retreat are in Massachusetts, where the State coastal zone management office has measured shoreline positions on historic maps and aerial photographs since the nineteenth century (http://www.appgeo.

com/atlas/project_source/czmcc/ccindex.html). Rates vary from greater than 1.0 m/yr on the outer bluffs on Cape Cod to 0.1 m/yr in sheltered locations.

At six locations in Maine, glacial-marine sediment bluffs were specifically studied by photogrammatic and direct surveying methods (Smith, 1990; Kelley and Dickson, 2000). Rates of erosion averaged 0.5 m/yr between 1985-1988 by direct survey methods and 0.22 m/yr and 0.40 m/yr between 1940-1972 and 1972-1985, respectively, by photogrammatic methods. These are not representative of all Maine bluffs, but were selected partly because of easy access across private property. Prior to a landslide in 1996, which involved 180 m of erosion in one day (fig. 16), the bluffs at Rockland were probably eroding at rates less than 0.5 m/yr (Berry and others, 1996; Kelley and Dickson, 2000). Landslides comparable in size to the Rockland event and involving property are documented in Maine from 1973, 1983, and 1989 (Berry and others, 1996); earlier large events are not well documented.

There are no published descriptions of bluff erosion in New Hampshire, Rhode Island, or Connecticut. New Hampshire's outer coast is largely composed of bedrock and beaches, but small bluffs of glacial sediment similar to those in Maine probably exist in the few estuaries of the State. Eroding till bluffs were probably common in Rhode Island and Connecticut (fig. 18), but human development has protected most bluffs from erosion with seawalls.

Human Occupancy of the Coast and Erosion Hotspots

The 9,847 km of tidally influenced shoreline in New England was the first coastal region in the United States settled by Europeans (Ringold and Clark, 1980). In some areas use of the coast has grown until the present day, but in many of the earliest settlement areas, the intensity of human occupation of the coast has declined since colonial times. Land use in contemporary coastal areas ranges from urban in Boston (Mass.),

Figure 17. Salt marsh deposit protecting a bluff from erosion in Brunswick, Maine.

Figure 18. Eroding bluff of till, Pine Island, Conn. (photograph by Nate Gardner, University of Maine).

Providence (Rhode Island), Bridgeport (Conn.), and Portland (Maine) to largely undeveloped in many locations in eastern Maine (fig. 1). Suburban residential development is probably most common, and is widespread across Connecticut, Rhode Island, and Massachusetts. Even formerly remote regions in central Maine are beginning to experience growing numbers of vacation homes along the coast.

Early settlers apparently shied away from unstable bluffs, although by the 19th century accounts of landslides in glacial-marine sediment were described near Portland, Maine (Bouve and Jackson, 1859; Morse, 1869). By the 20th century, construction of large-scale protective, engineering structures and extensive filling of intertidal areas near cities had removed any erosion hazard from urban areas. Early suburban residents constructed houses near eroding bluffs and began to armor bluffs as the threat to residences increased (fig. 19). For most low-relief bluffs of glacial sediment in sheltered locations, well maintained seawalls are adequate to stop bluff erosion for a hundred years or more. In several locations, however, the scale of the bluffs and consequences of seawall construction have posed larger problems by cutting off sand supply to adjacent beaches.

The outer coasts of Cape Cod, Martha's Vineyard, and Nantucket and Block Islands are especially precarious. Erosion

rates on the order of a meter per year are common, and measurements of erosion have led to the movement of several lighthouses prior to their collapse. Highland Light, constructed in 1797, for example, was recently moved 150 m to lengthen its lifetime (fig. 5). Short-term rates of retreat are even more extreme, and greater than 10 m of retreat has been observed during individual storms (fig. 20; Sunamura, 1983).

In many places bluff erosion directly provides sand for nearby beaches (Duffy and others, 1989). Humarock Beach, in Scituate, Mass., has eroded and lost many buildings since engineering structures were built to stablize nearby drumlins that had acted as sediment sources (Woods Hole Oceanographic Institute Sea Grant, 2001). Nearby in the Plymouth area, the erosion of high bluffs of outwash threatens buildings (fig. 21), but stabilization will eliminate beaches and is generally not allowed under Massachussetts law (J. O'Connell, oral commun., 2002). On Siaconset Beach, eastern Nantucket Island, a costly "dewatering" system was emplaced to induce accumulation of beach sand by waves because stable beaches ultimately protect the bluffs behind them (Allen, 1996).

In Maine, Rockland Harbor has been a landslide erosion hotspot for decades (Berry and others, 1996; Kelley and Dickson, 2000; Kelley and others, 1989). Here 10 m bluffs of glacial-marine mud fail catastrophically from time to time (fig.

Figure 19.   Typical response of homeowner to bluff erosion in Jonesport, Maine. *A*, 1983. *B*, 1985. *C*, 1989. *D*, 1993.

Figure 20. Bluff erosion on the south shore of Cape Cod, Mass. threatened condominiums during the "Halloween Storm" of 1991. The bluff retreated at least a meter at the beginning of the storm, and sand was dumped onto the beach to protect the buildings.

