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The Characteristics that Control the Stability of Eroding Coastal Bluffs in Maine

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THE CHARACTERISTICS THAT CONTROL THE STABILITY OF ERODING COASTAL BLUFFS IN MAINE

By

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Thesis Advisor: Dr. Joseph T. Kelley

An Abstract of the Thesis Presented
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Bluffs of glacigenic sediment exist along 53% of the tidal shoreline of Maine. Under the current regime of rising sea level, waves, groundwater, and subaerial processes easily erode these materials. The hazardous nature of the bluffs is not widely recognized by the public, and new homeowners are often shocked to find out that their property is disappearing. To better educate the public, the Maine Geological Survey is mapping the stability of coastal bluffs. This report utilizes that database along with other available data to determine what controls the relative stability of bluffs.

A geographic information system (GIS) was used to relate the external forcing mechanisms (bluff orientation, exposure, and nature and width of the intertidal zone) and the internal characteristics (degree of human development in the upland, and the surficial geological materials that compose the bluffs) that contribute to erosion of coastal bluffs in the Freeport, ME 7.5' quadrangle.

ACKNOWLEDGEMENTS

Funding for the MGS bluff mapping project was from the Maine State Planning Office and the Maine Coastal Program. The author would like to thank Joe Kelley and Dan Belknap for all of their generosity, guidance, support, and encouragement throughout each stage in the completion of this work. She would also like to thank her committee members, Steve Dickson and Kate Beard, for their helpful comments, and those who helped with bluff mapping duties for the past two summers, Kristie Ferland, Alex Roy, Nate Gardner, Jeny Hall, and Kendra Murray. A special thanks goes to Alice Kelley for her support, encouragement, and friendship, and to Dianne Perro for her patience and assistance with printing parts of this thesis and for her wealth of knowledge concerning administrative policies.

This thesis is dedicated to my parents, Denise and Andrew Keblinsky, to my brother Steve, and sister-in-law Julie, and to my wonderful nephew Sam. I love you all so very much.

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Chapter 1

INTRODUCTION

The coast of Maine is commonly referred to as "rockbound" (Figure 1-1). While this distinction is true for many kilometers of the coastline, there are portions that consist of unconsolidated sediment that was deposited during the retreat of the Late Wisconsinan continental ice sheet (Kelley et al., 1989; Thompson and Borns, 1985). At numerous locations along the coast, these sediments form high bluffs and are subject to erosional processes when they come in contact with the sea (Kelley and Dickson, 2000). Bluffs are also subject to slope failure by blockfalls, slumping, mudflows, and erosion from groundwater seepage and surface water runoff. Often, areas where bluffs are located serve as prime oceanfront real estate as more people move to the coast of Maine each year. There is often a great risk to life and property when residences are constructed on top of bluffs. For example, in April of 1996, two houses along the north shore of Rockland Harbor were destroyed as a steep, 15m-high bluff slumped in a series of discrete landslide events (Berry et al., 1996).

Slope failures have historically occurred at many locations on the coast of Maine (Novak, 1987) in the manner similar to the Rockland event. In addition, slow, but chronic, bluff retreat occurs along many portions of the coast that are not subject to frequent mass-wasting activity. The hazardous nature of bluff retreat is not widely recognized by the public, and new homeowners are often shocked to find that their land is disappearing. Unfortunately, the public does not generally become aware of bluff

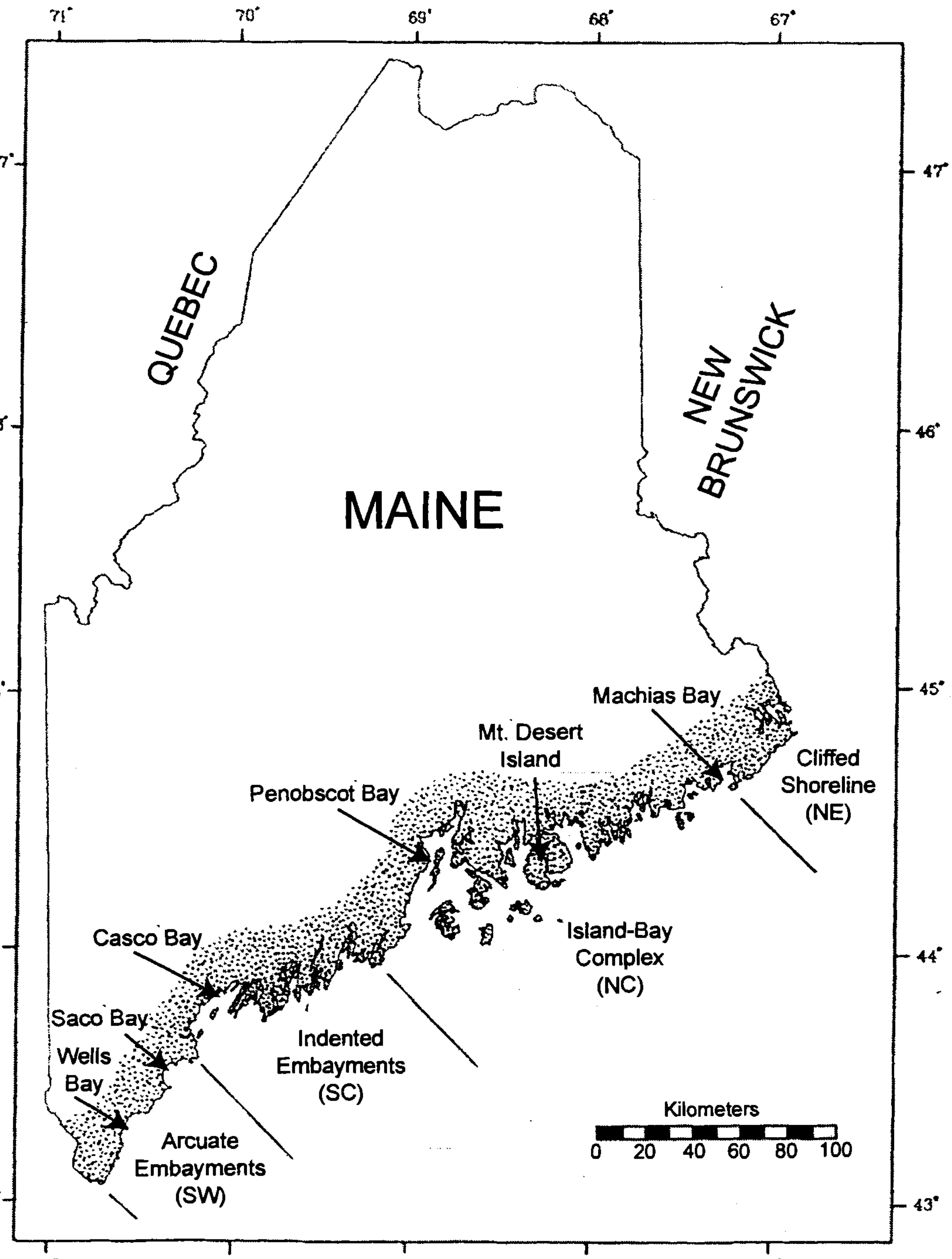


Figure 1-1: Location map of Maine with accompanying coastal geomorphic compartments (modified from Kelley, 1987).

retreat or slope failure unless there is a threat to, or damage of property. At that point, what would otherwise be thought of as a natural process becomes a geologic hazard.

To better educate the public, the Maine Geological Survey (MGS) has created a series of maps that classifies the relative stability of coastal bluffs (highly unstable, unstable, stable, and no bluff) and the intertidal shoreline type (armored, bedrock, salt marsh, and tidal flat/beach) at the bluff toe (Kelley and Dickson, 2000). They are intended to inform a property owner of the risk of developing on top of a coastal bluff. Although bluffs are mapped according to their apparent stability, little is known of the factors that control the retreat rate of bluffs (Amos and Sandford, 1987). At the most general level, it is not known whether bluff-retreat rates are controlled by characteristics internal or external to the bluff. On one hand, bluff retreat may be dependent solely upon the degree of exposure, its orientation, and other external factors. On the other hand, internal factors such as surficial geology and land use may be considered the primary causes of retreat. The principal goal of this work is to evaluate the influence of various internal parameters and external forces on bluff stability in Maine through the use of the MGS maps and a geographical information system (GIS).

Chapter 2

BACKGROUND AND PREVIOUS WORKS

2.1. Deglaciation and Sea-Level Changes in Coastal Maine

Many features of the landscape of coastal Maine and the inner continental shelf of the Gulf of Maine are a result of Wisconsinan glaciation, deglaciation, and accompanying fluctuations in relative sea-level. At the last glacial maximum between 20 and 18 kya, the Laurentide Ice Sheet extended into the Gulf of Maine to Georges Bank. It became a floating ice shelf by 16 ka, and a calving embayment with a tidewater margin by about 15 ka (Hughes et al., 1985, Belknap et al., 1989; Schnitker et al., 2001) (Figure 2-1). By 14 ka, the ice margin was located well inland of the present Maine coastline (Dorion et al., 2001; Stuiver and Borns, 1975). Retelle and Weddle (2001) provide a detailed chronology of deglaciation and sea-level changes based on a number of radiocarbon dates of marine fauna in the Casco Bay Lowland in south-central Maine. They concluded that deglaciation of southern coastal Maine occurred between 14 and 13 kya, accompanied by marine submergence of the isostatically-depressed region. By 12.8 kya, relative sea-level began to drop as isostatic rebound dominated the sea-level signal (Retelle and Weddle, 2001).

The isostatic loading and subsequent unloading, caused by the weight of glacial ice, resulted in large fluctuations of the relative sea level in the area since ~14 kya and have caused major shifts in the shoreline and changes in the location of and processes in sedimentary environments (Belknap et al., 1987; 1989; Barnhardt et al., 1997) (Figure 2-2). Because ice retreated in contact with relatively deep water, the sea transgressed up to the inland marine limit (Figure 2-3) (Thompson and Borns, 1985), allowing

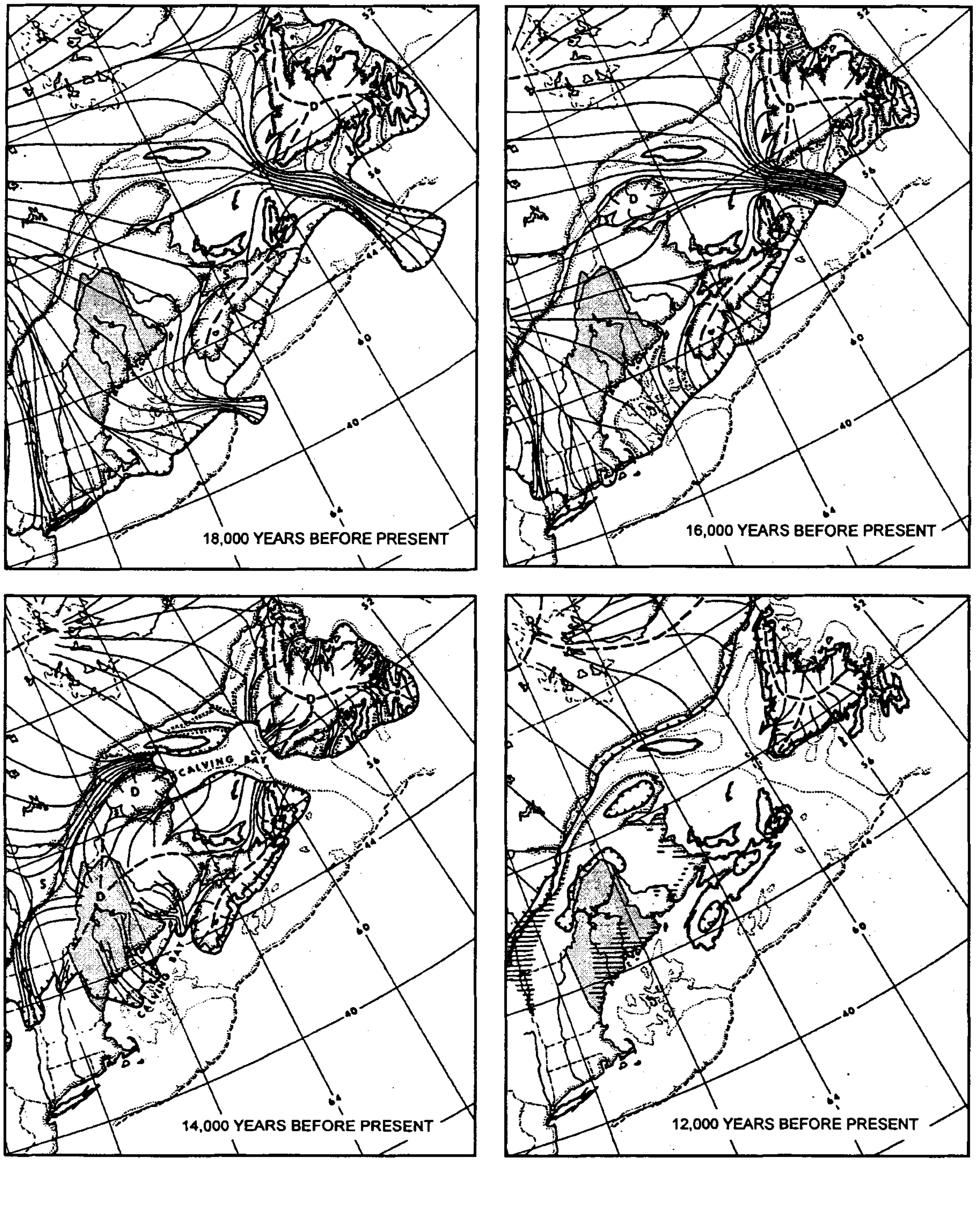


Figure 2-1: Deglaciation of New England and the Canadian Maritimes from 18 kya to the present (modified from Hughes et al., 1985).

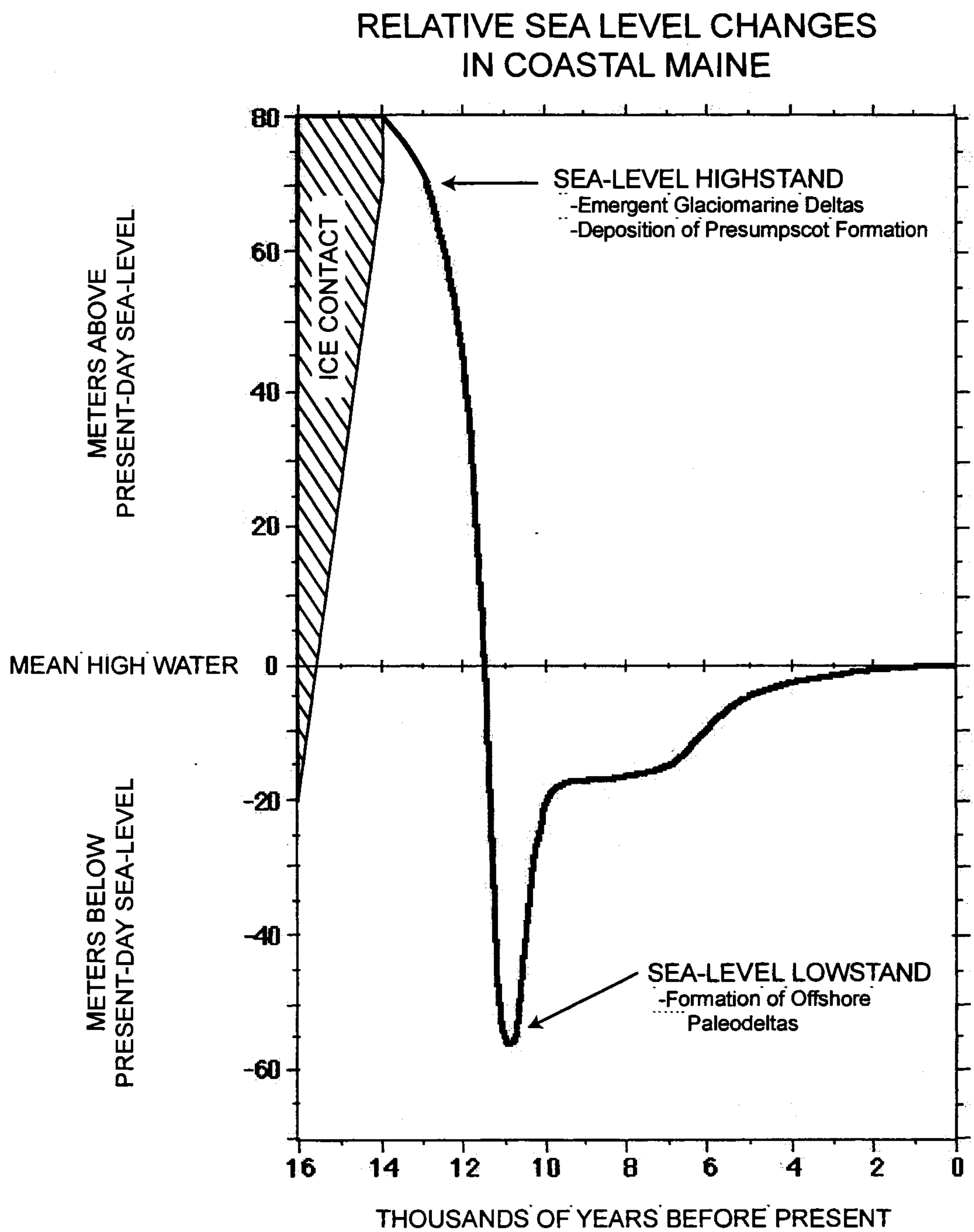


Figure 2-2: Relative sea-level changes in Coastal Maine subsequent to Wisconsinan deglaciation (modified from Barnhardt et al., 1997).

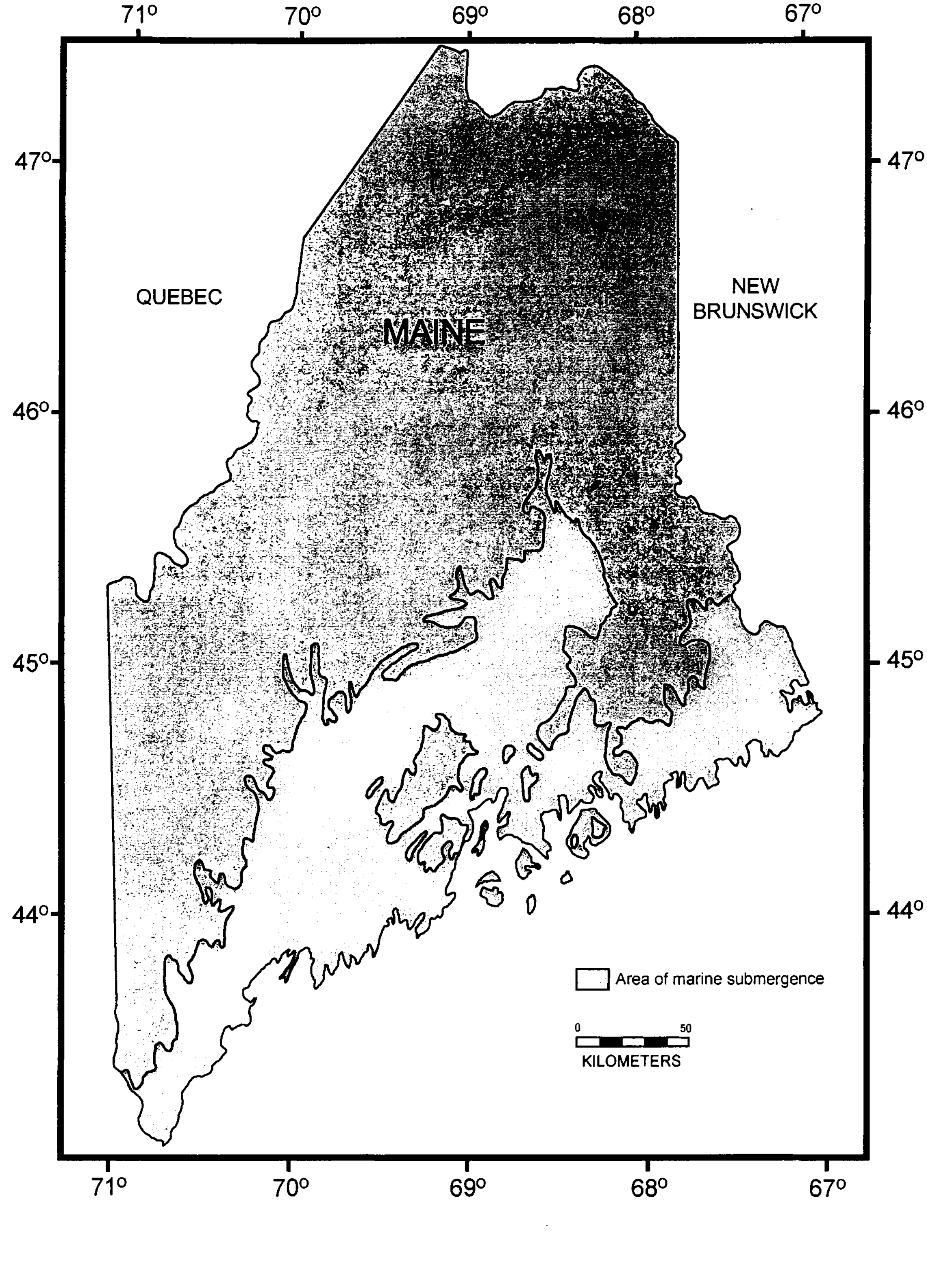


Figure 2-3: Inland marine limit during the sea-level highstand ca. 12.8 kya (modified from Belknap et al., 1989; after Thompson and Borns, 1985).

deposition of a locally thick layer of glaciomarine sediments, formally named the Presumpscot Formation by Bloom (1960) distal from the ice margin in areas now exposed above present sea level.

As a result of rapid rebound from the unloading of glacial ice, the present coastline emerged from the sea between 12 and 11 ka and deposits of the Presumpscot Formation were raised above sea-level (Thompson, 1982). At approximately 10.8 ka, the local relative sea-level dropped to an elevation of about 55m below its current level (Figure 2-2) (Barnhardt et al., 1997). Evidence for this lowstand exists offshore as of submerged shorelines and glaciomarine deltas near the mouths of major rivers such as the Kennebec and Merrimack. After reaching the lowstand, isostatic rebound slowed and eustatic sea-level rise and marine transgression dominated the sea-level record from about 9.2 ka to the present (Barnhardt et al., 1997).

2.2. Maine Coast

2.2.1. Coastal Compartments.

The configuration of Maine's 5564 km-long tidally influenced shoreline (Kelley, 1987) is a result of a complex mix of intrusive, metasedimentary, and metavolcanic rocks that crop out along the coast (Osberg et al., 1985). Four individual coastal compartments are identified based on this variation (Figure 1-1) (Kelley, 1987; Kelley et al., 1989). The southwest (SW), or arcuate embayments compartment extends from the Maine-New Hampshire border to Cape Elizabeth, Maine. It is underlain by northeast-striking metasedimentary rocks with several isolated intrusive bodies that form resistant headlands. These headlands separate arcuate bays with abundant sand

beaches and extensive salt marshes. The south-central (SC), or indented shoreline compartment, is one of northeast-trending peninsulas with intervening deep estuaries in glacially scoured strike-aligned bedrock valleys. It extends for 1627 km from Cape Elizabeth to the western margin of Penobscot Bay. The north-central (NC) compartment, also called the island-bay complex, is the longest compartment on the Maine coast. The total length of this compartment from the western margin of Penobscot Bay to the east of Machias Bay is 2448 km. It is characterized by broad estuaries containing numerous granitic islands. The northeast (NE), or cliffed compartment, is composed of high cliffs of metavolcanic rocks along the Atlantic coast, with a highly indented estuarine region in the Cobscook Bay area. It extends for 677 km from the eastern margin of Machias Bay to the Canadian border.

2.2.2. Indented Embayments Shoreline.

Deep, narrow, elongate estuaries that lie parallel to the strike of bedrock peninsulas characterize the physiography of south-central Maine's Indented Embayments Shoreline. High-grade Ordovician metavolcanic rocks underlie the western portion of the compartment, where the bedrock of the eastern portion is high-grade metasedimentary rock of the same age (Osberg et al., 1985). The bedrock framework in this compartment is the primary control on the orientation of coastal environmental settings. The north-northeast strike (mean azimuth N 55^{O} E) of the elongate peninsulas results in shoreline environments facing WNW and ESE and is probably a result of deep glacial scouring in the pre-existing bedrock valleys (Kelley, 1987). Extensive mudflats and small salt marshes are the principal coastal

environments in this compartment. They result from the erosion of bluffs that supply fine-grained sediment to the flats and provide a substrate for colonization of salt marsh vegetation. In areas where salt marshes exist, bluff erosion rates are reduced due to the dampening effect the vegetation has on incoming waves (Smith, 1990). The marshes themselves, however, can erode as sea level rises and once again lead to increased wave attack at the toe of the bluff. Mudflats and salt marshes comprise 49% and 26%, respectively, of the compartment's tidally influenced shoreline (Kelley, 1987). The smaller rivers entering Casco Bay provide minor amounts of mud to the intertidal zone as they flow through the finer-grained Presumpscot Formation, but are less important than bluffs as a sediment source (Hay, 1988; Kelley et al., 1989).

2.2.3. Estuarine Zonation.

A generalized model for the sedimentary characteristics of Maine's estuaries arose from a number of studies that considered the effects of relative wave energy on coastal environments. In a study of the controls and zonation of geomorphology in Gouldsboro Bay, Maine, Shipp et al. (1987) found that the three controls of coastal geomorphic distribution within an estuary are the underlying bedrock framework, the distribution of glacial sediment, and the present-day coastal processes within the embayment. They also were able to show that Gouldsboro Bay displays three distinct zones of intertidal coastal geomorphology in accordance with the generalized model of Maine's estuaries defined by Dalrymple et al. (1991), Kelley (1987), and Belknap et al. (1986) (Figure 2-4). In the most landward zone (Zone I), contributions of sediment from rivers, where they exist, are the greatest and the exposure to waves is minimal.

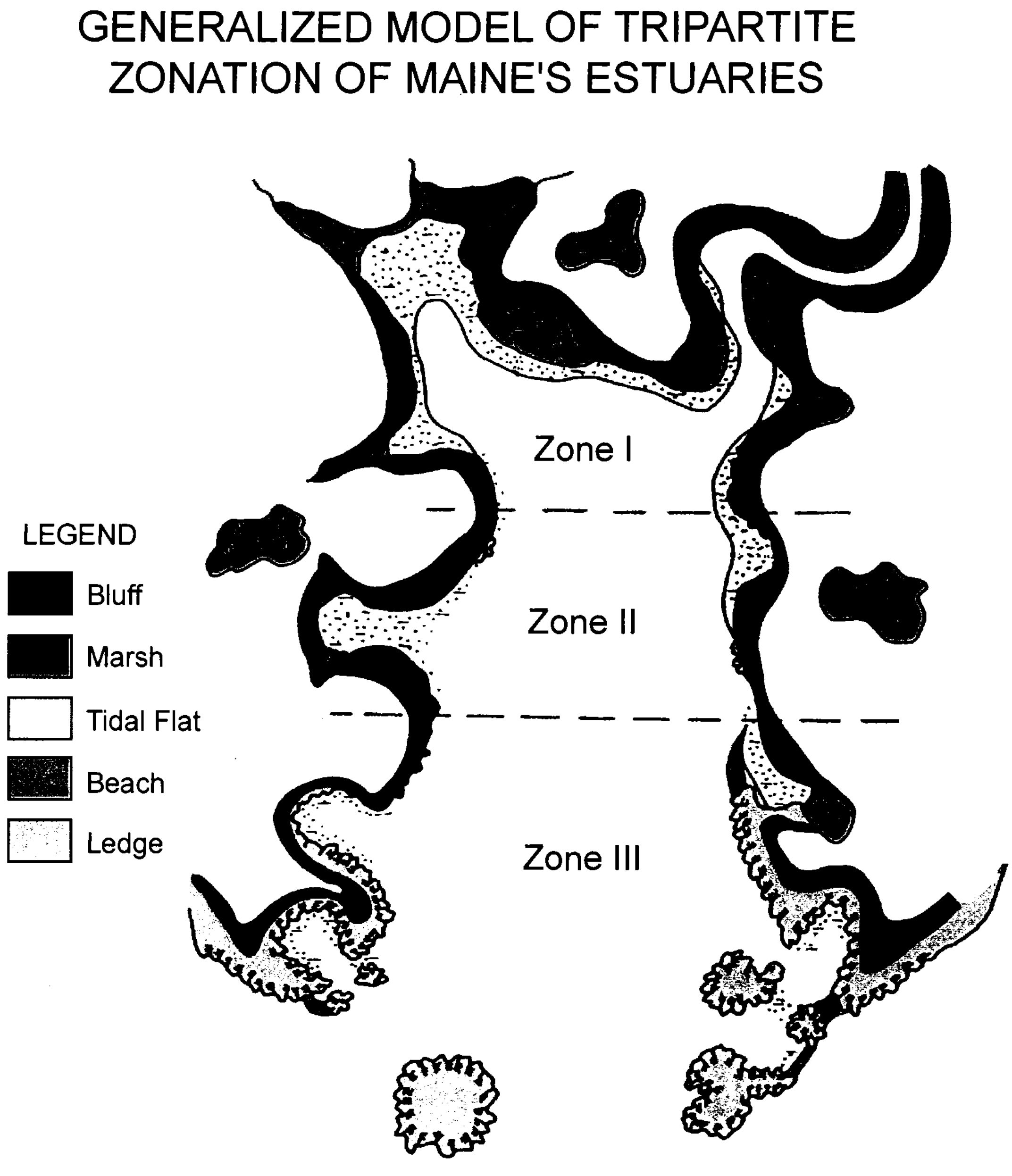


Figure 2-4: Generalized model of tripartite zonation in a representative Maine estuary (modified from Kelley, 1987).

This combination allows sediment to accumulate rapidly and permits the establishment of wide salt marshes. Wave exposure is greater in the central portion (Zone II) of the estuary. Here, episodic bluff erosion provides most of the sediment to the extensive tidal flats of mud or of mixed texture that dominate in the intertidal zone. The exposure of bedrock outcrops and small pocket beaches are the most abundant geomorphic environments in the seaward portion of the estuary (Zone III). Here, wave energy is the most intense, and all but the coarsest sediment has been stripped away.

2.3 Bluff Erosion Studies

2.3.1. In Maine.

In 1983, a landslide in Gorham, ME raised public awareness of land failures within the state (Novak, 1987). Subsequently, a proposal was submitted to the United States Geological Survey (USGS) with three major goals: 1) to develop a more extensive survey of literature describing Maine landslides, 2) to provide an inventory of landslides within the state by means of a questionnaire that was distributed to the public, and 3) to acquire geotechnical data of landslides that occurred in the Presumpscot Formation (Novak, 1987). Novak (1987) provided the information required for the first two goals. The report generated from the results of the questionnaire concluded that the most dominant slide types were earth flows/soil flows (36%) and slumps (28%). The report also concluded that the principal material involved in the landslides was glacial-marine mud.

The third goal of the USGS proposal was fulfilled by Amos and Sandford (1987). Their report included geotechnical information about two specific slides that

occurred in the Presumpscot Formation. The first slide was a relatively small rotational slide that occurred along the coast, and the second was an extensive retrogressive slide that occurred inland, adjacent to a small river (the Gorham, ME slide mentioned previously). The intent of their study was to develop "predictive indicators of imminent sliding." Through field investigations, field mapping, field and laboratory testing, and data analysis, they concluded that 1) the rotational slide occurred in a thick deposit of the Presumpscot Formation and was caused by oversteepening from wave erosion at the toe of the bluff, and 2) low shear strength caused by high pore pressure, and a high water content in the clay were the primary factors that caused the inland retrogressive slide.

In his M.S. thesis, Hay (1988) applied the cycle of bluff erosion as a function of rising sea-level developed by Kelley and Hay (1986) to the Casco Bay area and provided specific locations as examples for each stage (Figure 2-5). The first stage (A) shows a steep, unvegetated face of a glaciomarine bluff whose toe is undergoing active marine erosion during mean high water. Second, (B) the oversteepening of the face leads to a bluff failure in the manner of a rotational slump. The next stage (C) involves the colonization by *Spartina alterniflora* of the landslide debris as it is inundated during high tide. In the fourth stage (D), the marsh reaches maturity as *Spartina patens* flourishes and the bluff exhibits a period of stability. With continued sea-level rise, the fringing marsh is eroded (E) by wave and tidal action until the toe of the bluff is again subject to marine erosive processes and susceptible to failure (Hay, 1988). The time frame for each of these stages is unknown, but is presumed to be on the order of decades to centuries (Kelley, pers. comm.).

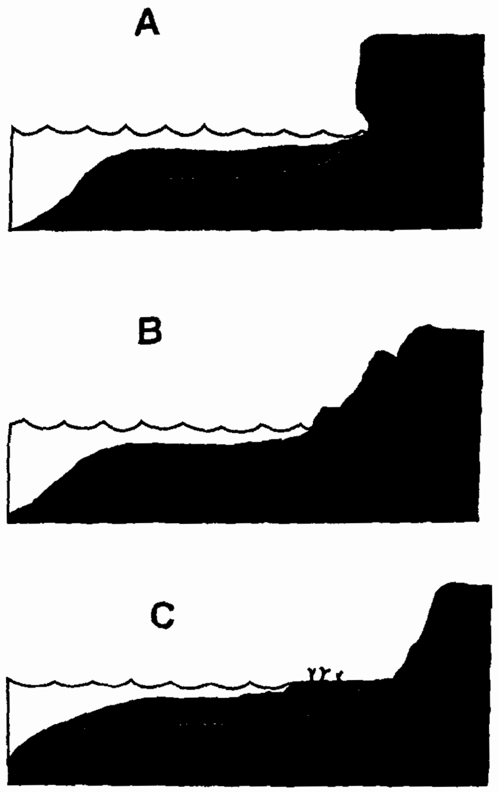


Figure 2-5: Stages of bluff erosion and development of a fringing marsh. See text for a description of each stage (modified from Kelley and Hay, 1986).

Smith (1990) examined the characteristics of eroding bluffs in three Maine embayments and developed a model that divides and embayment into inner, middle and outer zones based on sedimentary environments, energy conditions, and dominant processes occurring within each zone (Smith, 1990). She found that the zonation of each embayment is dependent upon the bedrock framework, type and abundance of glacial deposits, and relative energy conditions within the embayment in terms of the degree of exposure to incoming waves (Smith, 1990).

Kelley and Dickson (2000) introduced a series of maps published by the Maine Geological Survey with a 1:24000 scale that establish where eroding bluffs are located along the coast and inform property owners of their relative stability. The nature of the intertidal zone directly seaward of the bluff and the relative stability of the bluff were the two main variables mapped. These maps are the primary topic of examination in this work and are discussed in greater depth later.

2.3.2. Outside Maine.

Many studies of coastal bluff erosion outside Maine focus on bedrock cliffs as well as bluffs of unconsolidated sediment. It is important to realize that many of the same processes act upon both types of materials, but at different rates. Therefore, studies that focus on rock cliffs may be applicable to bluffs.

In a study of sea-cliff processes and classification along a portion of the California coast, Emery and Kuhn (1982) found that varying combinations of marine and subaerial erosion, along with the degree of homogeneity of materials that are eroded, shape the profiles of sea cliffs. They also determined that sea cliffs undergo

three main stages: (1) active cliffs are continuously retreating under the influence of marine and subaerial erosion; (2) inactive cliffs have talus slopes at their bases that commonly support vegetation; and (3) former cliffs are removed from the influences of marine processes, and subaerial processes now dominate (Figure 2-6) (Emery and Kuhn, 1982).

Sunamura (1983) stated that marine erosion at the toe of a cliff is essential for continual cliff retreat to occur and that cliff recession is an intermittent and localized process (Figure 2-7). The average retreat rate of cliffs or bluffs may appear slow, as represented by the straight line in the figure. This behavior, however, is rarely seen. Instead, the actual retreat occurs in a series of specific erosion events, either a landslide, or the movement of a small block over a short period of time. Until wave or tidal action clears the debris that results from the event, there is little retreat of the bluff and a period of stability is observed.

In a study of the geological factors that control bluff recession rates along the Lake Erie shoreline in Ohio, Mackey and Haines (1998) found that long-term recession rates are controlled by shoreline orientation, bluff composition, and the elevation of bedrock with respect to lake level. Because the prevailing winds in their study area are from the southwest, erosion is enhanced on those bluffs facing west. Bluffs composed of glacial-lacustrine sediment exhibit the greatest long-term recession rates, followed by glacial diamicts and bedrock. Mackey and Haines (1998) also found that short-term recession rates (superimposed upon the long-term rates) are controlled by changes in beach width at the toe of the bluff, intensity and direction of individual storms, precipitation, and changes in lake-level.

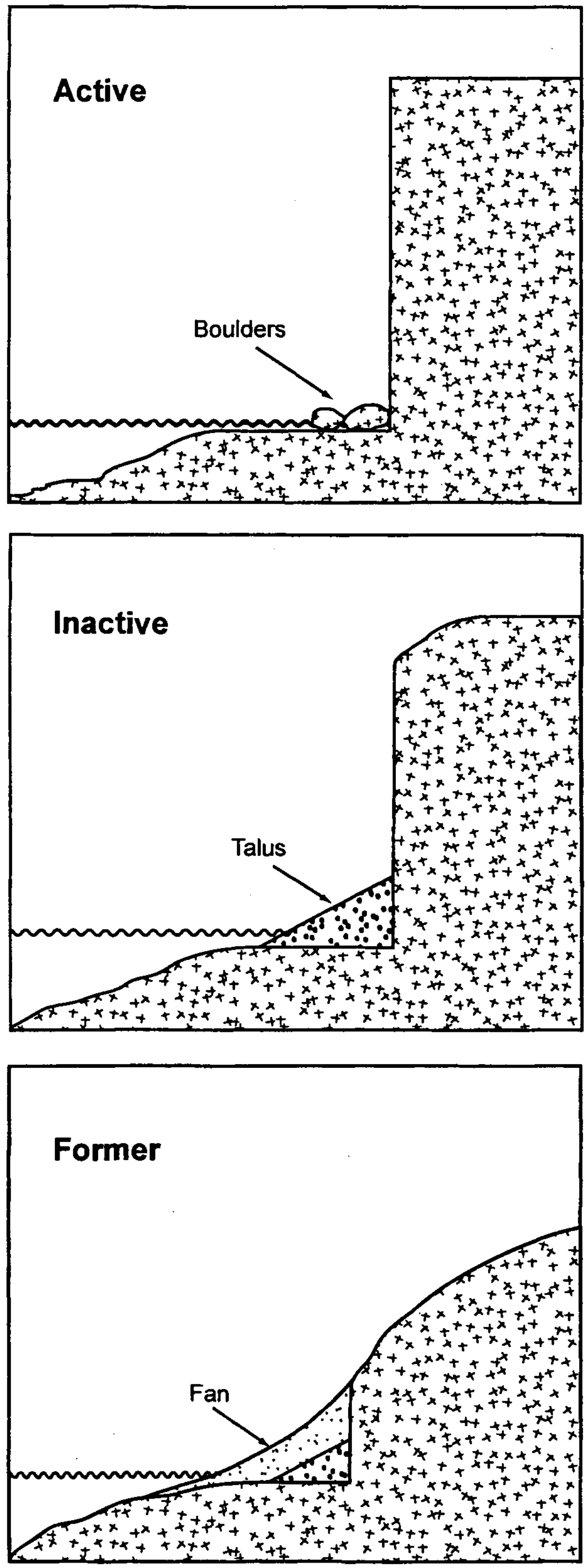


Figure 2-6: Idealized stages in the geological history of a sea cliff (modified from Emery and Kuhn, 1982).

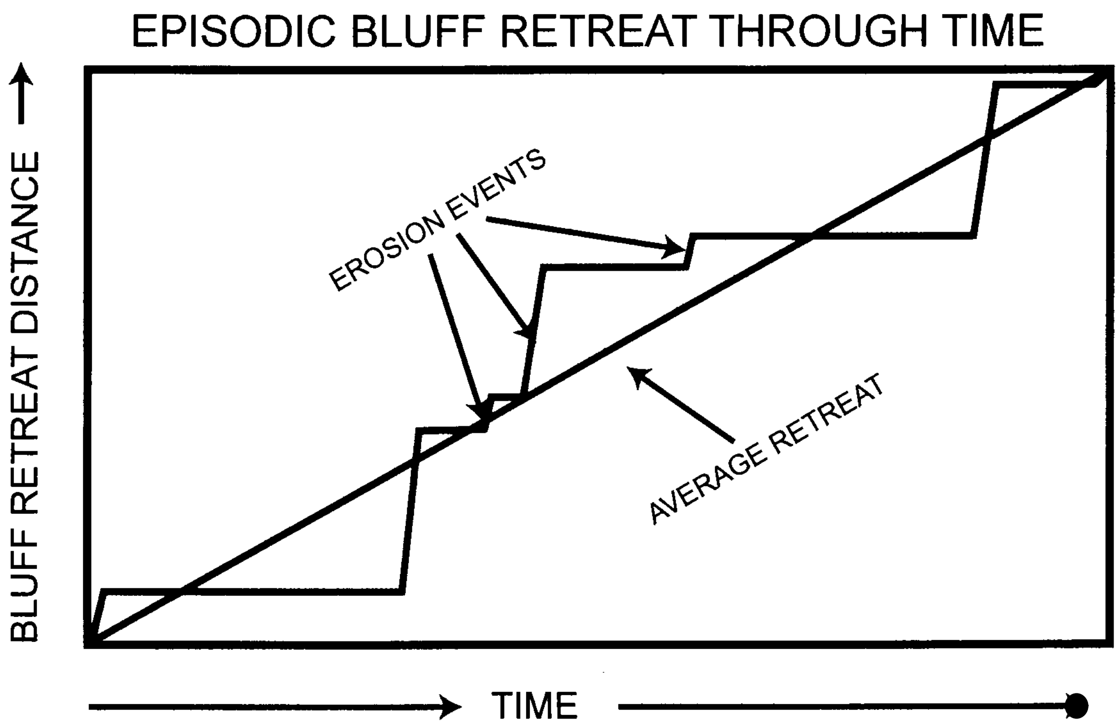


Figure 2-7: Schematic representation of episodic bluff retreat through time (modified from Sunamura, 1983).

Other studies relating to the processes effecting erosion of sea-cliffs and bluffs exist for the Great Lakes (Dawson and Evans, 2001; Bryan and Price, 1980; Carter and Guy, 1988), Cape Cod, MA (Geise and Aubrey, 1987), California (Kuhn and Shepard, 1983; Everts, 1991; Kuhn and Osbourne, 1987; Thornton et al., 1987), Oregon (Komar and Shih, 1991; Shih and Komar, 1994), and Northern Ireland (McGreal, 1979a; 1979b). Because sea-cliffs and bluffs occur along ~80% of the ocean coasts of the Earth (Emery and Kuhn, 1982), in addition to those occurring along the shores of large lakes, there are a large number of studies relating to the processes affecting erosion of cliffs and bluffs, but to list them all here is beyond the scope of this work. Two excellent summaries are Trenhaile (1987) and Sunamura (1992).

2.4. Erosion of Bluffs by Subsurface Water

Erosion of bluffs by subsurface water, both above the water table and below, occurs in several ways. Spring sapping is a process in which the flow of water that emerges on the bluff face undermines portions of the bluff, mechanically loosening sediments and causing intermittent landsliding or gullying of the bluff face. Similarly, piping occurs when water from rain, irrigation, or septic tanks penetrates into interstices in unconsolidated sediment, animal burrows, dessication cracks, or channels left by decayed tree roots. These natural drains may enlarge, lengthen, and coalesce and significantly contribute to the erosion of the bluff face (Norris, 1990).

When natural forest cover is removed and replaced with lawns, parks, sports fields, and pastures that commonly accompany an increase in suburban or agricultural development, the amount of precipitation that infiltrates into the subsurface may increase and lead to an acceleration of erosive processes on the bluff face. In a study of

the environmental performance of land cover types for urban planning in Munich, Germany, Pauleit and Duhme (2000) found that out of 950 mm of annual precipitation, 21.4% contributed to infiltration in natural wooded areas. That percentage rises to 34.3%, 39.0%, and 43.9% when woodlands are replaced with grasslands, arable fields, and construction sites, respectively (Pauleit and Duhme, 2000). The effects of watering lawns and gardens adds the equivalent of 1800 to 2000 mm/yr of precipitation for incorporation into the subsurface water system in communities on the California coast (Norris, 1990). In addition, coastal communities are commonly not on sewer lines, and considerable quantities of wastewater are disposed of in septic tank systems. Up to 3000 l/day of wastewater per residence may be discharged into the subsurface, contributing to accelerated bluff erosion (Norris, 1990; Lahousse and Pierre, 2003).

In Maine, rates of groundwater recharge for the major types of surficial geologic materials were determined by Gerber and Hebson (1996). In areas overlain by sand and gravel, surface water runoff and subsurface flow are insignificant, and 50-60% of the average annual precipitation is incorporated into groundwater aquifers. On the other hand, areas overlain by till and glaciomarine mud is dominated by surface runoff and subsurface flow (Figure 2-8) and precipitation is less likely to be available for groundwater recharge. Subsurface flow and surface runoff in till and glaciomarine mud accounts for about 27-40% and 60% of the average annual precipitation, respectively (Gerber and Hebson 1996).

Figure 2-8: Evidence of subsurface water flow in a highly unstable bluff composed of Presumpscot Formation. Alternating dark and light color layers show a difference in water content accociated with differences in grain size. Bunganuc Bluff, Brunswick.

Chapter 3

PHYSICAL SETTING

3.1. Location.

The Freeport, Maine 7.5' Quadrangle (Figure 3-1) was selected as a study site for several reasons: 1) the stability of the bluffs in this area have been mapped (Bryant et al., 1998); 2) it contains a variety of orientations, surficial-material types and bluff-stability types; 3) Smith (1990) and Novak (1987) worked here and developed a database of bluff-retreat rates and historic landslides; and 4) digital data sets for many different parameters exist for this area and are easily obtainable for use in a geographical information system (GIS).