Figure 22. Erosion of glacial-marine mud bluffs in Rockland, Maine, proceeds relentlessly between large landslide events.

16). Even without landslides, the bluffs are retreating through creep (fig. 22). Similar bluffs comprise extensive stretches of the Maine coast. In undeveloped areas there is little concern about bluff retreat. In the suburban areas near Portland, Maine, however, more than 25 km of bluff shoreline is deemed "highly unstable" by the State (Kelley and Dickson, 2000), and valuable properties are now at risk (fig. 23).

Human Responses to Bluff Erosion

The initial response to bluff erosion in most places in New England was to armor the bluff. In urban areas massive engineering structures and artificial fill eliminated the problem of erosion. In areas where bluffs supplied beaches with sediment, there was no early connection made between sediment source and sink. Winthrop, Mass., for example, eliminated the supply

Figure 23. Aerial photo of Cumberland Foreside, Maine, with slowly retreating bluffs and valuable nearby houses.

Figure 21. Bluff of outwash sand and gravel at the White Cliffs area of Plymouth, Mass., have historically eroded at rates between 1m/yr and 2 m/yr (James O'Connell, Woods Hole Sea Grant, oral commun., 2002). The gabion wall was built prior to laws prohibiting such structures to slow shoreline retreat.

of sand to its beaches by the early 20th century and has used seawalls, groins, breakwaters, and replenishment to hold the beach shoreline in place (fig. 24). Because so many beaches in New England are associated with eroding bluffs (Duffy and others, 1989), bluff stabilization may be a major cause of chronic beach erosion and the growing need to replenish beaches (Haddad and Pilkey, 1998). In many residential coastal areas, all of the original eroding bluffs of glacial sediment are armored. In Maine, 20 percent of the 1,250 km of Casco Bay's shoreline is armored (Kelley and Dickson, 2000); an additional 20 percent is bedrock.

Massachusetts has mapped the erosion rate of its entire coastline and placed the data on a web site (Massachusetts Coastal Zone Management, 2002; Theiler and others, 2001). The maps on this site depict shoreline positions from 19th century maps and 20th century aerial photographs (fig. 25). Connecticut is presently mapping the rate of shoreline change along its coast, but no products are yet available from this effort (Ralph Lewis, Connecticut State Geologist, oral commun., 2002). New Hampshire and Rhode Island have no map-

Figure 24. Stabilization of the eroding drumlins in Winthrop, Mass., cut off the supply of sediment to adjacent beaches. Seawalls, groins, and offshore detached segmented breakwaters are needed, along with occasional beach replenishment, to maintain the shoreline position.

ping or other programs in existence regarding bluff erosion (Jon Boothroyd, Rhode Island State Geologist, oral commun., 2002).

The Maine Geological Survey and University of Maine have mapped bluff stability for several years (Kelley and Dickson, 2000) and hope to complete the mapping in 2004. They map (1) presence or absence of a bluff, (2) the relatively

stability of the bluff, (3) the nature of the intertidal zone at the base of the bluff, and (4) the possibility of a landslide at the location (fig. 26). In Maine a permit is required to armor a bluff, and the Natural Resources Protection Act precludes "unreasonably interfering with the natural transfer of soil from the land to the sea," but this has not deterred construction of protective structures on eroding bluffs.
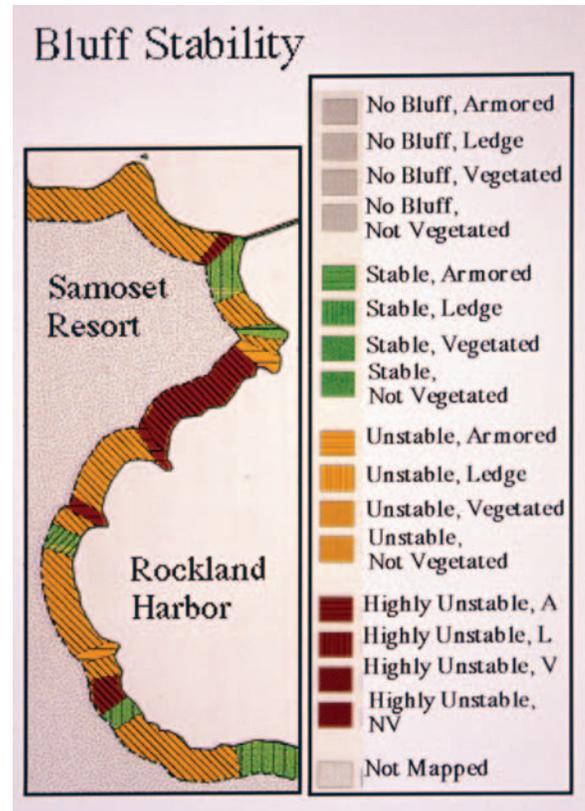
Figure 26. An example of the bluff stability maps produced by the Maine Geological Survey (from Kelley and Dickson, 2000).

Figure 25. An example of the Massachusetts Coastal Zone Management Web site on bluff erosion (Massachusetts Coastal Zone Management, 2002). The lines paralleling the coast represent shoreline positions in the past. Erosion rates were calculated at the location of lines perpendicular to the coast.

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