3.2. Climate.

The humid, north temperate climate of coastal Maine has an average annual temperature of 7^{o} C and an average precipitation of 112 cm (Lautzenheiser, 1974). The prevailing winds in the summer come from the southwest and are relatively light. In the winter, the winds are generally from the northeast (Belknap et al., 1988; Fefer and Schettig, 1980). Historical wind speed data from the NOAA Portland Buoy 44007 show that average sustained winds range from 15-25 km/hr for the period from February 1982 to December 1993 with the highest sustained wind speed of 89 km/hr (NOAA, 2002). Tropical storms and hurricanes are rare. Winter storms produce the strongest seasonal winds, typically out of the northeast during the passage of an offshore low pressure system (Davis and Dolan 1993; Heinze 2001). These winds,

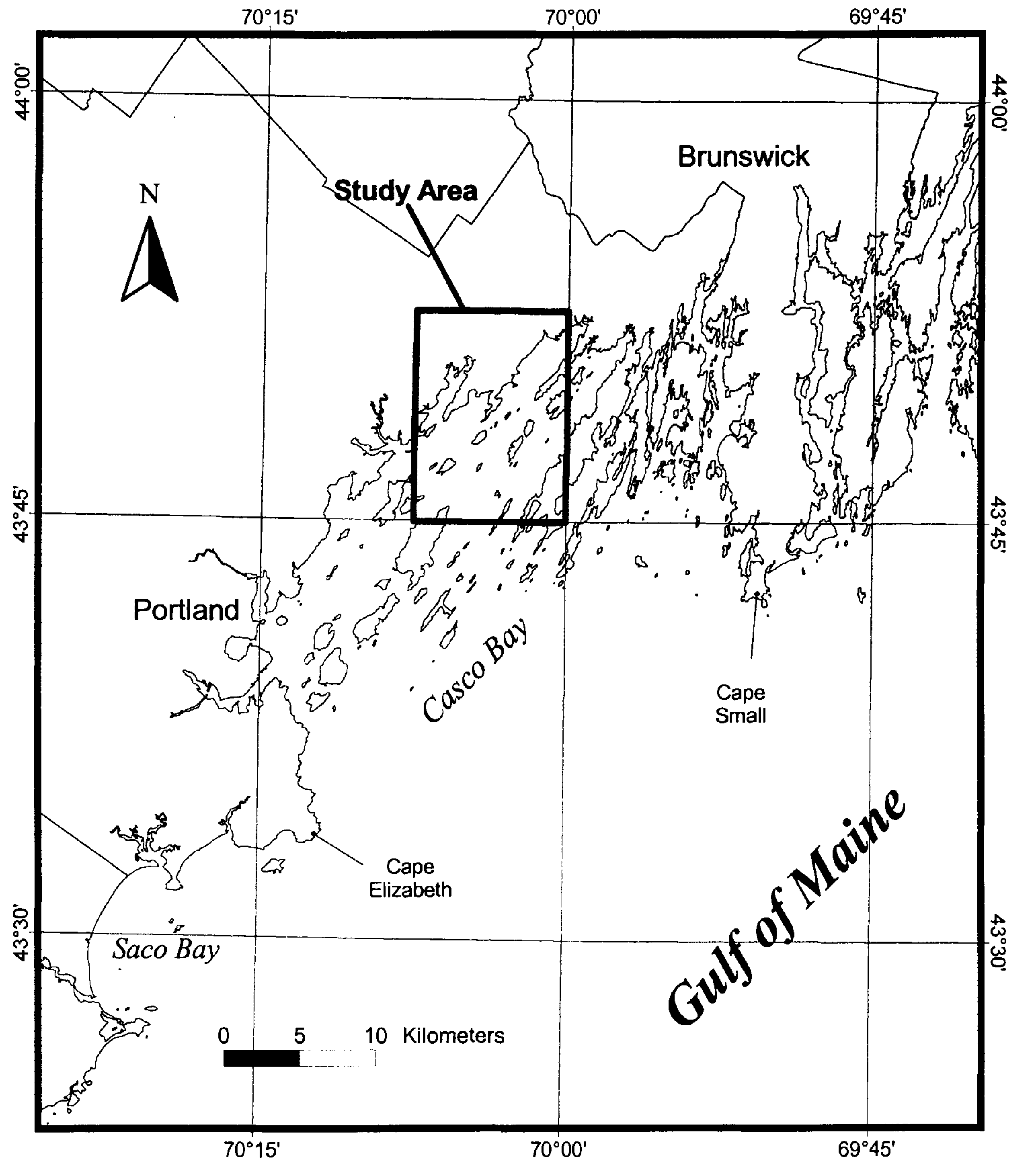


Figure 3-1: Location map of study area. Freeport, ME 7.5' Quadrangle.

greater than 100 km/hr, have the greatest potential for creating large, destructive waves (NOAA, 2002; Barnhardt, 1992; Dolan and Davis, 1992).

3.3. Bedrock Geology.

The study area is underlain by a complex sequence of metasedimentary and metavolcanic rocks of Precambrian to Silurian age (Osberg et al., 1985; Hussey, 1981). These rocks primarily include the Casco Bay Group of Precambrian to Ordovician age and minor exposures of the Vassalboro Formation of Late Ordovician to Silurian age. The Casco Bay Group was regionally metamorphosed and deformed during the Acadian Orogeny of Early Devonian time and possibly by a previous Early Ordovician event (Hussey, 1981). The portion of the Casco Bay Group observed in the study area includes the Cushing Formation, Cape Elizabeth Formation, Scarboro Formation, Spurwink Limestone, and Jewell Formation (Hussey, 1981, Osberg et al., 1985).

3.4. Surficial Geology.

Till and thin glacial drift, though patchy in their distribution, represent the base of the Quaternary section. The fine-grained glaciomarine mud of the Presumpscot Formation overlies till or bedrock and is the thickest and most dominant surficial deposit in the region (Figure 3-2) (Thompson and Borns, 1985, Weddle 1999a). The Presumpscot Formation is composed primarily of silt, clay, and minor amounts of sand and gravel. It commonly crops out along the Casco Bay shoreline as high bluffs and is thus subject to erosion by marine and subaerial processes.

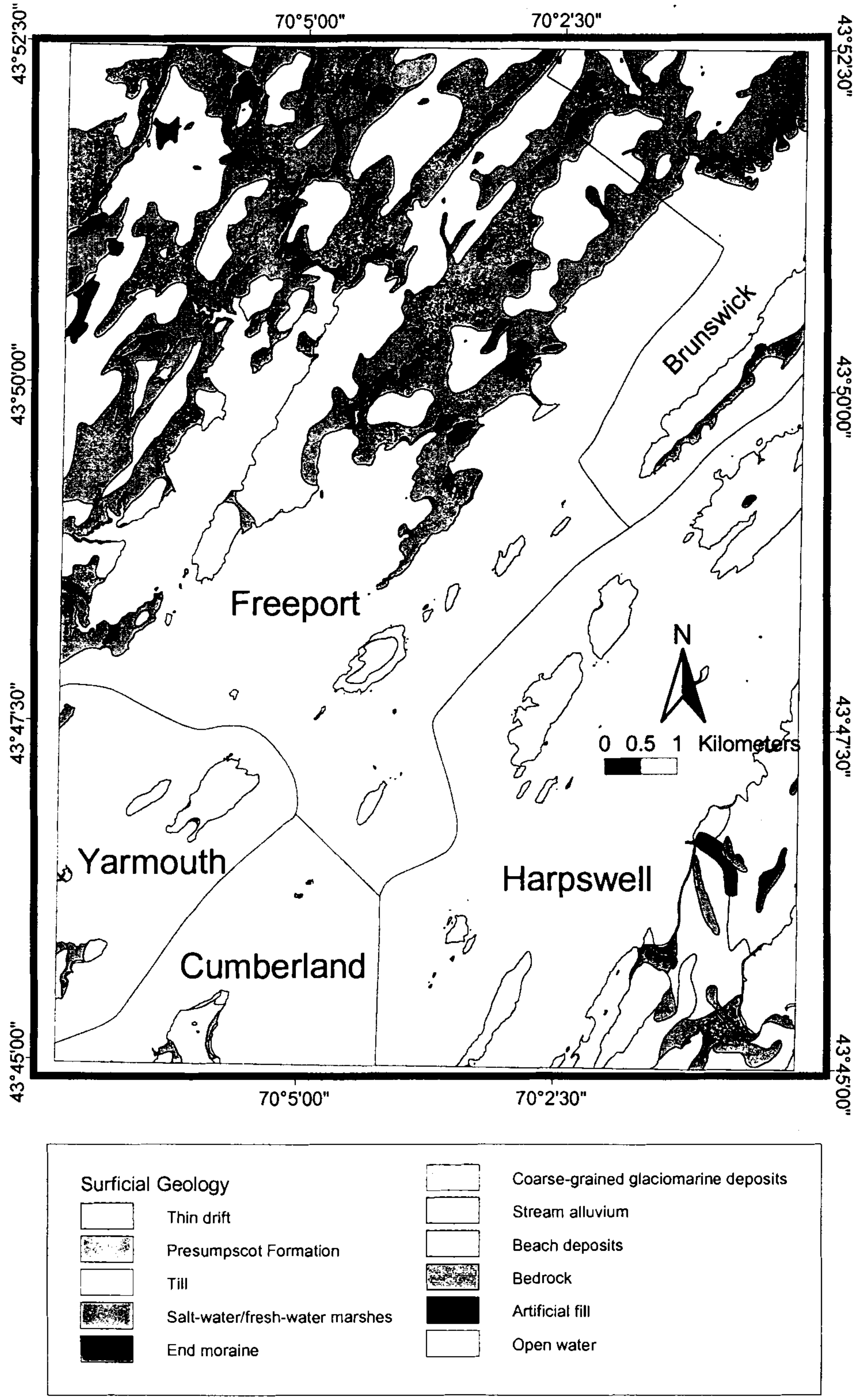


Figure 3-3: Surficial geology of the Freeport, ME 7.5' quadrangle (modified from Weddle, 1999b; data courtesy of the Maine Geological Survey).

3.5. Intertidal Environments.

The predominant intertidal environment in the study area is mudflat, with minor amounts of gravel flats, beach deposits, and salt marshes (Figure 3-3). There are also numerous rocky outcrops scattered throughout the region. The mudflats are characterized by low-relief deposits of sand, silt, and clay deposited by tidal currents and are highly valued for their populations of the soft shell clam *Mya arenaria* (Timson, 1983). Gravel flats are composed of coarser-grained sediments and occur along shorelines that are exposed to greater tidal and wave energies than finer-grained flats (Timson, 1983). Beaches can occur as sand, mixed sand and gravel, or gravel deposits that are exposed to higher wave energies and are only partially submerged at mean high water. Salt marsh environments consist of peat, mud, or sand flats that are densely overgrown with salt-tolerant vegetation such as *Spartina alterniflora* between mean low water and mean high water, and *Spartina patens* situated at or slightly above mean high water (Timson 1983). They commonly occur along the mouths of rivers or streams in sheltered estuaries.

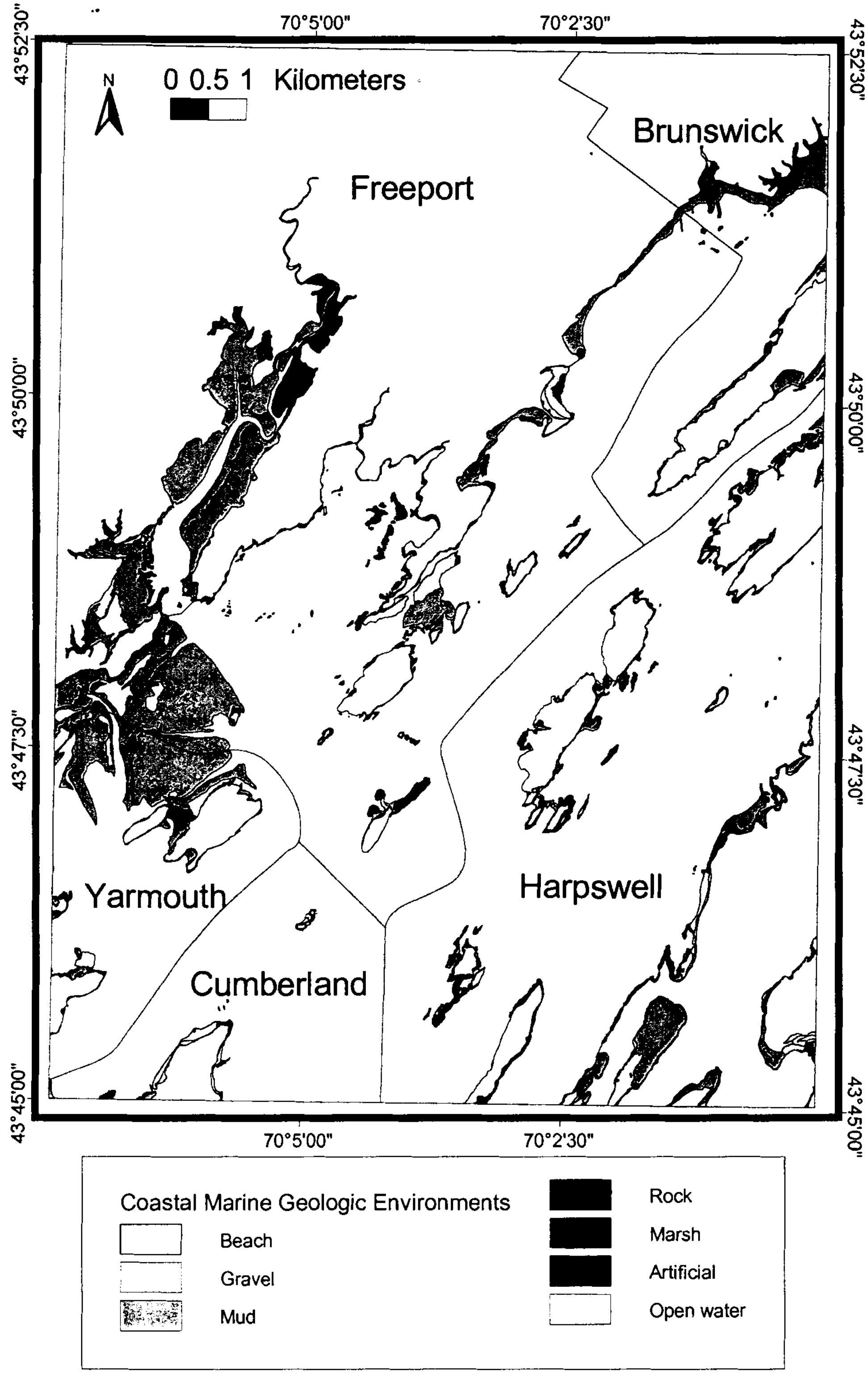


Figure 3-4: Coastal marine geologic environments for the Freeport, ME 7.5' Quadrangle (modified from Timson, 1976; data courtesy of the Maine Geological Survey).

Chapter 4

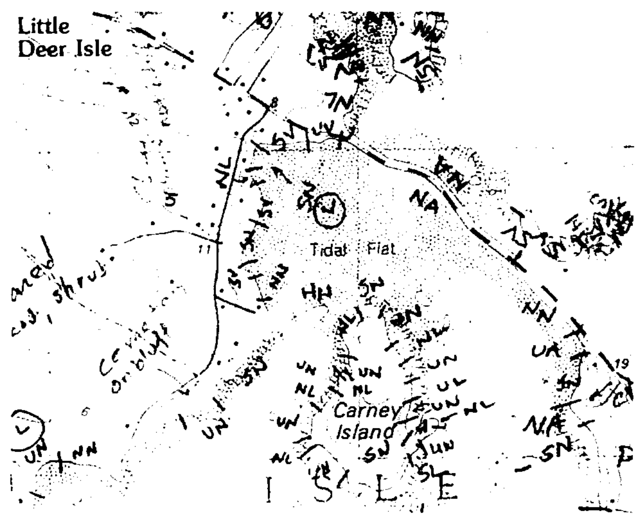
METHODS

4.1. Bluff Stability Mapping.

For the Maine Geological Survey (MGS) bluff stability mapping project (Kelley and Dickson, 2000), two features that were mapped along the shoreline were the relative stability of bluffs: highly unstable (H), unstable (U), stable (S), or no bluff (N); and the nature of the bluff-toe shoreline type: non-vegetated (N), vegetated (V), ledge (L), or armored (A). In addition, bluffs exceeding 6.1 m (20 ft.) in height were noted as having landslide potential (circled L's on field map (Figure 4-1) (Kelley and Dickson, 2000). Mapping took place in a small boat that was able to operate close to shore within a few hours of high tide. USGS 7.5' topographic quadrangles were used as a base. Boundaries between units drawn on the field map (Figure 4-1) are based on visual inspection of the shore from the boat and were determined using the following criteria from Kelley and Dickson (2000):

- Highly unstable bluffs (Figure 4-2) are very steep and sediments are exposed on their faces. Often, dead and dying trees are found on the slope and at the toe of the bluff.
- Unstable bluffs (Figure 4-3) have gentler slopes and are partially vegetated. There are commonly slump scars on the face of the bluff where sediments and tree roots are exposed. Mature trees on the slope are bent from soil creep.
- Stable bluffs (Figure 4-4) have very gentle slopes with mature vegetation completely covering the bluff face.

A



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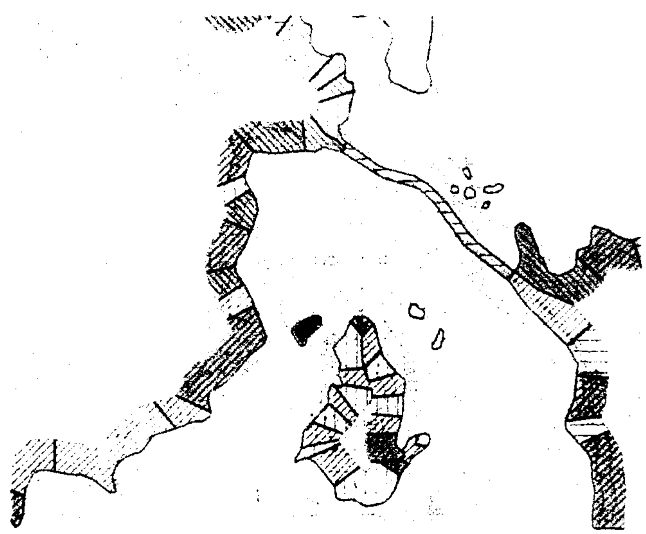

Figure 4-1: (A) A portion of the Sargentville, ME field map used for bluff stability mapping. (B) Completed bluff map for the corresponding area (Keblinsky et al., 2002). See text for descriptions of abbreviations (scale 1:24,000).

Figure 4-2: Typical highly unstable bluff with an abundance of exposed sediments and unvegetated shoreline. Bluff height approx. 12 m. Bunganuc Bluff, Brunswick.

Figure 4-3: Typical unstable bluff with patches of exposed sediments and tree roots and a mixed eroding salt marsh and unvegetated shoreline (photo courtesy of J.T. Kelley).

Figure 4-4: Typical stable bluff, with mature trees and grass on the face and an unvegetated shoreline. Bluff height approx. 3 m. West shore of Maquoit Bay, Freeport.

Any area that had only bedrock or less than 1m of unconsolidated material was mapped as "no bluff." In order to be visible on the map at a scale of 1:24000, each map unit had to crop out for at least 45m (Kelley and Dickson, 2000).

Once the field data were transferred to a clean map, the MGS digitized the field data into ArcView GIS. A buffer was created and colors and fill patterns were used to represent stability and the shoreline type, respectively (Figure 4-5) (Kelley and Dickson, 2000). The final product of this project is a series of 70 x 90 cm sheets, including the color map, which takes up approximately 50% of the sheet, a legend describing in detail each map unit, color photos depicting examples of the more common map units in the study area, and a table of the length of shoreline and stability type for each town in the map area (Kelley and Dickson, 2000). In addition, the digital Coastal Bluffs and Landslide Hazards (CBLH) dataset was created and made available to the author for analysis by the MGS.

4.2. GIS Analysis.

The primary methods of data collection, manipulation, and analysis for this study involve the use of ArcView and Arc/Info Geographical Information Systems (GIS) produced by Environmental Systems Research Institute (ESRI). Sample points were created by Arc/Info DENSIFY command. This program generated points at regularly spaced intervals along the coastline to produce an unbiased sample set. The new point theme was spatially joined to various data sets (Table 4-1) to assign attributes to each data point. The ultimate goal was to create a spreadsheet that tabulated measurements for a number of parameters for each sample point (Appendix). The

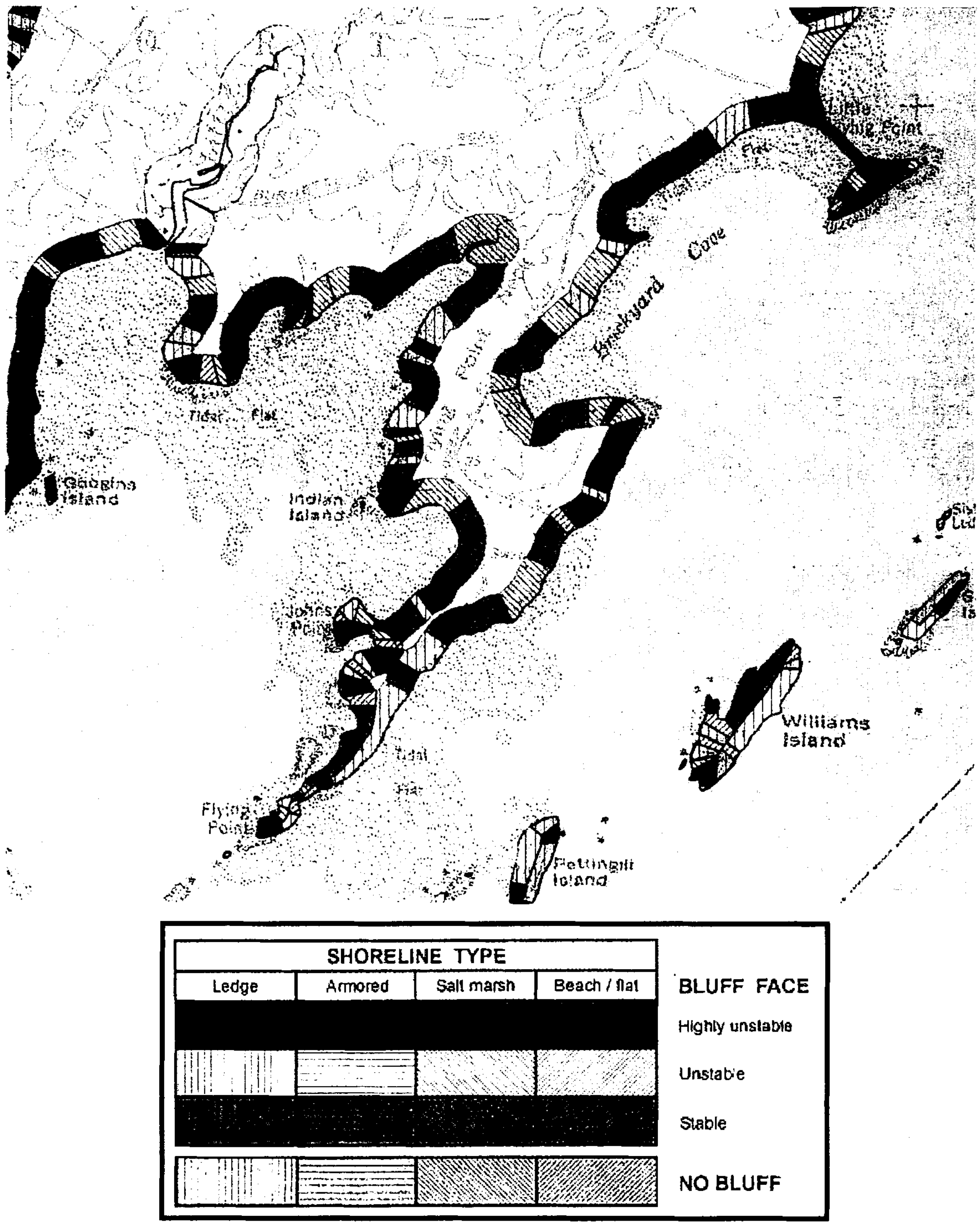

Figure 4-5: Portion of the completed bluff stability map for the Freeport, ME 7.5' Quadrangle (Bryant et al., 1998) (scale 1:24,000).

measured parameters were: bluff stability, intertidal environment type, intertidal width, bluff orientation, exposure, upland type, and surficial geology (Table 4-1).

High-resolution digital aerial photographs provided by the Maine Department of Marine Resources were analyzed in order to create the "upland type" data set. The photographs were imported into ArcView and georeferenced to the coastline. A mosaic was created for the entire quadrangle (Figure 4-6). The shoreline was then segmented according to type of vegetation (forest, grass/agricultural, unvegetated) and degree of development (buildings, or no buildings) (Figure 4-7).

Table 4-1: Sources of GIS Data

Measured Parameter	GIS Coverage Used*	Source Of Coverage
Bluff Stability	CBLH(1)	MGS(3)
Intertidal Zone	CMGE(2)	"
-nature	"	"
-width	"	"
Shoreline Orientation	Coastline	MOGIS(4)
Shoreline Exposure	"	"
Upland Type	Aerial Photographs	MDMR(5)
Surficial Geology	Surficial Geology	MGS

(1) Coastal Bluffs and Landslide Hazards
(2) Coastal Marine Geologic Environments
(3) Maine Geological Survey
(4) Maine Office of GIS
(5) Maine Department of Marine Recources
* All data were projected to UTM zone 19, NAD 27.

The width of the intertidal zone, the shoreline orientation and, the degree of exposure to incoming waves (fetch) was generated in ArcView using the Coastline dataset from the Maine Office of GIS and the Coastal Marine Geologic Environments

Figure 4-6: Airphoto mosaic of the Freeport, ME 7.5' Quadrangle. (Photos courtesy of Maine Department of Marine Resources. Photos taken in the spring of 1996).

Figure 4-7: Examples of upland units shown on aerial photographs. (A) Forest; (B) Forest with house; (C) Grass/agricultural; (D) Grass with house. (Photos courtesy of Maine Department of Marine Resources.)

(CMGE) dataset from MGS (Figure 4-8). At each data point (A), a vector was constructed normal to the shoreline that extended to the mean low water line (MLW) (B). This length was recorded as the intertidal zone width. The vector was then extended beyond MLW until it intersected another shoreline or the quadrangle boundary (C). This length was recorded as the exposure. The orientation of the bluff at the data point was given as the vector's bearing.

Once all of the data were collected in ArcView for each sample point, a spreadsheet was created in Microsoft Excel, and a chi-square statistical analysis was performed for each of the measured parameters, as discussed in more detail below.

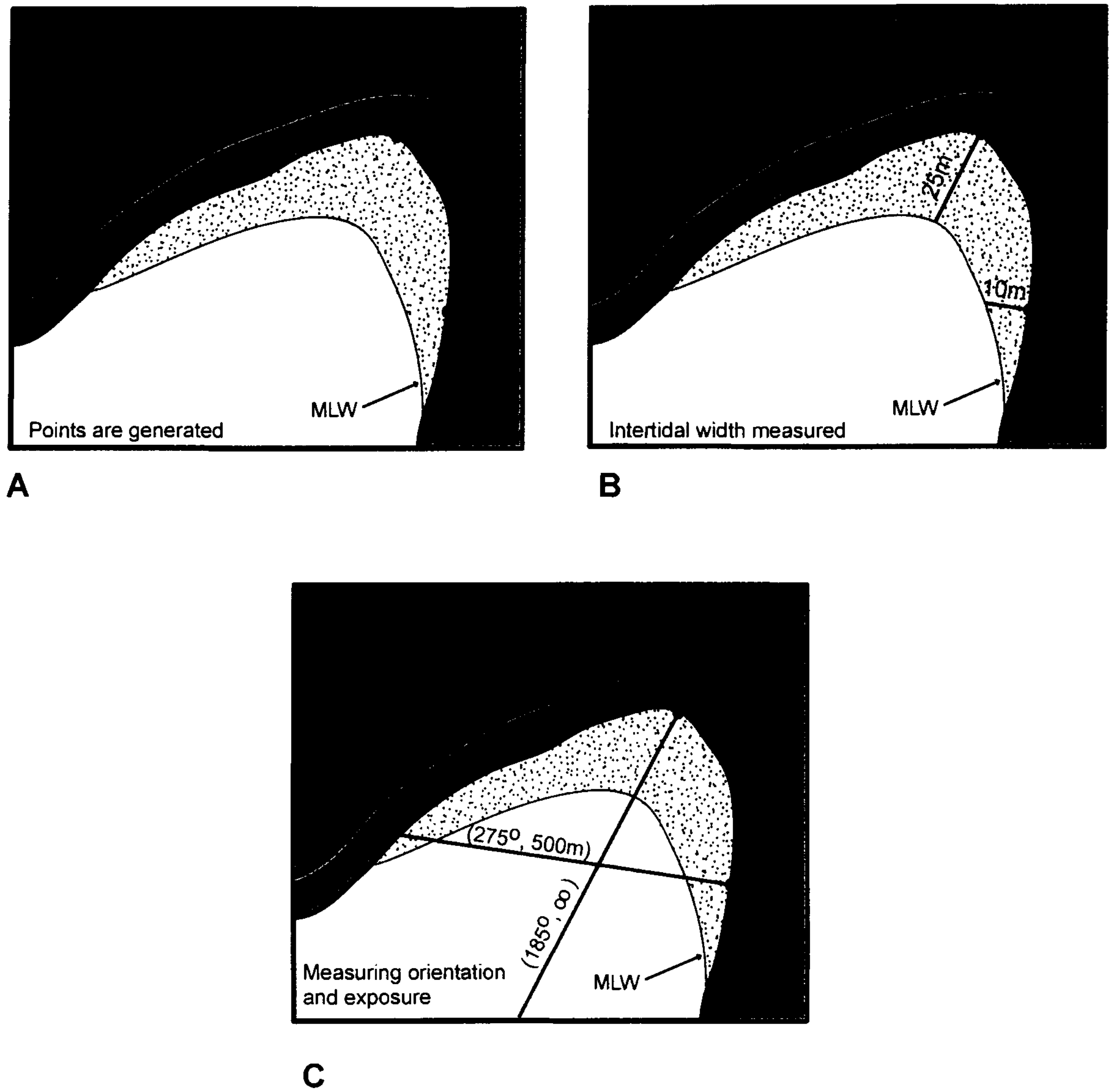

Figure 4-8: Cartoon illustration of the steps taken to measure bluff orientation, exposure, and intertidal zone width. See text for a description of the individual steps.

Chapter 5

RESULTS

5.1. Bluff Stability Mapping.

The completed map for the Freeport, ME 7.5' Quadrangle (Bryant et al., 1998) was published by the MGS in 1998 and is included at the end of this document. It provides not only the bluff stability and shoreline type for the entire study area, but also gives the total lengths of each bluff stability type for each town represented within the quadrangle boundary (Table 5-1).

Table 5-1: Lengths[1] of bluff types in the Freeport, ME 7.5' Quadrangle[2]

Town[3]	Highly unstable bluff	Unstable bluff	Stable bluff	No bluff shoreline	Unmapped shoreline
Brunswick	0.9	2.2	5.8	0.3	0.1
Cumberland	0.1	0.5	1.2	0.5	0.1
Freeport	4.9	7.2	16.9	7.1	5.8
Harpswell	1.2	4.9	11.4	11.8	0.9
Yarmouth	0.4	2.3	1.0	2.3	0.1
Total	7.5	17.1	36.3	22	7.0

(1) Lengths are in miles.
(2) From Bryant et al., 1998.
(3) Distances are only for the portions of the towns that are within the quadrangle boundary, not for the entire town or unmapped locations.

5.2. GIS Analysis.

The primary result of the GIS portion of this work is the creation of the data table provided in the Appendix. Manipulation of that spreadsheet in MS Excel provided the results of the statistical analyses that are provided below.

5.3. Statistical Analysis.

A chi-square (χ^2) statistical analysis was used to look for significance within the various measured parameters. The purpose of this test is to compare observed counts of particular cases to expected counts. For example, if each bluff type (stable, unstable, highly unstable, no bluff) were equally likely to occur at any given place in the study area, the probability for the likelihood of each category would be 25%. If the null hypothesis (H_O) is that out of 403 data points, each stability category were equally likely to occur, then the expected value for each category is 100.8. The χ^2 value is calculated using the following formula:

$$\chi^2 = \sum \frac{(Observed - Expected)^2}{Expected} \qquad (Eq.\ 1)$$

To reject H_O with 95% confidence, the calculated value of χ^2 must be greater than the critical value given in the table of cumulative distribution of χ^2 at a particular degree of freedom value. The critical value for 3 degrees of freedom is 7.81 (Snedecor and Cochran, 1967). Using equation 1, the χ^2 value for the observed occurrence of bluff stability types (Figure 5-1) was calculated:

$$\chi^2 = \frac{(149-100.8)^2}{100.8} + \frac{(64-100.8)^2}{100.8} + \frac{(36-100.8)^2}{100.8} + \frac{(154-100.8)^2}{100.8} = 106.3 \qquad (Eq.\ 2)$$

Here, the null hypothesis that each stability category is equally likely to occur in the study area is rejected (i.e., the obtained frequencies differ from the expected frequencies more than would be predicted by chance). As a result, the following proportions for stability types were considered the proportions of the population of bluff types and were used in each subsequent chi-square tests: S=37%, U=15.9%, H=8.9%, N=38.2%. If the

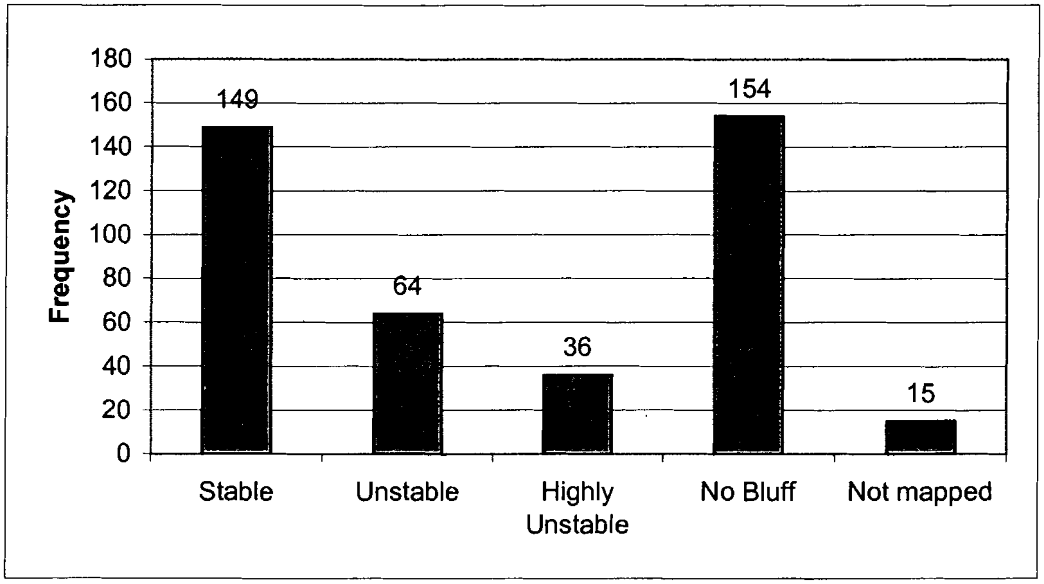

Figure 5-1: Occurrence of bluff stability types in the Freeport, ME 7.5' Quadrangle. Data points whose bluff stabilities were not mapped are not included in any of the statistical analyses.

null hypothesis is rejected for any of the categories within each test, then there is some unique quality about that particular category that would cause the observations to be significantly different from what is expected

5.3.1. Orientation.

A χ^2 test was performed for each 45-degree sector of compass bearing to determine whether bluff stability categories showed any preferred orientation. The critical value of 7.81 was exceeded for three sectors, ranging from due east (90°) to southwest (225°) (Table 5-2; Figures 5-2 & 5-3). In each of these three sectors, higher than expected counts for stable, unstable, and highly unstable bluffs were compensated for by lower than expected counts for no bluff.

Table 5-2: Chi-square test results for bluff orientation.

H_0: The total observed population for each orientation category is distributed according to the following proportions: S=37%, U=15.9%, H=8.9%, N=38.2%.

Orientation	Observed					Expected				
(degrees)	S	U	H	N	Total	S	U	H	N	X^2
0-44	11	4	3	3	21	7.8	3.3	1.9	8	5.19
45-89	12	5	1	6	24	8.8	3.8	2.2	9.1	2.34
90-134	22	7	5	6	40	14.8	6.4	3.6	15.3	**9.80**
135-179	27	16	7	9	59	21.8	9.4	5.3	22.5	**14.52**
180-224	16	3	8	3	30	11.1	4.8	2.7	11.5	**19.52**
225-269	6	3	3	3	15	5.6	2.4	1.3	5.7	3.68
270-314	21	8	4	22	55	20.4	8.7	4.9	21	0.29
315-359	19	9	4	16	48	17.8	7.6	4.3	18.3	0.65

5.3.2. Exposure.

The calculated χ^2 values exceeded the critical value of 7.81 for two exposure ranges (table 5-3). A higher than expected count for stable bluffs in the 0-1000m range and a higher than expected count for highly unstable bluffs in the 2000-3000m range

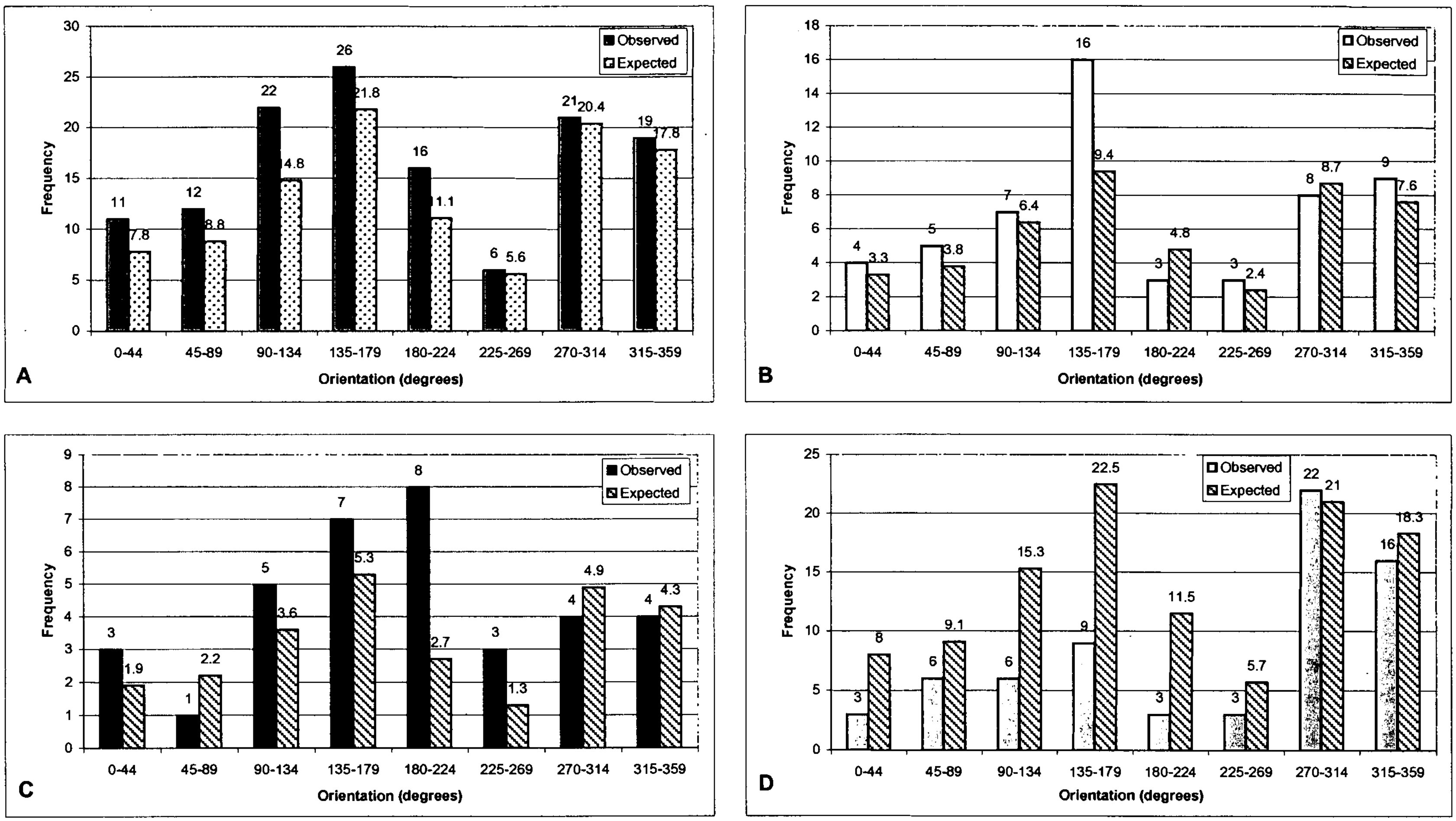

Figure 5-2: Observed vs. expected results for bluff orientation. (A) Stable bluffs; (B) Unstable bluffs; (C) Highly unstable bluffs; (D) No bluff.

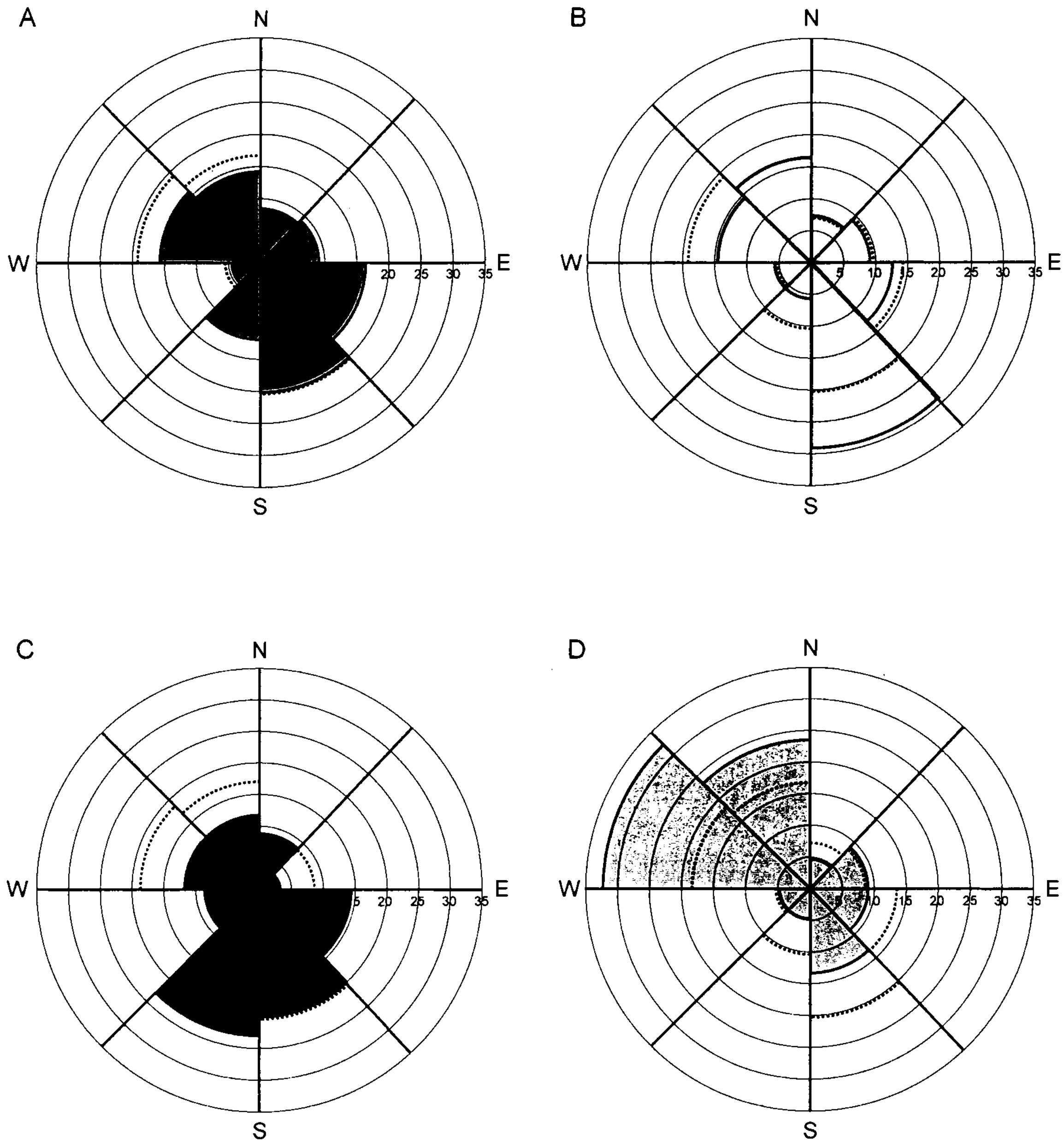

Figure 5-3: Orientations of bluffs expressed as percentages of the total number of observations for each stability category. (A) Stable bluffs, n=134; (B) Unstable bluffs, n=55; (C) Highly unstable bluffs, n= 35; (D) No bluff, n=68. Dotted lines represent expected percentages in each sector.

(Figure 5-4) suggests that bluffs have a tendency to be more unstable the less they are sheltered from incoming wave energy.

Table 5-3: Chi-square test results for bluff exposure.
H_0: The total observed population for each exposure category is distributed according to the following proportions: S=37%, U=15.9%, H=8.9%, N=38.2%.

Exposure (m)	Observed					Expected				
	S	U	H	N	Total	S	U	H	N	X^2
0-1000	87	25	12	32	156	57.7	24.8	13.9	59.6	**27.94**
1000-2000	16	10	7	15	48	17.8	7.6	4.3	18.3	3.24
2000-3000	19	12	10	10	51	18.9	8.1	4.5	19.5	**13.21**
3000-4000	3	4	2	5	14	5.2	2.2	1.3	5.4	2.79
>4000	8	4	4	6	22	8.1	3.5	2.0	8.4	2.88

5.3.3. Width of the Intertidal Zone.

The critical value of 7.81 was exceeded for three ranges of intertidal zone width (Table 5-4). Higher than expected counts for unstable and highly unstable bluffs in the narrower ranges are seen along with a higher than expected count for stable bluffs with intertidal zone widths greater than 400 m (Figure 5-5).

Table 5-4: Chi-square results for intertidal zone width.
H_0: The total observed population for each intertidal zone width category is distributed according to the following proportions: S=37%, U=15.9%, H=8.9%, N=38.2%.

Intertidal Width (m)	Observed					Expected				
	S	U	H	N	Total	S	U	H	N	X^2
0-100	73	40	23	53	189	70	30	16.8	72.2	**10.83**
101-200	26	6	5	7	44	16.3	7	3.9	16.8	**11.95**
201-300	12	2	3	3	20	7.4	3.2	1.8	7.6	6.88
301-400	5	3	2	2	12	4.4	1.9	1.1	4.6	2.93
>400	17	4	2	3	26	9.6	4.1	2.3	9.9	**10.54**

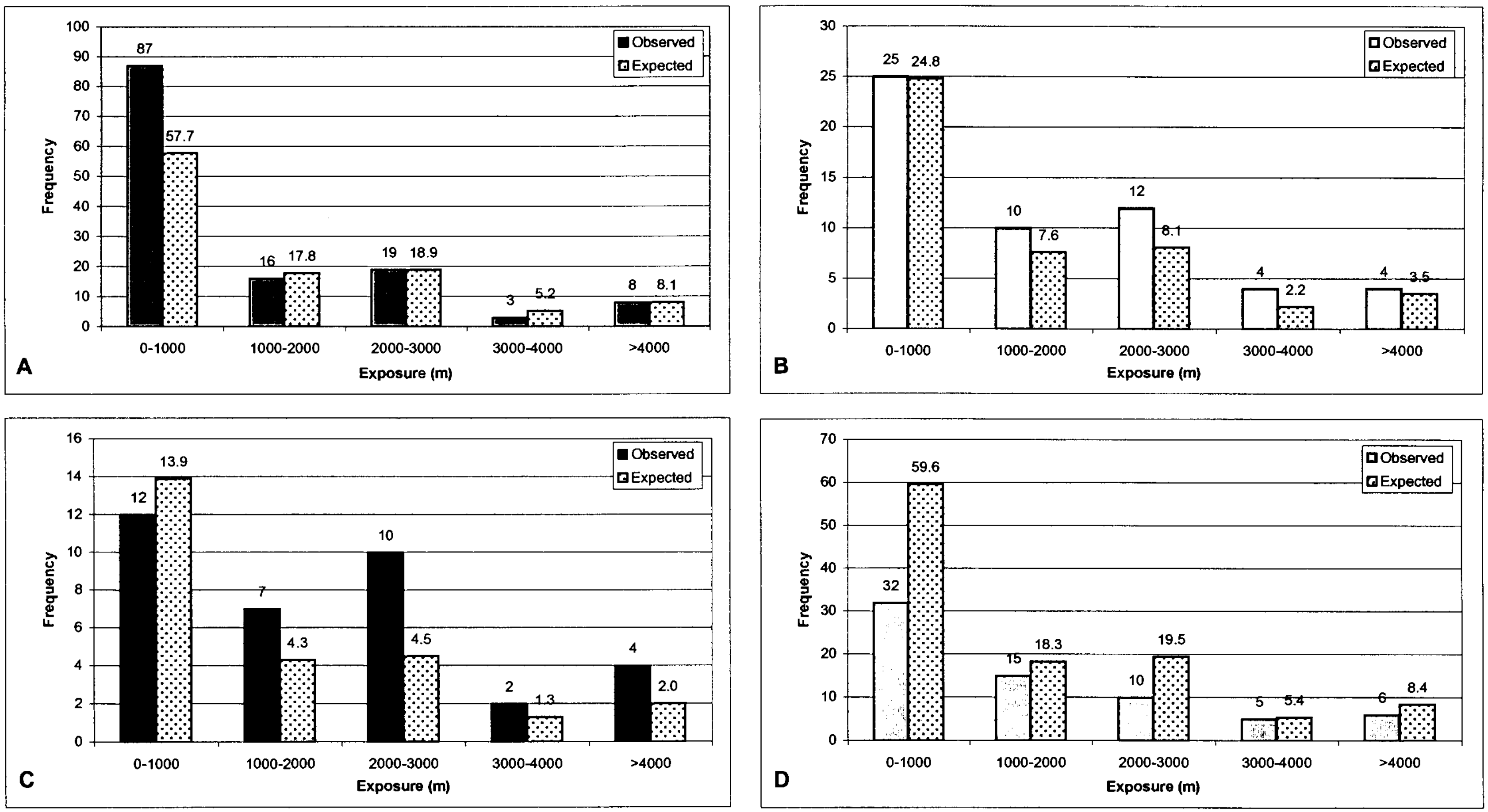

Figure 5-4: Observed vs. expected results for bluff exposure. (A) Stable bluffs; (B) Unstable bluffs; (C) Highly unstable bluffs; (D) No bluff.

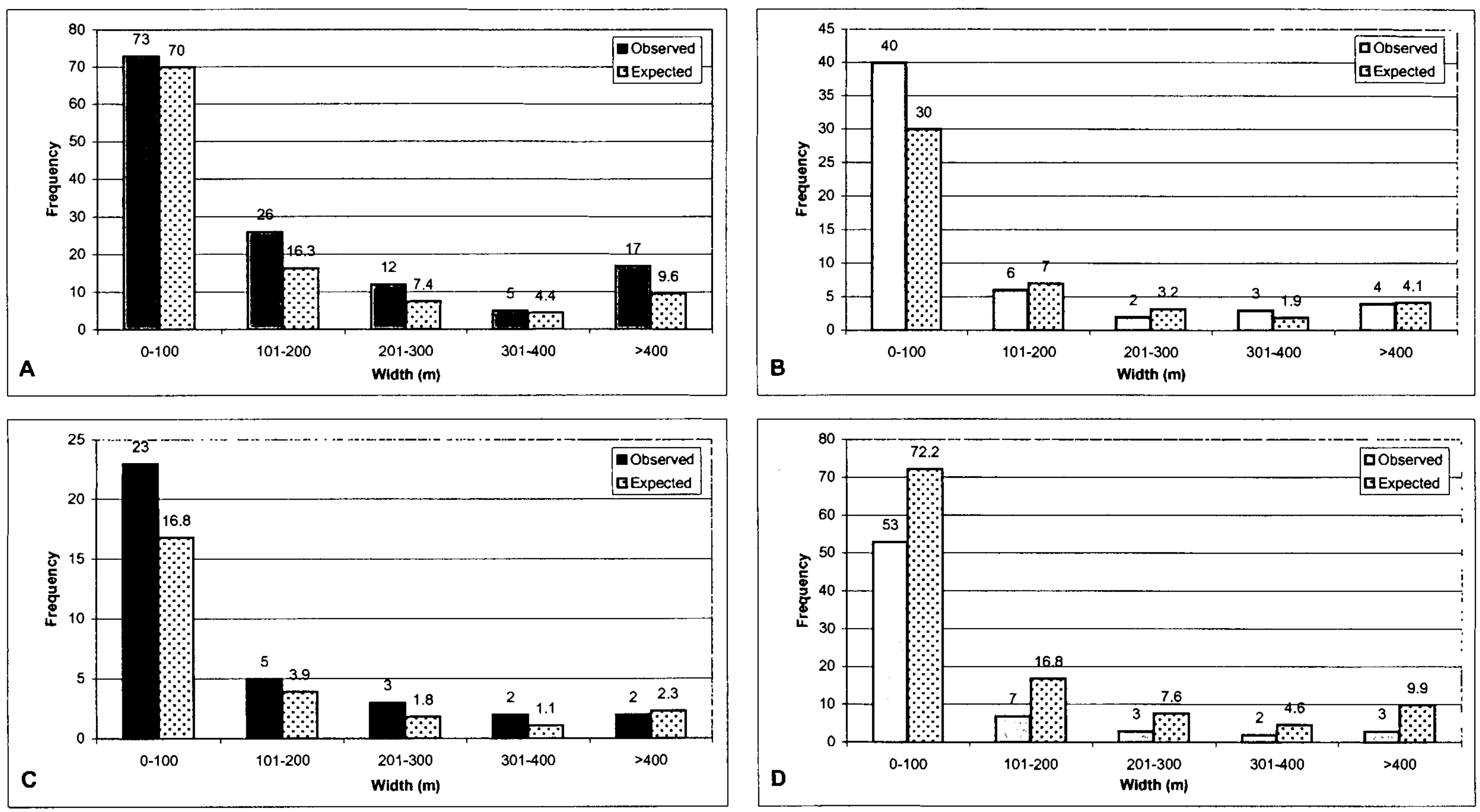

Figure 5-5: Observed vs. expected results for intertidal zone width. (A) Stable bluffs; (B) Unstable bluffs; (C) Highly unstable bluffs; (D) No bluff.

5.3.4. Nature of the Intertidal Zone.

Higher than expected counts for highly unstable bluffs and no bluff are seen for ledge environments, while observations of stable bluffs are much higher than expected for salt marsh environments (Table 5-5; Figure 5-6). Although the critical value for 95% confidence was not exceeded for the beach or mudflat categories, higher than expected counts for highly unstable bluffs are seen for both of these environments.

Table 5-5: Chi-square results for intertidal environment.
H_0: The total observed population for each intertidal environment category is distributed according to the following proportions: S=37%, U=15.9%, H=8.9%, N=38.2%.

Intertidal Environment	Observed					Expected				
	S	U	H	N	Total	S	U	H	N	X^2
Beach	5	1	4	11	21	7.8	3.3	1.9	8	6.05
Mudflat	15	5	4	7	31	11.5	4.9	2.6	11.8	3.77
Salt Marsh	17	1	1	4	23	8.5	3.7	2	8.8	**13.59**
Ledge	24	19	17	67	127	47	20.2	11.3	48.5	**21.27**

5.3.5. Upland Type.

The critical value was exceeded for four out of the five categories that were analyzed (Table 5-6; Figure 5-7). The higher than expected number of highly unstable bluffs for forested bluffs with a house built upon it suggests that building a house on a previously undisturbed portion of the shoreline promotes bluff instability. There is also a much higher than expected count of stable bluffs in areas that are developed with houses and lawns.

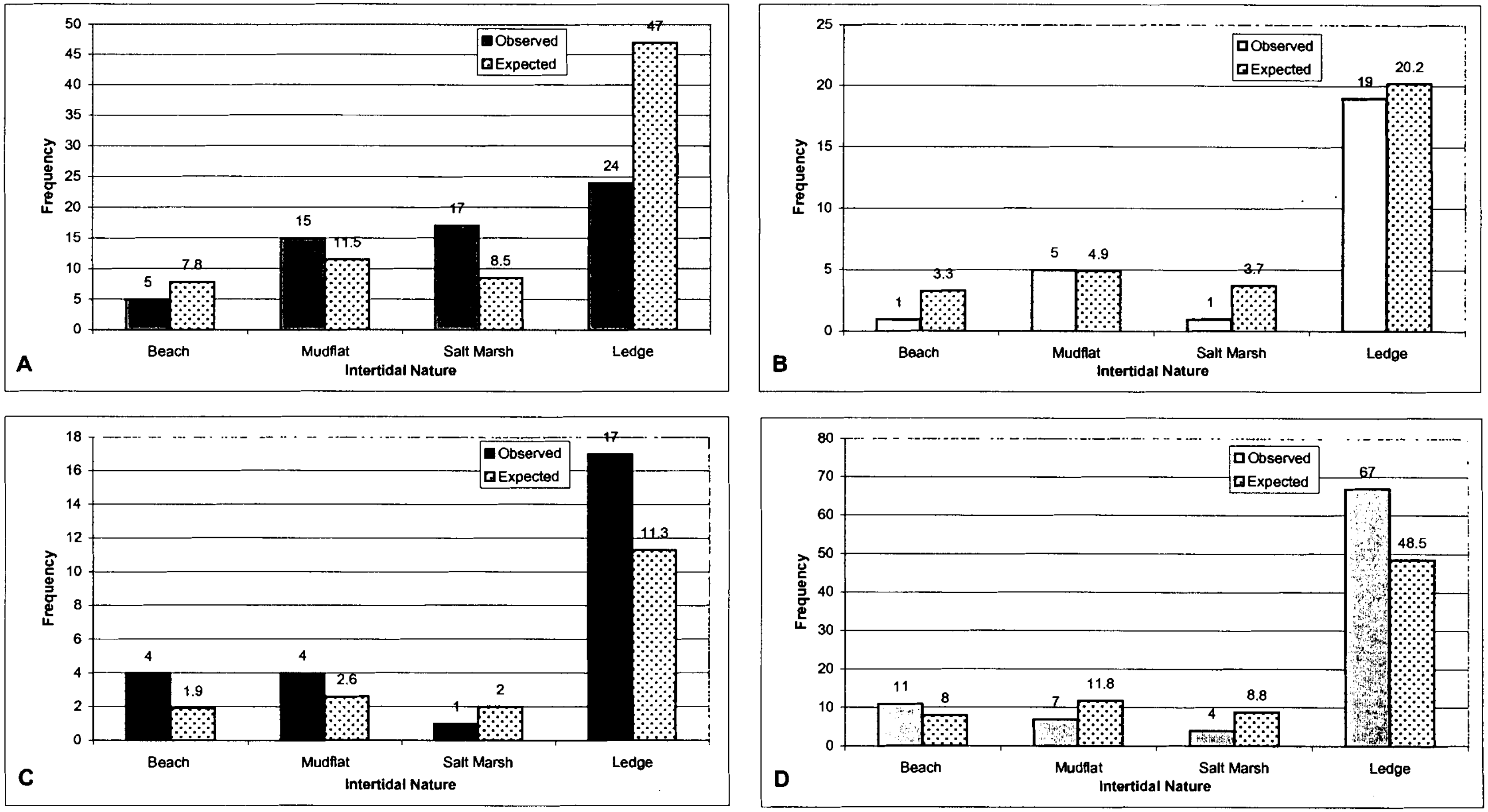

Figure 5-6: Observed vs. expected results for intertidal nature. (A) Stable bluffs; (B) Unstable bluffs; (C) Highly unstable bluffs; (D) No bluff.

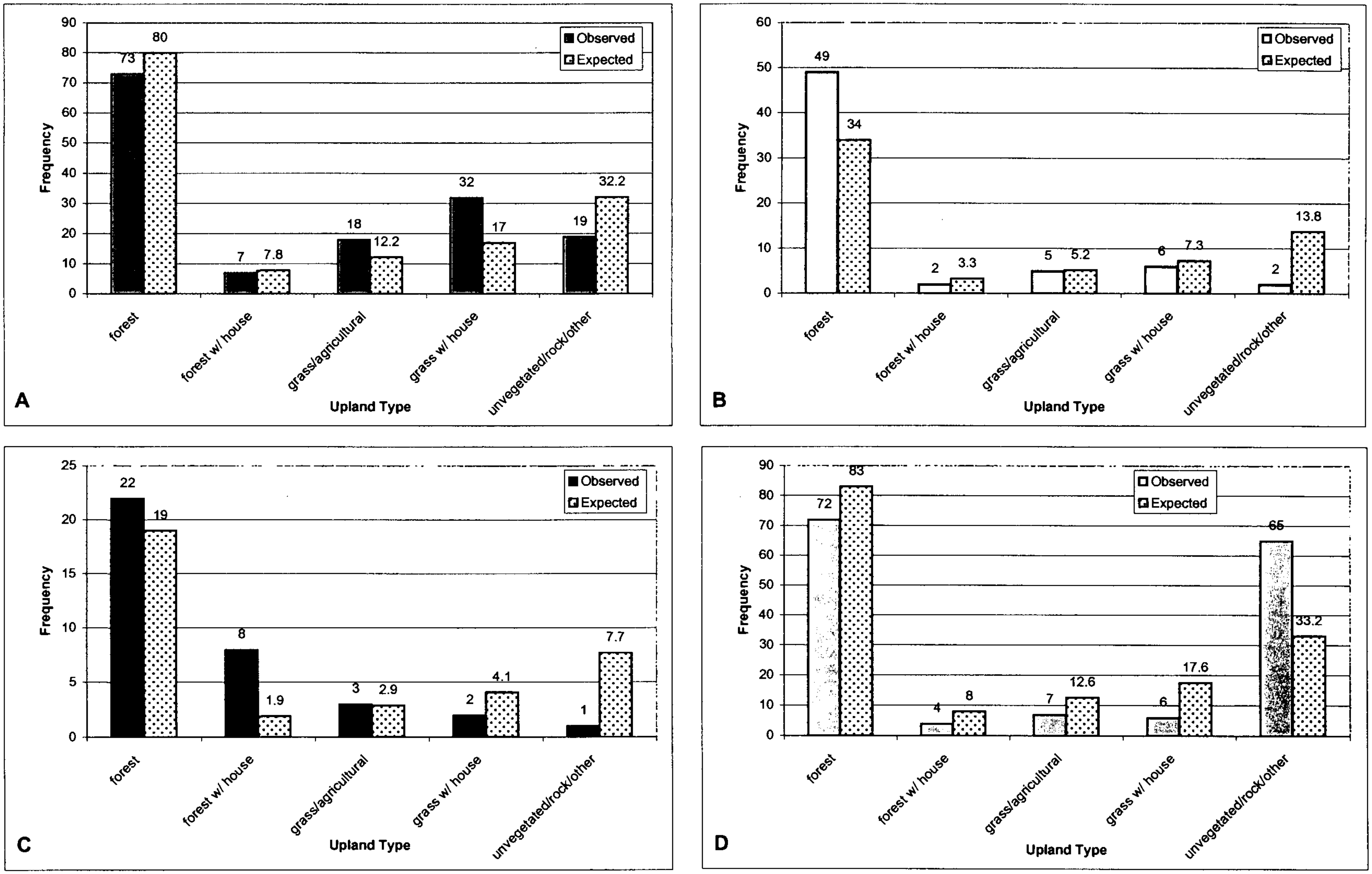

Figure 5-7: Observed vs. expected results for upland type. (A) Stable bluffs; (B) Unstable bluffs; (C) Highly unstable bluffs; (D) No bluff.

Table 5-6: Chi-square results for upland type.
H_0: The total observed population for each upland type category is distributed according to the following proportions: S=37%, U=15.9%, H=8.9%, N=38.2%.

Upland Type	Observed					Expected				
	S	U	H	N	Total	S	U	H	N	X^2
Forest	73	49	22	72	216	80	34	19	83	**9.16**
Forest w/ house	7	2	8	4	21	7.8	3.3	1.9	8	**22.17**
Grass/agricultural	18	5	3	7	33	12.2	5.2	2.9	12.6	5.26
Grass w/ house	32	6	2	6	46	17	7.3	4.1	17.6	**22.2**
Unvegetated/rock/other	19	2	1	65	87	32.2	13.8	7.7	33.2	**51.78**

5.3.6. Surficial Geology.

Because there were many observations of zero for the more specific surficial geologic units, the categories were condensed into glaciomarine deposits, which includes the Presumpscot Formation and subaqueous fan deposits, and glacial drift/ beach deposits, which includes thin drift, till, and sand and gravel beaches. In both categories, the critical value was exceeded (Table 5-7).

Table 5-7: Chi-square results for surficial geology.
H_0: The total observed population for each intertidal environment category is distributed according to the following proportions: S=37%, U=15.9%, H=8.9%, N=38.2%.

Surficial Geology	Observed					Expected				
	S	U	H	N	Total	S	U	H	N	X^2
Glaciomarine deposits	68	14	13	9	104	38.5	16.5	9.3	39.7	**48.2**
Glacial drift/beach	61	47	18	67	193	71.4	30.7	17.2	73.7	**10.8**

5.3.7. Averages.

Average values for exposure, intertidal width, and orientation were calculated for each bluff stability type (Figure 5-8). Stable bluffs have an average exposure of 1140 m (± 1434 m), 170 m (± 225 m) intertidal zone, an orientation of 184° (south) (±

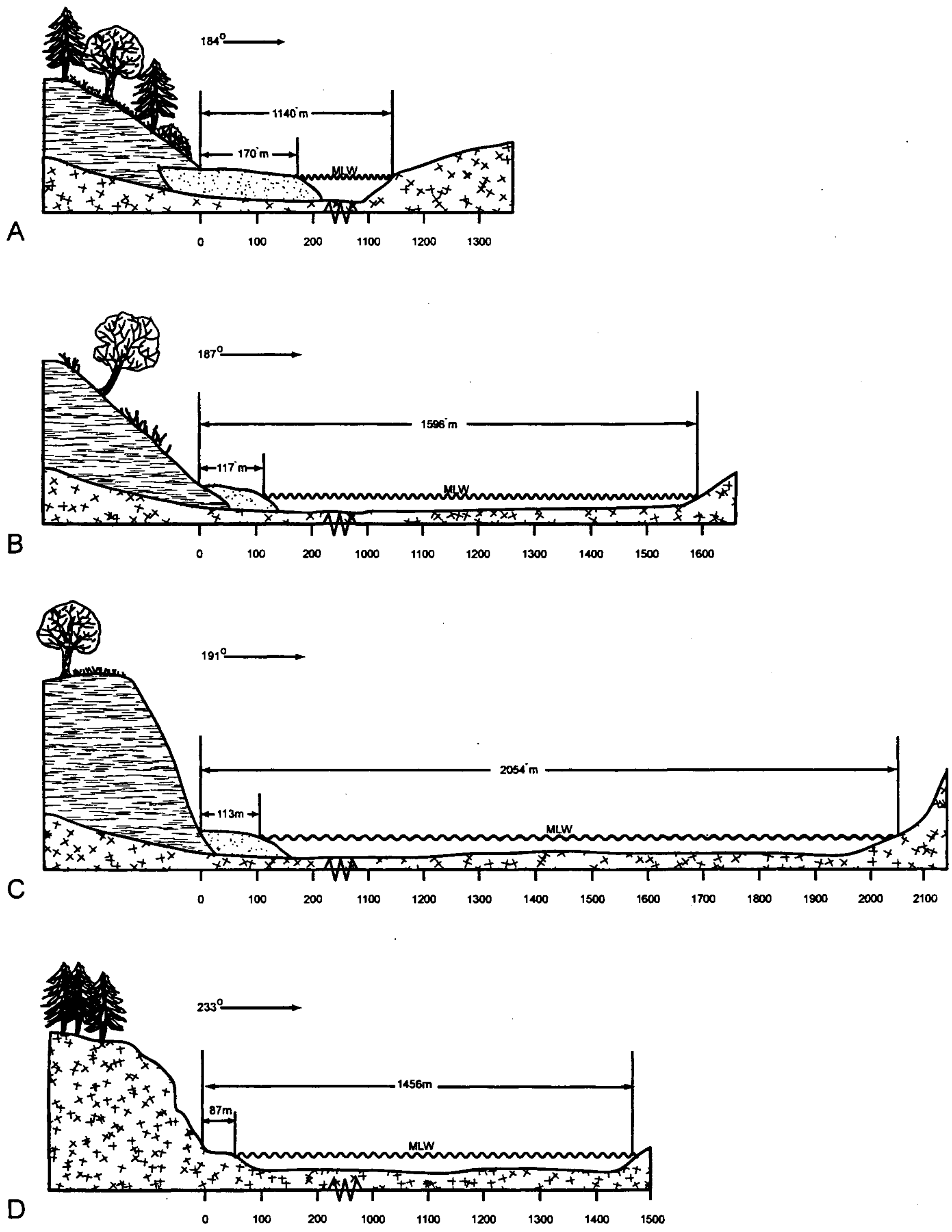

Figure 5-8: Cartoon illustration depicting average values of exposure, intertidal width, and orientation. (A) Stable bluffs; (B) Unstable bluffs; (C) Highly unstable bluffs; (D) No bluff (Vertical axis not to scale).

96°). The average unstable bluff has 1596 m (± 1471 m) of exposure, 117 m (± 174 m) intertidal zone, and an orientation of 187° (south-southwest) (± 97°). Highly unstable bluffs average 2054 m (± 1924 m)of exposure, 113 m (± 146 m) intertidal zone, and are oriented at 191° (south-southwest) (± 90°). Areas with no bluff have an average exposure of 1456 m (± 1534 m), 87 m (± 167 m) intertidal zone, and an orientation of 233° (west-southwest) (± 103°).

Chapter 6

DISCUSSION

6.1. External controls on bluff stability.

Several authors discuss the importance of external forces that affect the stability of coastal bluffs and cliffs (Griggs and Savoy, 1985; Carter et al., 1987; McGreal, 1979a) and agree that the primary external mechanism for decreasing the stability of bluffs is erosion at the base by direct wave attack. Along the coast of California, Griggs and Savoy (1985), state that bluff and sea cliff retreat is a result of the removal of protective beach material at their bases by highly energetic winter storm waves. Carter et al. (1987) also believe that beach width is critically important for the protection of bluffs along the coast of Lake Erie, and that wave energy (wave height) is crucial because the magnitude of wave energy in their study was proportional to the severity of erosion along the shore (Carter et al., 1987). The magnitude of wave energy at any given point along the coast is a function of the intensity, duration, and fetch of the winds. The orientation of the shoreline with respect to prevailing and storm wind directions is, thus, also an important factor in determining the amount of wave energy that is able to attack a particular portion of the coast.

Interpretation of the chi-square results reveals a strong tendency for higher instability for bluffs facing towards the south and east, and more stability (or no bluff) if the coastline faces towards the north and west. Approximately 40% of highly unstable bluffs face between 135° and 225° and almost 30% of unstable bluffs face between 135° and 180° (Figs. 5-2, 5-3). These observations are explained by a combination of

prevailing and storm wind directions, and by the orientation of the shoreline as a result of bedrock framework. Prevailing winds in the summer and winter are from the southwest and northwest, respectively (Belknap et al., 1988; Fefer and Schettig, 1980). However, the strongest winds occur during northeast storm events. These easterly winds have the greatest potential for generating large, destructive waves. It is reasonable to conclude that a bluff is more likely to be unstable or highly unstable, rather than stable, if it is exposed to greater incoming wave energy. The observed vs. the expected samples of bluff exposure (Figure 5-4) show a significantly greater percentage of stable bluffs with exposures less than 1 km (65%), while unstable and highly unstable bluffs have greater than expected percentages in all categories greater than 1 km (55% and 66%, respectively).

Although bluffs that face to the east are relatively sheltered as a result of the northeast-southwest trending peninsulas in the study area, the larger waves generated during northeast storms have sufficient energy to increase erosion at the bases of these bluffs and decrease their stability. In the Freeport Quadrangle, the average exposure of bluffs facing towards the east is approximately 1 km. If the average wind speed during a typical northeast storm is 74 km/hr (40 knots), the maximum wave height generated is 0.8 m (Komar, 1976). There are, however, 27 sample points that face in an easterly direction that have exposures greater than 1 km, with a maximum exposure of 4.6 km. Here, the maximum generated wave height is 1.2 m. Sixteen of these samples have ledge shorelines, indicating that marine processes have removed the sediment in the intertidal zone as a result of the elevation of the bedrock with respect to sea-level. There is also one stable bluff with an exposure greater than 4 km that faces to the east,

however, it is armored with an engineering structure at the toe of the bluff, indicating instability prior to the construction of the structure.

The bluffs that face in a southerly direction are subject to more frequent wave-attack as a result of the longer-duration, though slower speed southwest winds during the summer months. The average southerly exposure in the Freeport Quadrangle is 1.5 km, with a maximum exposure of 7.4 km, and an average wind speed of 28 km/hr (15 knots) out of the southwest in the summer generates an average of 0.3 m waves, and a maximum of 0.45 m waves. While these wave heights may appear small, they do have a high potential for bluff erosion, especially when the duration of wave attack is taken into consideration. For example, if the toe of a bluff is in contact with the water surface for a large portion of the tidal cycle, the constant battering of the bluff surface by these smaller waves decrease the bluff stability.

The width of the intertidal zone and the type of intertidal environment each play an important role as external controlling factors for bluff stability. Unstable and highly unstable bluffs both have greater-than-expected percentages (73% and 66%, respectively) for intertidal widths less than 100 meters, while 17 out of 23 bluffs with intertidal widths greater than 400 meters are stable (Figure 5-5). There were no observed highly unstable bluffs with intertidal widths greater than 600 meters, while only stable bluffs have intertidal widths greater than 1 kilometer (Appendix). This suggests that that the shorter the width of the intertidal zone, the more susceptible a bluff is to erosion by marine processes because the width and elevation of the intertidal zone determines the wave height and duration of wave attack over a tidal cycle,

respectively. This also suggests that sediment eroding from highly unstable bluffs does not remain on an adjacent tidal flat (Smith, 1990).

There are several correlations between intertidal environment and bluff stability (Figure 5-6). The lack of a salt marsh in the intertidal zone leads to greater instability of bluffs. Unstable and highly unstable bluffs are more likely to have an unvegetated intertidal zone such as ledge, mudflat, or low-energy beach deposits. An abundance of salt marsh vegetation, such as *Spartina alterniflora* and *Spartina patens*, on a flat slope near MSL to MHW, has a tendency to dampen the effects of wave action on the shore. The absence of such vegetation at the base of a bluff allows more energetic waves to attack the toe of the bluff. The presence of a mudflat or other unvegetated intertidal zone in front of an eroding bluff is associated with greater instability due to accelerated erosion by wave attack, therefore reducing the stability of the bluff.

6.2. Internal controls on bluff stability.

Several studies are concerned primarily with internal processes that cause increased erosion rates on coastal bluffs (McGreal, 1979b; Terich, 1987), and others that examine a combination of both internal and external characteristics (Kuhn and Shepard, 1983; Griggs et al., 1985; Carter et al., 1987). In a bluff erosion study in Northern Ireland, McGreal (1979b) concluded that increased slope instability is a result of the reduction of the strength of geologic materials caused by elevation of the groundwater table during times of increased rainfall. Terich (1987) concluded that, in Puget Sound, WA, bluff instability is most influenced by the geologic material, and the water within and on the surface of the bluff, while wave erosion is less important due to

the relatively sheltered nature of the Sound. Bluffs in this area are more stable when they are dry than when saturated with groundwater and by human activities such as watering lawns, cutting and clearing natural vegetation, and diverting water onto the surface of the bluffs from rooftops, pavement, and sewers, increase the amount of water in the bluff and promote slope instability.

Two internal characteristics of bluffs that were examined in this study are human activities on top of bluffs in terms of land use in the upland, and the surficial geological materials that comprise the bluffs. The initial hypothesis was that the more intense the development, in terms of clearing natural vegetation and building structures on top of a bluff, the greater tendency for instability. This assumed that a forested upland is the natural state of bluffs and would tend to be more stable. The chi-square results, however, reveal that slightly higher-than-expected percentages of unstable and highly unstable bluffs have forested uplands. Seventy-six percent of unstable bluffs and 61% of highly unstable bluffs were observed to have forested uplands while the expected percentages were 53% for each (Figure 5-7). Houses on bluffs without cleared vegetation show significantly more highly unstable bluffs than expected (22% observed versus 5.3% expected), while stable and unstable bluffs show no strong association. Land that is cleared of trees, yet remains vegetated with grass or crops, tends to show greater stability, but this trend is not very significant. In fact, the "grass/agricultural" category was the only land-use category in which the null hypothesis was not rejected for upland type. There are an anomalously large number of stable bluffs associated with the grass-with-house category, which is the opposite of what was initially hypothesized. Further investigation, however, revealed that 19 out of the 32 stable

bluffs in this category were armored at the shoreline with some type of engineering structure (Appendix 1). The presence of armoring suggests that these shorelines were once subject to erosion and would probably have been mapped as unstable or possibly highly unstable had the structure not been present at the time of mapping. Field inspection (Figure 6-1) further supports the suggestion that armored but stable bluffs were once subject to an unstable period before the engineering structures were emplaced. The significantly higher than expected percentages of no bluff (42% observed versus 22% expected) in the "unvegetated/rock/other" category is a result of the numerous rocky outcrops scattered throughout the study area.

The types of surficial geologic material that were examined in this study are glaciomarine deposits as characterized by the Presumpscot Formation, and glacial drift/beach deposits, which include thin drift, till, and sand and gravel beach deposits. The bluffs that are composed of glaciomarine mud were expected to exhibit the same distribution of stability types that was used for each chi-square test. The results, however, show that there is a significantly greater number of stable bluffs observed than what was expected (38.5). Out of 104 observations of bluffs composed of glaciomarine mud, 68 of them are mapped as stable. Bluffs of the Presumpscot Formation may appear to be stable for long periods, and then fail with little or no warning by slumping or blockfalls. It is easy for grass and shrubs to grow on the faces of these bluffs and give the appearance of stability at the time of mapping. The April 1996 landslide that occurred in Rockland, ME (Berry et al. 1996) occurred in an area that was mapped as unstable (Kelley and Dickson, 2000). There were mature trees and shrubs growing on the face of the bluff, however, there was evidence of soil creep occurring in this area.

Figure 6-1: Newly constructed shoreline armoring on a developed bluff. This bluff was originally mapped as highly unstable. Now, the bluff face is completely armored and would be mapped as having no bluff present. Flying Point Neck, Freeport.

The top portion of the Presumpscot Formation is often vertically jointed because of desiccation. If a buildup of water pressure in these joints occurs after rainy periods or snowmelt, then the probability of failure can increase significantly (Amos and Sandford, 1987). Bluffs composed of the Presumpscot Formation also tend to be more susceptible to erosion by a combination of wave action at the toe and groundwater seepage, as opposed to subareal erosion such as surface runoff (Kelley et al., 1987) There were a significantly higher number of bluffs made of glaciomarine deposits that were mapped as highly unstable than were expected. It is common for this type of material to exhibit steep, unvegetated faces, and to have very high tops that are at risk of landsliding (Dickson, 2001).

Bluffs composed of glacial drift such as till, thin drift, and beach deposits, are often likely to show signs of instability. These deposits have higher sand, gravel, and cobble contents, tend to erode in a "grain-by grain" fashion, and appear more susceptible to erosion by subareal processes such as rain spatter and surface runoff. In addition, it may be difficult to establish mature vegetation on these bluffs because of the higher porosity and lower cohesiveness of this material (Kelley, pers. comm.). The number of unstable bluffs observed in the "glacial drift/beach deposits" category was greater than expected (Table 5-4).

6.3. Extreme cases of bluff erosion.

There are several portions of the shoreline within the Freeport Quadrangle that are significant because they represent areas in which the bluffs are unusual compared to the average bluffs. With the exception of one of the following bluffs, (Little Flying

Point north) there are some similarities associated with these bluffs in that they are all oriented in generally the same direction (southeast to southwest), they are each well exposed to incoming waves because they face almost directly down the axes of the bays in which they lie, they all have narrow intertidal zones, and they are all composed of the Presumpscot Formation. The degree of development on each bluff varies, but they are all affected by human activities to some extent.

6.3.1. Bunganuc Bluff.

Bunganuc Bluff is located on the northeastern corner of the Freeport Quadrangle near the head of Maquoit Bay in the town of Brunswick (Figures 6-2, 6-3). It is approximately 12 meters high and 670 meters long with a nearly vertical face (Devin and Sandford, 1990). This bluff is subject to frequent slumping and blockfalls, and is one of the most highly unstable bluffs in Maine (Kelley et al., 1989). The short-term average annual erosion rate measured over 3 years by Smith (1990) is 0.45 m/yr ± 0.16 and the long-term rate for the period from 1940 to 1986 is 0.58 m/yr ± 0.15 (Smith, 1990). It has approximately 7.4 km of exposure with an orientation of 201°. It has a 110 m intertidal zone that is composed of low-energy beach deposits at the toe of the bluff with a mudflat farther seaward. Development on top of this bluff consists of low-density residential housing with some cleared trees and lawns. The only portion of this bluff that exhibits evidence of stability is armored with riprap that was accidentally emplaced after mapping (Figure 6-4). Rocks were placed at the top of the bluff for landscaping purposes, and then their weight caused a landslide. They were then piled up at the toe of the bluff as armor (Kelley, pers. comm.). Because the toe of the bluff is

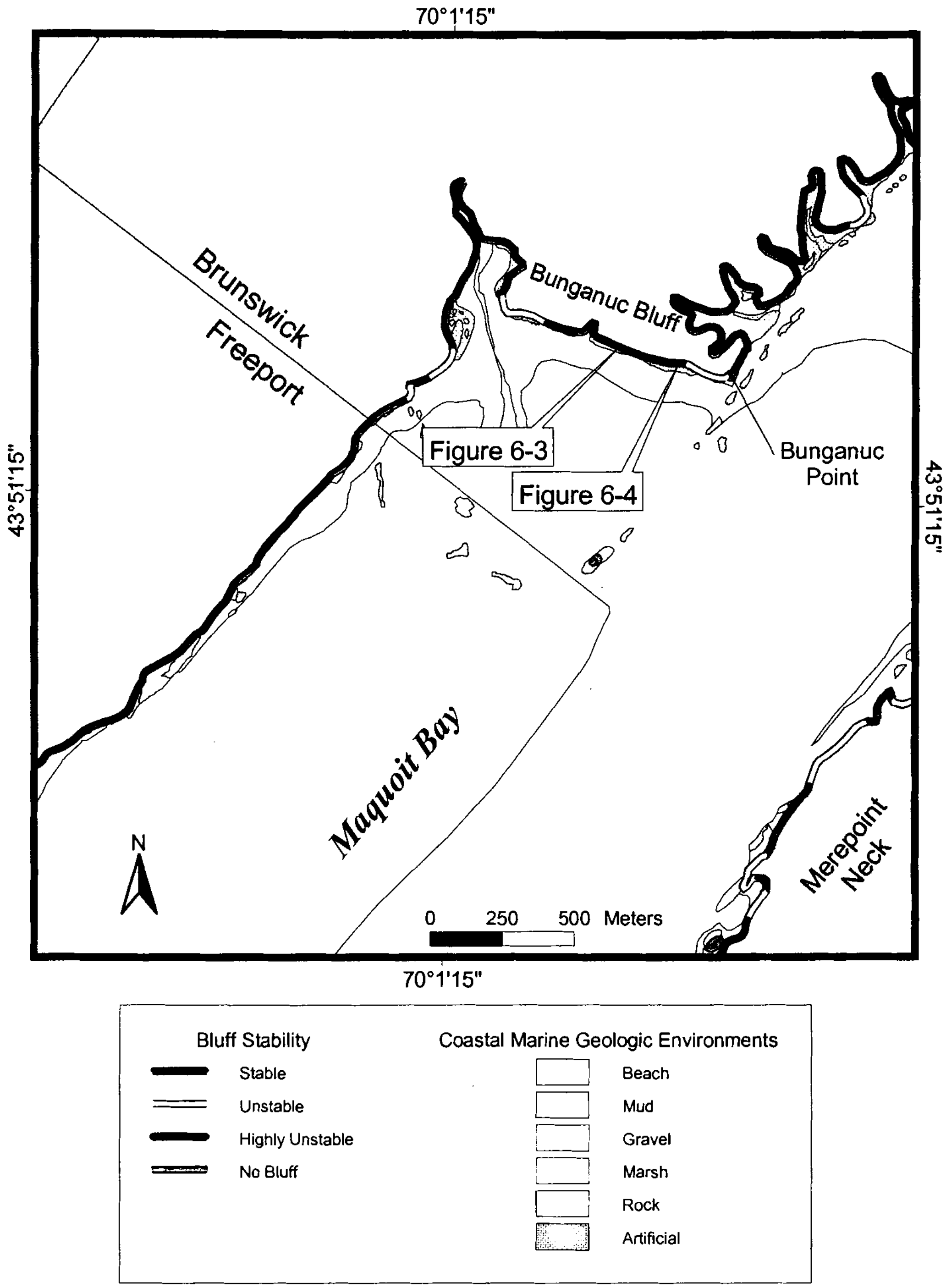

Figure 6-2: Location of Bunganuc Bluff.

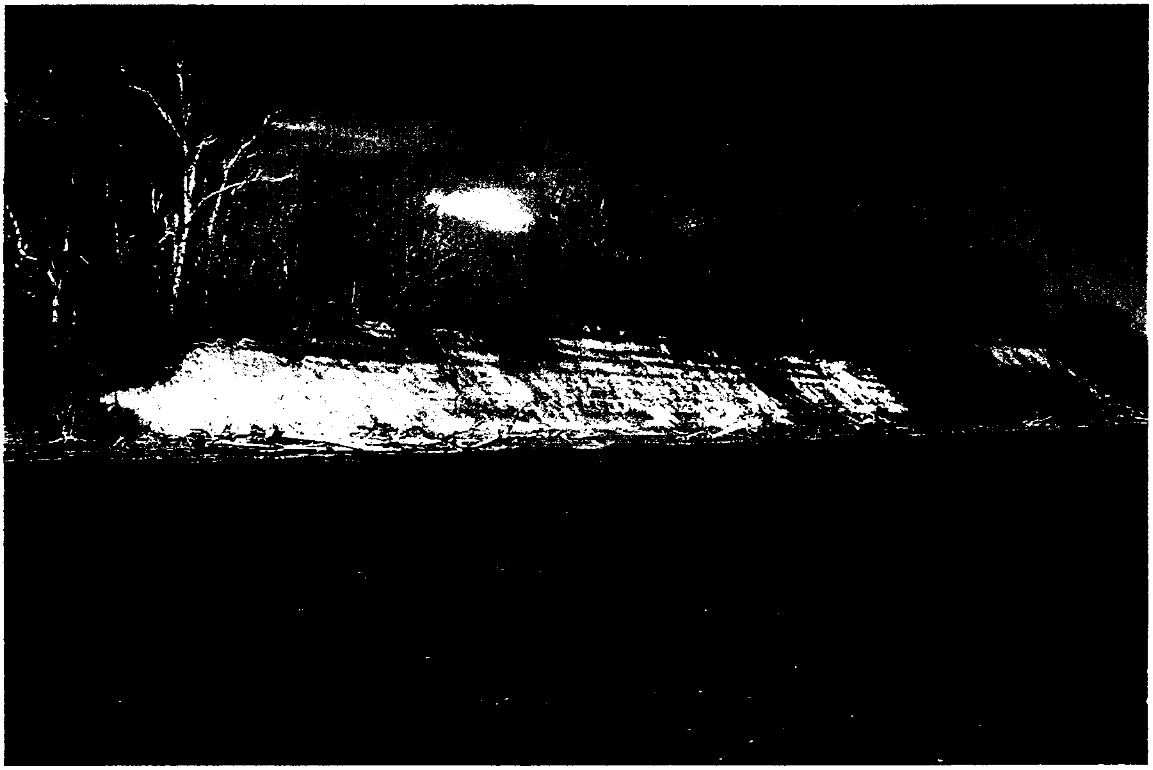

Figure 6-3: Eroding bluff at Bunganuc Bluffs, Brunswick, ME.

Figure 6-4: Eastern end of Bunganuc Bluff. This portion of the bluff is stable due to the presence of riprap armor at its base.

in contact with water at MHW, it is subject to continuous marine erosion and oversteepening due to undercutting, thus resulting in slumping (Smith, 1990). Groundwater seepage is evident during wet periods through springs on the face of the bluff, which cause significant subaerial erosion (Figure 2-8). This bluff has all of the ingredients associated with high instability, and both internal characteristics and external forces play major roles in keeping this bluff highly unstable. It is also exhibits the step-wise retreat pattern demonstrated by Sunamura (1983) (Figure 2-6) for the erosion of cliffed and bluffed coasts with periods of rapid erosion separated by periods of little or no retreat when landslide deposits protect the bluff (Smith, 1990).

6.3.2. Little Flying Point.

Little Flying Point is located on the western shore of Maquoit Bay in the town of Freeport (Figure 6-5). It is a peninsula that is attached to a small island by a causeway constructed of granite blocks. Both the north (Figure 6-6) and south (Figure 6-7) portions of Little Flying Point are experiencing active bluff erosion that may be associated with the construction of the causeway and the development of a campground on the point (Smith, 1990). Although the southern portion has a greater exposure (3.8 km) than the northern portion (2.1 km), the bluff on the north side exhibits a greater short-term erosion rate than the south. In fact, the bluff on the north side of Little Flying Point had the greatest short-term erosion rate (1.08 m/yr ± 0.25) in Casco Bay as measured by Smith (1990). Because of the presence of the causeway and because the bluff faces to the ENE, waves generated during northeast storms tend to be focused on the north side of Little Flying Point, thus decreasing the stability of the bluff.

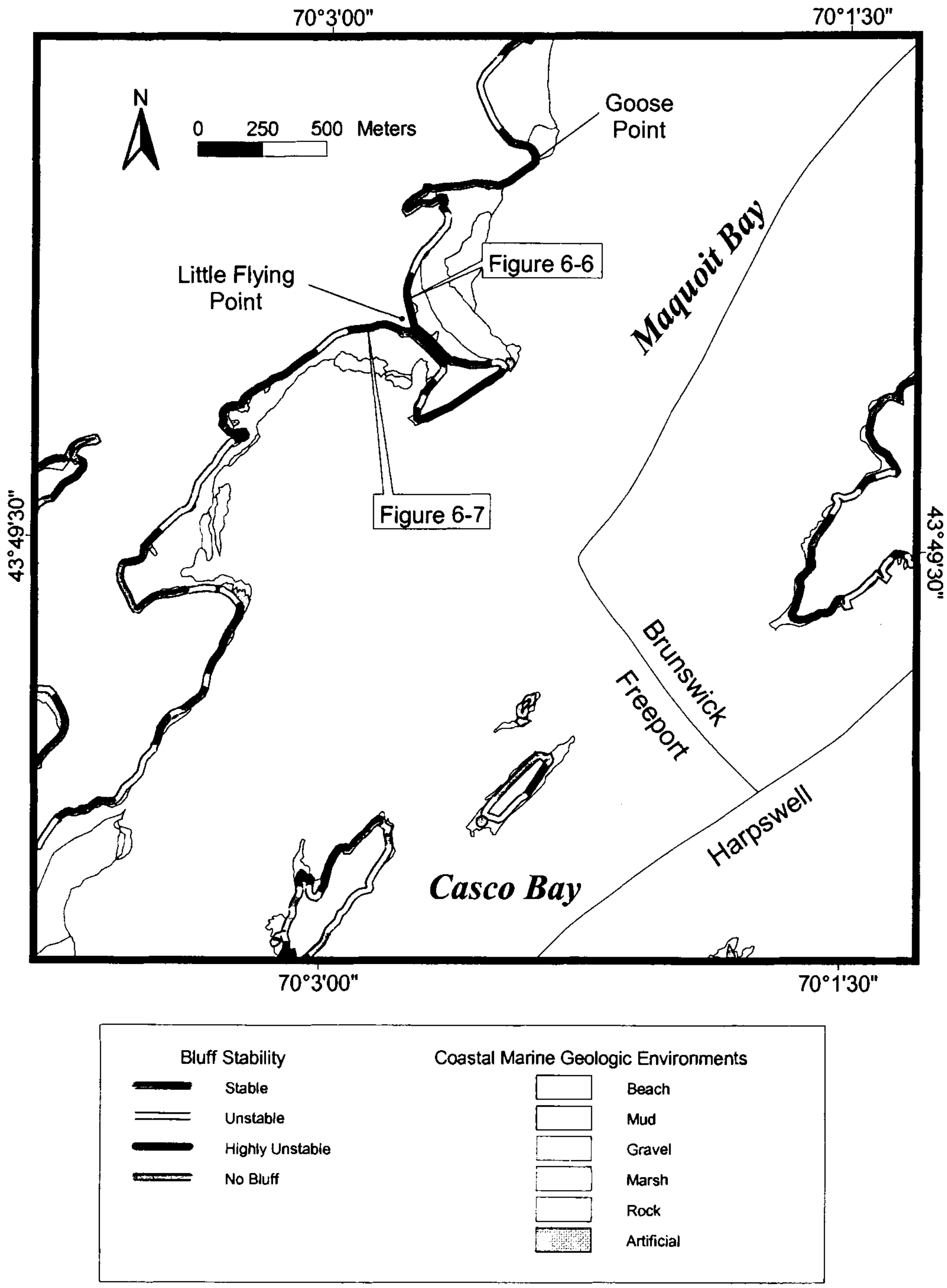

Figure 6-5: Location of Little Flying Point.

Figure 6-6: Eroding bluff on the north side of Little Flying Point, Freeport.

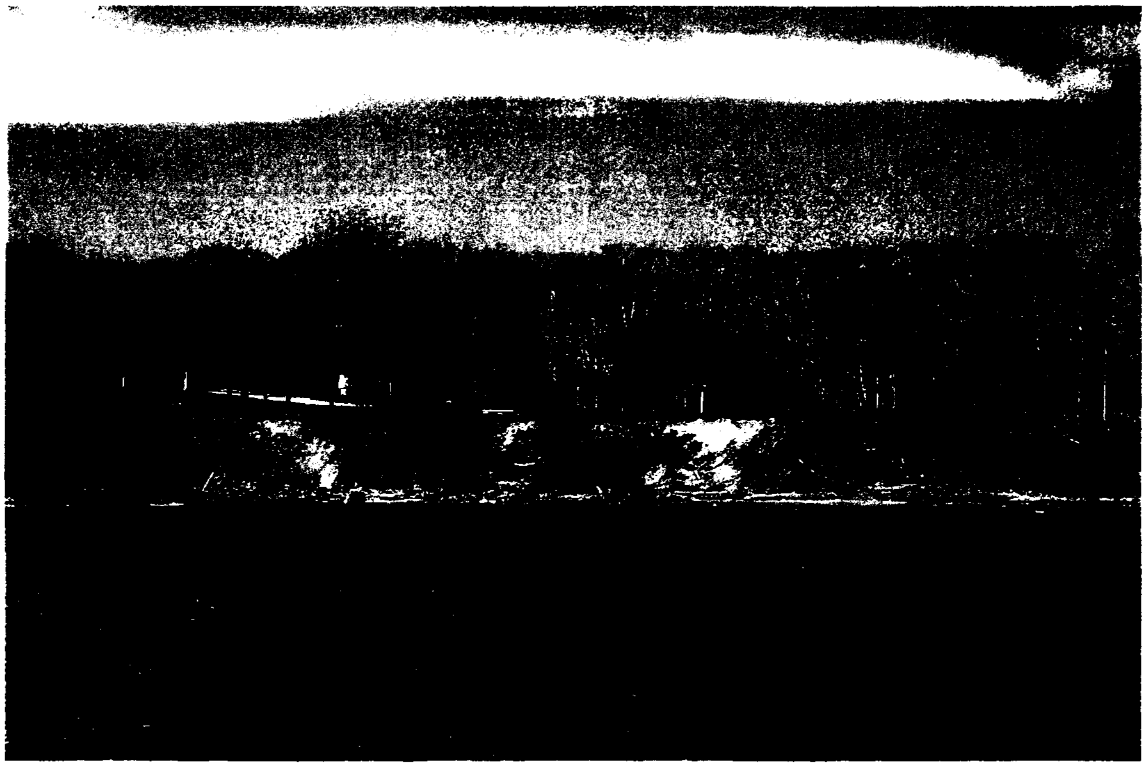

Figure 6-7: Eroding bluff on the south side of Little Flying Point, Freeport.

The bluff on the south side of Little Flying Point also exhibits high instability, however the short-term retreat rate is considerably less than the north (0.01 m/yr ± 0.02) (Smith, 1990). The orientation of this bluff is to the SSE (175°) with an exposure of 3.8 km and a 181 m wide mudflat in the intertidal zone. There are some minor areas of an eroding salt marsh in the intertidal zone and those portions of the bluff landward of the marsh exhibit signs of stability (Smith, 1990), suggesting that the nature of the intertidal zone is a controlling factor of the stability of the bluff in this area. However, this marsh rests on a landslide deposit (Kelley, pers. comm.) and therefore the bluff is in a stage of stability as demonstrated by the evolutionary cycle of bluff erosion as demonstrated by Kelley and Hay (1986) (Figure 2-5). Increased erosion from surface runoff is a result of the construction of the campground which cleared off most of the trees, established lawns, and emplaced subsurface drainage pipes that discharge onto the bluff face (Smith, 1990). Human activities on Little Flying Point appear to have had the greatest influence on the stability of the bluffs in this area, although contributions to instability from orientation and exposure also play a major role.

6.3.3. Little River.

The bluff at Little River is located to the west of the mouth of the Little River in Freeport and is at the head of the bay bounded to the west by Wolf Neck and to the east by Flying Point Neck (Figure 6-8). It is fronted by a 32 m eroding salt marsh with wide, shallow mud flat seaward of the marsh (Timson, 1983). The upland portion of this bluff is farmland and has been so since at least 1940 (Smith, 1990). The presence of a scarp and shrub vegetation on the face allowed for it to be originally mapped by

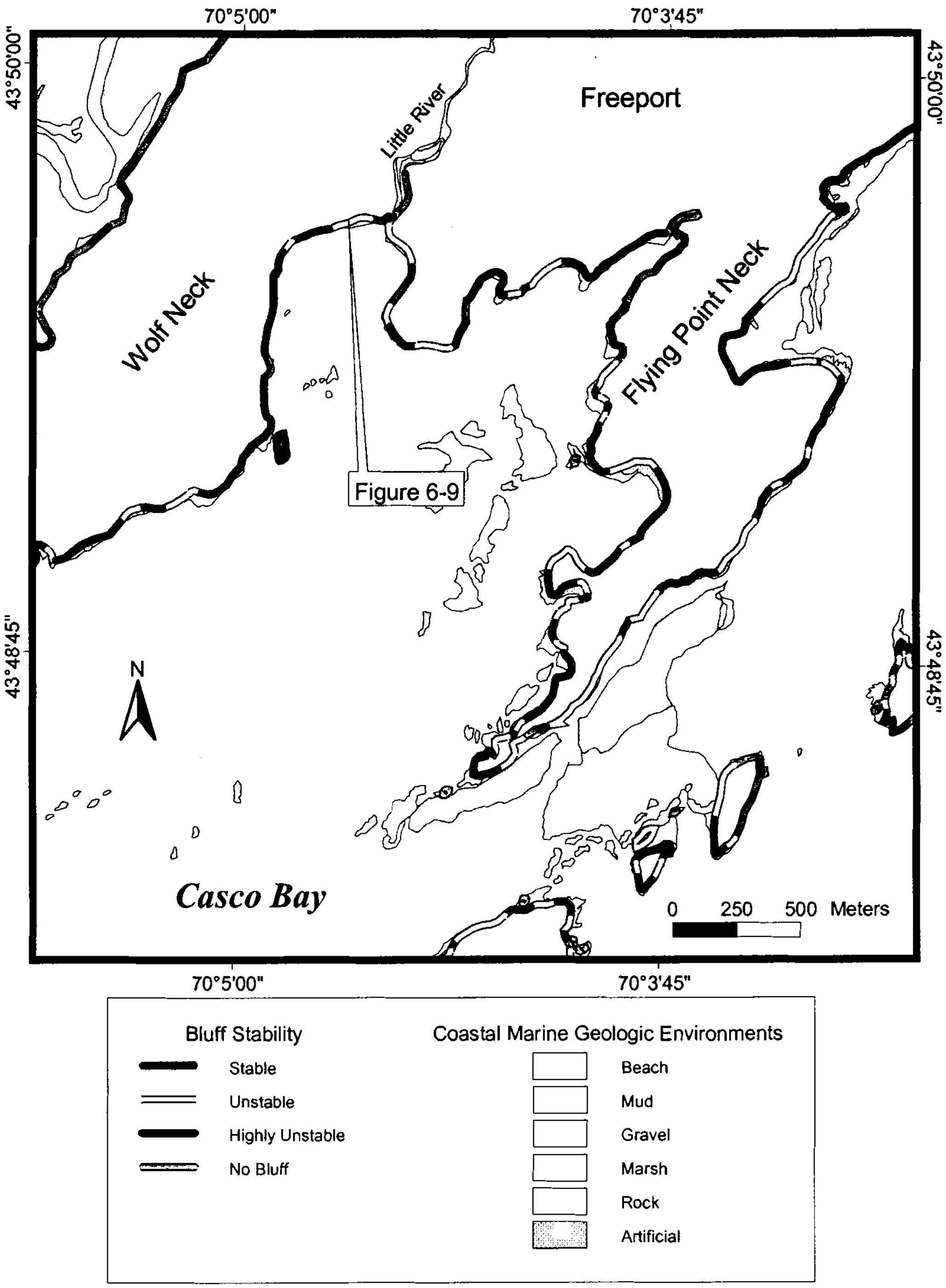

Figure 6-8: Location of the bluff at Little River.

Bryant et al. (1998) as unstable, but as a result of a recent slumping event, is now highly unstable (Figure 6-9). The short-term erosion rate for the slump deposits at the toe of this bluff is 0.82 m/yr ± 0.25 (Smith, 1990). Because the toe of this bluff is occupied by a salt marsh, and is not as prone to rapid undercutting at the toe by marine processes (except possibly during spring tides or as a result of storm surge), it is reasonable to conclude that internal characteristics and processes occurring in the upland, whether natural or human influenced, are primarily responsible for the instability of this bluff.

6.4. Application to the Remainder of Maine's Coast.

The procedures used in this study for measuring the different parameters that contribute to instability of bluffs in the Freeport, ME 7.5' Quadrangle are applicable to the remainder of the coast of Maine. The coast has a variety of orientations and exposures in each of the coastal compartments (Kelley, 1987). In the SW and the NE compartments, bluff erosion is of less importance than in the SC and the NC compartments. In the remainder of the indented embayments (SC) compartment to the east of Casco Bay, the estuaries and embayments become narrower, more irregular, and more elongate and the orientation of the bedrock strike becomes more north to south. Here, the coastline is more sheltered and it is likely that erosion by marine processes is of less importance than subaerial erosion. In the island-bay complex (NC), the highly exposed nature of the shorelines in the large bays and islands results in the likelihood of greater marine erosion of bluffs as well as subaerial erosion from surface water runoff and subsurface flow of groundwater. Subaerial erosion in the NC compartment may be

Figure 6-9: Eroding bluff on the west side of the mouth of the Little River, Freeport.

most significant compared to marine erosion in areas where there are protected harbors, such as in Rockland on the southwestern shore of Pencobscot Bay.

Chapter 7

CONCLUSIONS

The goal of this work was to determine the characteristics of bluffs that would cause them to be stable, unstable, or highly unstable. External characteristics, such as shoreline orientation, degree of exposure to incoming waves, width of the intertidal zone, and the type of intertidal environment, all contribute to determine the magnitude of marine erosion at the base of a bluff. Internal characteristics, such as the type of land use on top of a bluff, and the type of geologic material that it is composed of, contribute to the severity of subaerial erosion of the bluff as they affect how water moves on the surface and through the subsurface.

The average orientation of highly unstable bluffs in the Freeport quadrangle is to the southwest (191^{o}) with an average exposure of 2054 m. These bluffs are commonly located at the heads of bays, formed by the orientation of the elongate peninsulas in the region, or anywhere there is a high degree of exposure to incoming wave energy. The average width of the intertidal zone is 113 m and it is most commonly unvegetated ledges, mudflats, or low-energy beach deposits. The relatively narrow, unvegetated intertidal zones allow more energetic waves to attack the bases of highly unstable bluffs. The uplands are commonly forested, but partial clearing of vegetation and the construction of houses contributes to higher instability.

Unstable bluffs have some similar characteristics of highly unstable bluffs, but to a lesser degree. On average, they, like highly unstable bluffs, also face to the southwest (187^{o}). However, many unstable bluffs face to the southeast. Their average

intertidal width is 117 m with rock ledge or mudflat as the most usual type of intertidal environment. An undeveloped forested area is the most common type of land cover on the upland portion of unstable bluffs.

Stable bluffs have a variety of orientations, with an average orientation to the south (184°). Stable bluffs are more sheltered than unstable and highly unstable bluffs with an average exposure of 1140 m. Wide intertidal zones (170m average) composed of salt marsh vegetation are typical and result in less erosion by wave attack at the toe of stable bluffs. Stable bluffs are often forested or have grassland or agricultural fields in the upland. There are many bluffs mapped as stable that have houses and lawns in the upland, however more than half of them have some type of shoreline armoring structure at their bases, indicating a period of instability prior to the emplacement of the structures.

Areas where no bluffs exist are most commonly bare rock outcrops on the seaward ends of the peninsulas and on outlying islands. In these areas, wave energy is greatest as a result of high degrees of exposure. Any sediment that has accumulated in the past has been stripped off the ledges and removed from the coastal system.

The procedures used in this work are applicable to any portion of coastline, particularly in areas where there are a variety of orientations and exposures. Further work is needed to apply these procedures to the remainder of the coast of Maine in order to build a model that can be used to predict where chronic bluff erosion is and will continue to be a problem, and to use this information to assist in the creation of legislation to regulate development in these areas.

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Appendix

DATA TABLE GENERATED BY GIS ANALYSIS

Appendix 1: Data table generated by GIS analysis.

SAMPLE #	STABILITY	SHORELINE TYPE	INT_WIDTH (m)	EXPOSURE (m)	ORIENTATIO (deg)	UPLAND_CODE	INT_TYPE	SURFICIAL GEOLOGY	COMMENT
1	S	V	-	-		10		Presumpscot Formation	
2	S	V	-	-		10		Presumpscot Formation	
3	S	V	18.73	18.73	38.65	10		Presumpscot Formation	
4	S	V	-	-		10	Mudflat	Presumpscot Formation	
5	S	V	699.06	2000.85	186.00	10	Mudflat	Presumpscot Formation	
6	S	V	33.71	33.71	90.00	10	Salt Marsh	Salt Marsh	
7	S	V	0.00	10.44	259.04	7	Subtidal	Presumpscot Formation	
8	S	V	56.29	56.29	286.16	1		Presumpscot Formation	
10	S	V	28.15	28.15	194.37	1	Salt Marsh	Presumpscot Formation	
11	S	V	70.63	176.73	116.34	1		Presumpscot Formation	
12	S	V	62.79	155.20	275.00	1	Salt Marsh	Presumpscot Fm/Marine Fan	
13	S	V	235.68	1145.60	151.34	1		Presumpscot Formation	off edge of map
14	S	V	56.03	56.03	177.11	1	Salt Marsh	Presumpscot Formation	
15	X	X	12.21	12.21	311.02	10		Salt Marsh	
16	H	V	110.36	7351.23	200.75	4	Beach deposits	Presumpscot Formation	
18	S	V	21.83	24.37	146.06	1	Salt Marsh	Presumpscot Formation	
19	S	V	144.93	774.21	119.91	1		Presumpscot Formation	off edge of map
20	X	X	10.73	10.73	140.28	10	Man-Made Land	Artificial Fill	
21	U	L	88.36	2007.00	145.70	3	Ledge	Presumpscot Formation	
22	X	X	12.13	12.13	339.50	10	Salt Marsh	Salt Marsh	
23	X	X	94.58	94.58	131.35	10	Salt Marsh	Salt Marsh	
24	X	X	16.76	16.76	262.76	10	Salt Marsh	Salt Marsh	
26	S	L	119.28	2171.64	140.07	1		Presumpscot Formation	
27	X	X	18.31	18.31	133.19	10		Salt Marsh	
28	N	X	-	-		9	Ledge	Rock	rock
29	X	X	16.76	16.76	244.46	10	Salt Marsh	Salt Marsh	
30	S	L	52.72	2119.87	131.25	1		Presumpscot Formation	
31	S	A	78.41	1175.71	327.14	4	Mudflat	unknown	off edge of map
32	X	X	38.03	38.03	19.70	10	Subtidal	Presumpscot Formation	
33	H	L	147.94	147.94	200.75	4	Mudflat	unknown	
34	X	X	16.61	16.61	284.38	10	Subtidal	Salt Marsh	
35	U	V	184.79	2088.98	306.00	1	0	Thin Drift	

SAMPLE #	STABILITY	SHORELINE TYPE	INT_WIDTH (m)	EXPOSURE (m)	ORIENTATIO (deg)	UPLAND_CODE	INT_TYPE	SURFICIAL GEOLOGY	COMMENT
36	U	V	184.61	1591.68	316.00	1		Thin Drift	
37	S	V	456.33	456.33	210.03	3	Salt Marsh	Salt Marsh	
38	H	L	21.74	2097.39	123.94	3	Ledge	Presumpscot Formation	
39	X	X	17.74	17.74	170.85	10	Subtidal	Salt Marsh	
40	X	X	19.19	19.19	344.20	10	Subtidal	Salt Marsh	
41	N	V	47.51	47.51	17.54	1		Presumpscot Formation	
42	U	L	68.49	1760.16	327.50	1		Thin Drift	
43	S	V	48.58	48.58	144.95	1	Salt Marsh	Presumpscot Formation	
44	U	L	68.73	2104.87	135.00	1	Mudflat	Presumpscot Formation	
45	N	V	108.62	108.62	291.52	1		Thin Drift	
46	S	V	172.26	399.63	309.64	1		Thin Drift	
47	S	V	81.81	81.81	186.86	4		Presumpscot Formation	
48	S	V	130.03	285.40	202.73	1	Mudflat	Presumpscot Formation	
49	U	L	11.23	2012.81	317.00	1		Thin Drift	
50	S	V	213.99	2023.70	130.64	4		Presumpscot Formation	
51	S	A	50.68	50.68	141.16	7		Presumpscot Formation	armored
52	S	V	182.33	182.33	76.49	1		Salt Marsh	
53	S	V	53.98	53.98	292.01	3		Presumpscot Formation	
54	S	V	200.77	200.77	318.43	1	Mudflat	Thin Drift	
55	N	V	119.51	119.51	111.15	3		Presumpscot Formation	
56	S	V	303.14	303.14	28.71	1	Mudflat	Presumpscot Formation	
57	S	N	147.55	147.55	125.58	1	Mudflat	Presumpscot Formation	
58	N	X	-	-		9	0	Rock	rock
59	S	L	89.05	2492.15	283.95	1	Ledge	Thin Drift	
60	N	V	229.52	229.52	284.80	1	Salt Marsh	Presumpscot Formation	
61	S	V	-	-		1		Presumpscot Formation	endpoint
62	S	V	10.93	10.93	135.00	1	Mudflat	Presumpscot Formation	off edge of map
63	H	L	245.17	820.08	17.12	1	Ledge	Presumpscot Formation	
64	S	V	694.80	1457.19	162.52	1	Mudflat	Presumpscot Formation	
65	S	V	695.13	695.13	173.81	3		Presumpscot Formation	
66	S	V	443.34	443.34	205.03	2		Salt Marsh	
68	S	V	109.10	475.89	140.99	1	0	Presumpscot Formation	
69	S	L	39.17	2394.23	284.87	2	Ledge	Thin Drift	
70	S	V	462.71	462.71	281.09	1	Mudflat	Presumpscot Formation	

SAMPLE #	STABILITY	SHORELINE TYPE	INT_WIDTH (m)	EXPOSURE (m)	ORIENTATIO (deg)	UPLAND_CODE	INT_TYPE	SURFICIAL GEOLOGY	COMMENT
71	S	V	151.60	151.60	31.57	1	Coarse-grained flat	Presumpscot Formation	
72	S	V	199.22	790.47	130.40	3		Presumpscot Formation	off edge of map
73	H	L	386.74	386.74	253.28	1	Ledge	Presumpscot Formation	
74	S	V	678.71	678.71	77.26	1		Salt Marsh	
75	X	X	-	-		3		Salt Marsh	
76	N	L	348.72	541.26	309.42	1		Thin Drift	
77	N	L	61.02	2221.76	334.58	1		Thin Drift	
78	S	L	15.10	783.96	156.37	4		Presumpscot Formation	
80	X	X	-	-		11		Salt Marsh	not mapped
81	S	A	263.97	4447.50	57.65	4	Salt Marsh	Artificial Fill	off edge of map
82	S	A	203.19	2744.95	200.78	4	Salt Marsh	Presumpscot Formation	armored
83	S	A				7	Salt Marsh	Artificial Fill	duplicate see 82
84	S	V	160.44	1068.92	77.89	1		Thin Drift	
85	S	A	253.58	3952.77	41.26	7		Artificial Fill	armored
86	N	X	-	-		9	Beach deposits	Rock	rock
87	S	A	60.53	917.90	249.68	7	Salt Marsh	Artificial Fill	armored
88	H	L	40.06	2866.63	144.46	1		Presumpscot Formation	
89	X	X	-	-		1	Mudflat	Salt Marsh	not mapped
90	N	L	1132.57	1132.57	306.69	1		Thin Drift	
91	S	V	77.43	2618.38	350.67	1	Ledge	Thin Drift	
92	X	X	-	-		11	Mudflat	Salt Marsh	not mapped
93	H	L	11.03	4077.08	147.72	1		Thin Drift	
94	S	V	31.36	783.12	133.94	4	Ledge	Presumpscot Formation	
95	S	A	46.05	713.22	107.24	4	Ledge	Thin Drift	armored
96	N	X	-	-		3		Salt Marsh	not mapped
97	H	L	204.33	204.33	23.30	2	Mudflat	Presumpscot Formation	
98	S	A	20.36	20.36	141.10	11		Artificial Fill	armored
99	U	V	384.08	384.08	160.97	3	Salt Marsh	Presumpscot Formation	
100	S	A	19.15	19.15	340.95	3	Salt Marsh	Artificial Fill	armored
101	N	X	-	-		9	Mudflat	Rock	rock
102	S	V	99.97	848.23	111.67	1	Coarse-grained flat	Salt Marsh	
103	H	L	32.15	107.81	200.60	1	Beach deposits	Thin Drift	
104	S	V	-	-		1		Thin Drift	endpoint
105	H	L	532.41	1900.78	185.94	3	Ledge	Thin Drift	

SAMPLE #	STABILITY	SHORELINE TYPE	INT_WIDTH (m)	EXPOSURE (m)	ORIENTATIO (deg)	UPLAND_CODE	INT_TYPE	SURFICIAL GEOLOGY	COMMENT
106	S	V	115.10	115.10	147.87	1		Salt Marsh	
107	S	N	138.77	825.03	320.63	1	Ledge	Thin Drift	
108	N	L	428.70	1305.80	330.58	1		Thin Drift	
109	S	V	83.66	83.66	337.75	1		Presumpscot Formation	
110	S	V	427.01	1008.50	110.56	2		Presumpscot Formation	
111	U	V	-	-		1	Ledge	Thin Drift	endpoint
112	U	V	458.01	458.01	143.55	1	Mudflat	Presumpscot Formation	
113	S	V	76.38	623.39	126.29	3	Coarse-grained flat	Presumpscot Formation	
114	H	L	28.44	96.76	205.98	1	0	Rock	
115	U	V	30.38	30.30	110.38	1	Beach deposits	Thin Drift	off edge of map
116	S	V	519.31	519.31	87.35	1	Beach deposits	Presumpscot Formation	
117	S	N	34.69	1845.28	315.13	4	Ledge	Thin Drift	
118	U	V	177.60	338.88	139.90	4		Presumpscot Formation	
119	S	V	1189.15	1189.15	155.32	3		Presumpscot Formation	
120	S	L	0.00	726.03	336.21	1		Thin Drift	
121	S	V	15.16	36.93	240.62	1		Thin Drift	
122	N	X	-	-		9	Ledge	Rock	rock
123	H	L	567.52	567.52	240.53	3	Ledge	Presumpscot Formation	
124	U	L	18.52	790.19	121.20	4	Ledge	Presumpscot Formation	
125	H	L	88.75	88.75	189.56	1		Presumpscot Formation	
126	S	V	709.86	1661.19	67.47	2		Presumpscot Formation	
127	S	V	119.97	119.97	347.74	1		Thin Drift	
128	U	V	-	-		1	0	Thin Drift	endpoint
130	S	V	159.52	159.52	323.18	4		Presumpscot Formation	
131	H	L	17.19	2713.51	162.55	1	Beach deposits	Thin Drift	
132	N	L	42.30	2085.22	259.49	4		Thin Drift	
133	S	V	8.19	8.19	225.00	1	Mudflat	Thin Drift	
134	H	L	15.92	2214.26	127.78	2	Salt Marsh	Presumpscot Fm/Marine Fan	
135	S	N	1373.89	1373.89	83.00	1		Presumpscot Formation	
136	N	L	578.35	1007.26	337.20	1	Mudflat	Thin Drift	
137	S	A	36.35	715.55	139.34	6	Man-Made Land	Presumpscot Formation	armored
138	H	L	56.59	1376.15	74.70	1	Mudflat	Rock	
139	H	L	381.36	1339.29	286.80	2	Ledge	Presumpscot Formation	
140	S	V	26.18	26.18	295.17	1		Salt Marsh	

SAMPLE #	STABILITY	SHORELINE TYPE	INT_WIDTH (m)	EXPOSURE (m)	ORIENTATIO (deg)	UPLAND_CODE	INT_TYPE	SURFICIAL GEOLOGY	COMMENT
141	N	X	-	-		1	0	Rock	rock
142	N	L	-	-		9	Ledge	Rock	rock
143	U	L	16.25	4933.01	243.07	1	Ledge	Rock	
144	S	A	34.90	819.18	144.78	4		Presumpscot Fm/Marine Fan	armored
145	U	N	34.91	3689.54	189.71	1		Thin Drift	
146	N	X	-	-		9	Ledge	Rock	rock
147	U	L	-	-		1	Ledge	Thin Drift	endpoint
148	S	V	652.65	1524.31	279.23	1		Salt Marsh	
149	S	V	276.97	276.97	212.37	1	Salt Marsh	Thin Drift	
150	U	L	392.47	613.19	298.91	2		Thin Drift	
151	U	L	9.01	68.26	133.11	1		Thin Drift	off edge of map
152	N	X	174.27	1077.93	139.74	2	Salt Marsh	Thin Drift	
153	U	V	89.39	89.39	211.10	1	Mudflat	Presumpscot Formation	
154	S	V	69.28	69.28	117.65	1		Thin Drift	
155	S	A	10.03	2480.14	304.56	1		Thin Drift	armored
156	N	X	-	-		9	Ledge	Rock	rock
157	H	L	56.21	2400.50	156.80	1		Thin Drift	
158	S	V	74.90	74.90	124.04	1	Mudflat	Salt Marsh	
159	S	V	329.89	349.89	254.38	2		Thin Drift	
160	N	X	-	-		9	Ledge	Rock	rock
161	N	L	-	-		1		Thin Drift	rock
162	U	V	465.26	465.26	44.55	4	Ledge	Presumpscot Formation	
163	S	V	220.04	750.12	168.80	4		Presumpscot Formation	
164	S	V	117.40	117.40	180.00	3		Salt Marsh	
165	U	L	19.71	954.23	137.67	1	0	Thin Drift	
166	S	V	96.40	96.40	137.62	1	Salt Marsh	Presumpscot Formation	
168	H	L	56.72	2431.98	149.18	1	Ledge	Presumpscot Formation	
169	N	X	-	-		9	Ledge	Rock	rock
170	U	L	6.14	130.72	160.59	1		Thin Drift	
171	S	N	30.59	113.30	276.80	1		Presumpscot Formation	
172	N	L	30.02	111.17	321.84	1	Salt Marsh	Thin Drift	
173	U	L	12.69	694.21	146.54	1	Ledge	Thin Drift	
174	S	V	79.00	312.52	11.90	4	Salt Marsh	Salt Marsh	
175	S	V	147.32	748.61	306.33	3	Ledge	Thin Drift	

SAMPLE #	STABILITY	SHORELINE TYPE	INT_WIDTH (m)	EXPOSURE (m)	ORIENTATIO (deg)	UPLAND_CODE	INT_TYPE	SURFICIAL GEOLOGY	COMMENT
176	H	L	20.57	2602.44	309.60	2	Beach deposits	Thin Drift	
177	N	L	43.99	4257.30	248.92	1		Thin Drift	
178	S	N	15.94	831.56	315.36	1		Thin Drift	
179	U	N	36.82	2383.35	119.18	4		Thin Drift	
180	S	A	229.94	2800.06	120.41	4		Presumpscot Formation	armored
181	U	L	803.93	803.93	149.43	1		Thin Drift	
182	U	L	0.00	1737.27	170.33	1		Thin Drift	
183	U	N	15.23	1106.74	273.75	1		Thin Drift	
184	H	L	214.27	1522.16	301.10	1	Ledge	Presumpscot Formation	
185	N	L	0.00	1109.19	142.78	1		Thin Drift	off edge of map
186	N	L	4.22	515.97	309.10	1	Ledge	Thin Drift	
187	U	V	198.47	1050.00	284.08	4	Mudflat	Thin Drift	
188	N	X	-	-		9	Ledge	Rock	rock
190	H	L	127.62	127.62	111.13	1	Mudflat	Rock	
191	U	L	21.44	1619.76	143.13	1		Thin Drift	off edge of map
192	N	X	-	-		9	Ledge	Rock	rock
193	H	L	21.82	507.20	245.96	1	Ledge	Thin Drift	
194	S	N	45.68	2511.67	175.97	4		Thin Drift	
195	U	L	128.14	698.42	175.84	4		Presumpscot Formation	
196	H	L	7.05	7556.46	152.73	9	Ledge	Rock	
197	S	V	20.06	20.06	71.01	2	Subtidal	Presumpscot Formation	
198	H	L	44.23	1030.40	224.88	2	Ledge	Thin Drift	
199	U	L	15.27	3793.99	346.87	1		Thin Drift	
201	H	L	117.57	1645.02	349.63	1		Presumpscot Formation	
202	N	L	16.27	750.46	335.40	1	Ledge	Thin Drift	
203	H	L	20.49	2464.60	340.52	1		Thin Drift	
204	N	X	0.00	229.04	60.18	2	Subtidal	Rock	
205	N	X	-	-		9	Ledge	Rock	rock
206	N	X	-	-		9	Subtidal	Rock	rock
207	N	L	26.06	649.66	311.22	9	Ledge	Rock	
208	N	X	-	-		9	Mudflat	Rock	rock
209	N	X	-	-		9	Ledge	Rock	rock
210	U	L	63.97	3336.41	79.45	3		Presumpscot Formation	
211	U	L				3	Ledge	Presumpscot Formation	duplicate 210

SAMPLE #	STABILITY	SHORELINE TYPE	INT_WIDTH (m)	EXPOSURE (m)	ORIENTATIO (deg)	UPLAND_CODE	INT_TYPE	SURFICIAL GEOLOGY	COMMENT
212	N	X	-	-		9	Subtidal	Rock	rock
213	N	V	21.24	21.24	75.85	1		Presumpscot Formation	
214	U	L	94.65	309.31	58.80	1	Mudflat	Rock	
216	U	L	734.96	734.96	334.90	1		Presumpscot Formation	
217	S	N	10.21	1382.69	45.00	1		Thin Drift	
218	H	L	70.86	3208.33	31.42	1	Ledge	Thin Drift	
219	H	L				1	Ledge	Thin Drift	duplicate 218
220	N	X	-	-		9	Ledge	Rock	rock
221	N	L	16.35	1302.20	304.93	1		Thin Drift	
222	H	L	23.32	6446.50	197.32	1	Ledge	Thin Drift	
223	N	V	25.94	35.94	77.94	1		Presumpscot Formation	
224	N	X	139.86	139.86	287.05	2	Ledge	Thin Drift	
225	N	X	-	-		9	Ledge	Rock	rock
226	S	V	120.51	2141.07	150.12	4	Salt Marsh	Presumpscot Formation	
227	N	V	71.59	71.59	223.22	1		Presumpscot Formation	
228	N	V	300.55	600.65	328.54	1		Salt Marsh	
229	H	L	31.21	2509.51	92.16	2	Ledge	Thin Drift	
230	N	V	29.18	29.10	285.14	1	Salt Marsh	Presumpscot Formation	
231	N	V	40.47	40.47	110.56	1		Salt Marsh	
232	U	L	317.79	2019.36	332.47	1		Thin Drift	
233	N	V	18.04	18.04	296.57	1	Mudflat	Presumpscot Formation	
234	N	X	-	-		9	Ledge	Rock	rock
235	N	X	-	-		9	Ledge	Rock	rock
236	U	L	16.32	2756.79	135.00	1	Ledge	Thin Drift	
237	N	X	-	-		9	Ledge	Rock	rock
238	N	X	-	-		9	Ledge	Rock	rock
240	U	N	11.68	190.19	233.08	1	Ledge	Thin Drift	
241	S	A	327.03	2988.37	190.73	7	Ledge	Presumpscot Formation	armored
242	U	L	13.18	2606.93	78.36	1		Thin Drift	
243	N	X	-	-		9	Ledge	Rock	rock
244	S	V	94.03	2007.83	135.00	3		Presumpscot Formation	
245	U	V	280.52	280.52	222.68	1		Thin Drift	
246	N	L	13.12	2241.57	288.15	1	Ledge	Thin Drift	
247	N	L	0.00	2264.28	312.46	1	0	Thin Drift	

SAMPLE #	STABILITY	SHORELINE TYPE	INT_WIDTH (m)	EXPOSURE (m)	ORIENTATIO (deg)	UPLAND_CODE	INT_TYPE	SURFICIAL GEOLOGY	COMMENT
248	S	V	381.97	2159.72	155.79	4		Presumpscot Formation	
249	N	X	-	-		9	Ledge	Rock	rock
250	N	X	-	-		1	Beach deposits	Rock	rock
251	S	V	-	-		4	Ledge	Presumpscot Formation	endpoint
252	N	X	-	-		1	Ledge	Rock	rock
253	U	V	26.59	193.13	80.45	1		Thin Drift	
254	N	L	20.91	1180.27	294.49	1	Ledge	Sand/Gravel Beaches	
255	S	L	4.94	5012.92	138.91	4	Ledge	Thin Drift	
256	U	V	83.40	1068.73	36.74	1	Ledge	Thin Drift	
258	U	L	-	-		1		Thin Drift	endpoint
259	N	X	-	-		9	Ledge	Rock	rock
260	N	L	22.53	2225.00	315.17	4	Ledge	Thin Drift	
261	N	L	21.55	1249.87	138.90	1		Thin Drift	
262	S	N	5.07	4392.61	150.75	4		Thin Drift	
263	N	X	-	-		9	Ledge	Rock	rock
264	N	X	-	-		9		Rock	rock
265	N	L	29.35	2538.58	338.39	1		Thin Drift	
266	N	X	-	-		9	Ledge	Rock	rock
267	N	X	-	-		9	Ledge	Rock	rock
268	N	X	-	-		9	Ledge	Rock	rock
269	U	N	66.89	2374.80	275.92	2	Ledge	Thin Drift	off edge of map
270	N	L	115.32	3038.84	152.02	1	Mudflat	Thin Drift	
271	U	L	86.76	599.72	0.00	1	Ledge	Pleistocene Nearshore	
272	S	N	207.96	2348.84	274.71	1	Ledge	Thin Drift	
273	N	L	27.73	27.73	354.33	1	Mudflat	Thin Drift	
274	N	L	-	-		9	Ledge	Rock	rock
275	N	X	-	-		9	Ledge	Rock	rock
276	U	L	18.85	7146.63	249.56	1		Thin Drift	
277	N	X	-	-		9	Ledge	Rock	rock
278	S	V	-	-		1		Pleistocene Nearshore	endpoint
279	H	L	19.67	3672.89	317.29	2		Thin Drift	
280	H	L	15.82	2417.96	326.49	2	Ledge	Thin Drift	
281	H	L	79.74	1703.43	299.25	1		Thin Drift	
282	N	X	-	-		9	Ledge	Rock	rock

SAMPLE #	STABILITY	SHORELINE TYPE	INT_WIDTH (m)	EXPOSURE (m)	ORIENTATIO (deg)	UPLAND_CODE	INT_TYPE	SURFICIAL GEOLOGY	COMMENT
283	U	L	31.10	3499.36	75.84	1		Thin Drift	off edge of map
284	S	V	-	-		1		Pleistocene Nearshore	endpoint
285	S	V	160.79	160.79	197.88	3	Beach deposits	Sand/Gravel Beaches	
286	N	L	28.44	1910.52	292.61	1	0	Thin Drift	
287	N	L	-	-		9	Ledge	Rock	rock
288	S	N	24.17	335.84	35.21	1		Sand/Gravel Beaches	
289	N	L	-	-		9	Subtidal	Rock	rock
290	U	L	16.11	392.31	143.65	1		Thin Drift	
291	N	X	-	-		9	Ledge	Rock	rock
292	N	L	32.73	2203.03	293.71	1		Thin Drift	
293	U	L	45.24	2795.51	279.98	1		Thin Drift	
294	N	L	20.98	20.98	40.65	1	Ledge	Thin Drift	
296	N	X	-	-		1	Ledge	Rock	rock
297	U	L	19.42	2049.00	325.00	1	0	Thin Drift	
298	N	X	-	-		9	Beach deposits	Rock	rock
299	N	L	15.90	1134.81	347.73	1		Thin Drift	
300	N	L	94.39	1340.68	16.87	1	Ledge	Thin Drift	
301	N	L	16.40	117.57	149.47	1	Beach deposits	Thin Drift	
302	N	X	-	-		9	Ledge	Rock	rock
303	N	X	-	-		9	Beach deposits	Rock	rock
304	N	L	72.86	2860.13	289.35	1		Thin Drift	
305	U	L	19.28	217.37	90.00	1	0	Thin Drift	
306	N	L	3.14	169.67	313.26	1	Ledge	Rock	
307	N	L	2.13	1886.29	317.00	1		Thin Drift	endpoint
308	N	X	-	-		9	Ledge	Rock	rock
309	S	N	155.08	1400.60	344.36	1		Thin Drift	
310	N	L	22.97	190.95	128.16	1	Ledge	Thin Drift	
311	H	L	123.33	325.92	133.96	1		Thin Drift	
312	U	L	59.94	2346.17	343.20	1	0	Thin Drift	
313	N	L	23.87	3943.74	126.11	1		Thin Drift	
314	N	L	3.47	4640.85	135.00	1	Ledge	Thin Drift	
315	N	X	-	-		9	Ledge	Rock	rock
316	U	N	202.49	467.49	270.00	1	Ledge	Thin Drift	
317	S	N	35.83	35.83	32.47	1		Thin Drift	

SAMPLE #	STABILITY	SHORELINE TYPE	INT_WIDTH (m)	EXPOSURE (m)	ORIENTATIO (deg)	UPLAND_CODE	INT_TYPE	SURFICIAL GEOLOGY	COMMENT
319	N	L	22.49	6778.75	254.10	1	Ledge	Thin Drift	
320	N	X	-	-		9	Ledge	Rock	rock
321	S	N	29.98	28.02.33	192.66	1	Beach deposits	Thin Drift	
322	N	X	-	-		9	Beach deposits	Rock	rock
323	S	N	300.22	3473.05	17.22	4		Sand/Gravel Beaches	off edge of map
324	N	L	11.70	941.85	277.13	1	Beach deposits	Thin Drift	
325	U	L	0.00	4173.46	145.76	1		Thin Drift	off edge of map
326	N	L	0.00	3465.48	165.38	1	Subtidal	Thin Drift	off edge of map
327	S	N	0.00	1478.59	286.49	1		Thin Drift	
328	U	L	149.57	149.57	124.56	1	Ledge	Thin Drift	
329	N	L	0.00	1242.21	217.97	1		Thin Drift	
330	U	N	50.09	410.57	333.60	1	Ledge	Thin Drift	
331	S	N	45.30	2444.29	302.00	5		Till	
333	S	N	29.48	3121.29	195.16	1		Thin Drift	off edge of map
334	S	N	116.15	4339.66	283.14	7		Sand/Gravel Beaches	
335	N	X	-	-		9	Mudflat	Rock	rock
336	N	L	-	-		1	0	Thin Drift	endpoint
337	N	X	-	-		9		Rock	rock
338	N	L	-	-		9	Ledge	Rock	rock
339	H	L	10.69	969.30	149.47	1	Ledge	Thin Drift	
340	U	V	-	-		1	0	Thin Drift	endpoint
341	N	X	-	-		9		Rock	rock
342	N	X	-	-		9		Rock	rock
343	N	X	-	-		9	Ledge	Rock	rock
344	N	X	-	-		9		Rock	rock
345	N	L	-	-		9	Beach deposits	Rock	rock
346	S	N	144.56	6419.64	279.88	1		Sand/Gravel Beaches	
347	N	X	-	-		9	Ledge	Rock	rock
348	N	L	-	-		1		Thin Drift	endpoint
350	N	X	-	-		9	Ledge	Rock	rock
351	N	L	65.31	3341.66	74.19	1	Ledge	Thin Drift	
352	N	L	-	-		1		Thin Drift	rock
353	N	X	-	-		1		Rock	rock
354	N	L	36.79	156.75	139.49	4		Thin Drift	off edge of map

SAMPLE #	STABILITY	SHORELINE TYPE	INT_WIDTH (m)	EXPOSURE (m)	ORIENTATIO (deg)	UPLAND_CODE	INT_TYPE	SURFICIAL GEOLOGY	COMMENT
355	N	X	-	-		9	Ledge	Rock	rock
356	N	X	-	-		9	Ledge	Rock	rock
358	S	N	175.03	334.20	271.84	1		Presumpscot Formation	
359	N	L	10.30	144.62	341.33	1		Thin Drift	
360	S	A	63.80	272.48	81.55	3		Thin Drift	armored
361	N	L	115.70	115.70	76.72	1	Ledge	Thin Drift	
362	N	L	271.09	2372.13	347.67	1		Till	
363	N	L	44.81	4874.44	267.31	1	Ledge	Thin Drift	
364	S	A	0.00	1233.61	184.98	1		Thin Drift	armored
365	N	L	-	-		1		Presumpscot Formation	endpoint
366	U	N	37.69	4486.52	14.44	1	0	Presumpscot Formation	
367	S	N	36.45	5095.44	318.81	4		Presumpscot Formation	
368	N	L	230.25	230.25	300.10	1	0	Thin Drift	
369	N	L	22.21	2109.90	74.16	1	0	Thin Drift	
370	N	L	-	-		9	Ledge	Rock	rock
371	U	L	2.32	1613.93	150.25	1	Ledge	Till	off edge of map
372	S	N	77.92	871.11	128.96	4		Sand/Gravel Beaches	off edge of map
374	N	L	41.65	3989.24	307.71	3		Thin Drift	
376	S	V	463.29	463.29	180.00	7		Presumpscot Formation	
377	N	L	34.08	621.97	315.08	1		Thin Drift	
378	S	N	24.90	15.78	141.95	1	Ledge	Sand/Gravel Beaches	off edge of map
379	S	V	515.75	515.75	95.44	4		Presumpscot Formation	
380	N	L	-	-		9	Ledge	Rock	rock
381	N	X	-	-		9	Ledge	Rock	rock
382	N	L	-	-		9	Ledge	Rock	rock
383	N	L	37.80	1049.76	96.82	1	0	Thin Drift	
384	S	N	55.81	626.61	108.23	4		Sand/Gravel Beaches	
385	S	V	84.71	7323.72	7.13	1		Thin Drift	
386	S	A	504.51	504.51	301.44	4	Ledge	Presumpscot Formation	armored
387	U	L	-	-		1		Till	endpoint
388	U	L	22.81	1799.06	119.52	3		Thin Drift	off edge of map
389	S	N	109.62	2811.91	344.85	1		Sand/Gravel Beaches	
390	S	N	-	-		9		Sand/Gravel Beaches	endpoint
391	S	V	-	-		9	Mudflat	Sand/Gravel Beaches	endpoint

SAMPLE #	STABILITY	SHORELINE TYPE	INT_WIDTH (m)	EXPOSURE (m)	ORIENTATIO (deg)	UPLAND_CODE	INT_TYPE	SURFICIAL GEOLOGY	COMMENT
392	S	L	28.32	6413.30	292.87	1	0	Thin Drift	
393	S	V	796.86	796.86	61.05	4		Thin Drift	
394	U	L	14.97	1381.82	303.42	1		Till	
395	S	A	105.27	105.27	138.64	3		Thin Drift	armored
396	S	N	95.52	593.51	326.85	4		Presumpscot Formation	
397	N	L	34.10	794.45	148.16	1	0	Thin Drift	
399	S	V	213.31	363.53	289.15	1	Ledge	Thin Drift	
400	S	N	262.22	262.22	76.79	1		Sand/Gravel Beaches	
401	S	V	-	-		2		Presumpscot Formation	endpoint
402	S	N	24.44	1577.99	106.43	4		Sand/Gravel Beaches	off edge of map
403	S	V	70.50	70.50	111.98	3	Salt Marsh	Salt Marsh	
404	N	X	-	-		9	0	Rock	rock
405	S	L	25.39	336.64	127.29	4		Thin Drift	
406	N	L	41.14	4605.84	314.60	1	0	Thin Drift	
407	N	L	87.10	87.10	90.00	1	Beach deposits	Thin Drift	
408	S	V	49.80	447.81	133.90	1	Beach deposits	Thin Drift	off edge of map
409	S	N	129.50	1511.76	323.44	3		Presumpscot Formation	
410	S	V	91.10	310.46	191.58	1		Presumpscot Formation	
411	N	L	-	-		4	Beach deposits	Thin Drift	endpoint
412	N	L	-	-		4		Thin Drift	endpoint
413	N	L	-	-		1	Beach deposits	Rock	rock
414	S	V	67.76	758.98	1.55	1	Ledge	Thin Drift	
415	S	N	150.57	230.24	225.58	1	Mudflat	Sand/Gravel Beaches	off edge of map
416	S	V	61.38	230.89	315.08	1		Presumpscot Formation	
417	S	N	52.78	52.78	333.00	3	Mudflat	Thin Drift	
420	U	N	-	-		10	Ledge	Rock	endpoint
421	U	N	-	-		10	Ledge	Rock	endpoint
423	N	L	116.32	1572.37	311.81	3		Thin Drift	
424	N	L	-	-		3		Thin Drift	endpoint
426	N	X	-	-		9	Ledge	Rock	rock
427	N	L	-	-		2		Thin Drift	endpoint
428	S	V	74.55	74.55	40.10	3		Thin Drift	
433	S	N	19.18	876.11	321.18	1		Thin Drift	
434	N	X	-	-		9	Ledge	Rock	rock

SAMPLE #	STABILITY	SHORELINE TYPE	INT_WIDTH (m)	EXPOSURE (m)	ORIENTATIO (deg)	UPLAND_CODE	INT_TYPE	SURFICIAL GEOLOGY	COMMENT
437	N	L	13.67	4703.53	323.89	3	Ledge	Thin Drift	
438	N	L	-	-		3	Ledge	Thin Drift	endpoint
439	S	N	-	-		3	Beach deposits	Thin Drift	endpoint
441	N	L	16.97	880.35	320.47	1	Ledge	Thin Drift	
443	N	L	-	-		1		Thin Drift	endpoint
444	N	L	-	-		1		Thin Drift	endpoint
445	N	L	-	-		1		Thin Drift	endpoint
446	N	L	-	-		1	Subtidal	Thin Drift	endpoint
447	N	L	-	-		4		Thin Drift	endpoint
448	S	N	-	-		4		Thin Drift	endpoint
450	S	V	-	-		1		Presumpscot Formation	endpoint
451	S	L	-	-		4		Thin Drift	endpoint

BIOGRAPHY OF THE AUTHOR

Corinn C. Keblinsky was born in Saratoga Springs, NY on February 26th, 1975. She grew up in Greenfield Center, NY and graduated from Saratoga Springs High School in 1993. She attended college at Plattsburgh State University in Plattsburgh, NY and graduated in December 1997 with a B.A. in Environmental Science with minors in Geology and Photography. She spent 2 years after graduation working at various jobs, the most memorable being at a locally owned, outdoor recreation shop that specialized in skis and bikes.

After her family's purchase of the Schooner Rachel B. Jackson in 1998, she spent the next two summers as a mate on board the vessel taking passengers on sailing excursions in various locations along the coast of Maine and New England. It was during this time that she decided that she decided to enroll at the University of Maine and study the processes that shape Maine's shoreline. Corinn is a candidate for the Master of Science degree in Geological Sciences at the University of Maine in August, 2003.