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Thesis

BLUFF EVOLUTION AND GEOMORPHOLOGY OF THE BOSTON HARBOR DRUMLINS, MASSACHUSETTS

by

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I would like to dedicate this thesis to the memory of Dr. James Allen of the United States Geological Survey a primary investigator on this project, who tragically passed away prior to its completion.

BLUFF EVOLUTION AND GEOMORPHOLOGY

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ABSTRACT

There are over two dozen islands scattered within Boston Harbor, all of which are composed of bedrock and/or glacially deposited material, such as till. The glacial deposits are commonly found in drumlin form and easy to identify due to their distinctive hill shape. These oblong mounds lie partially submerged within the harbor and many sections of the island drumlins have been impacted by wave attack resulting in the formation of bluffs. The physical processes responsible for the long-term evolution of the Boston Harbor drumlins operate on many different spatial and temporal scales. An evolutionary model was constructed to describe the surface process history and enabled identification of the current factors operating on eroding bluffs.

The regional processes responsible for reworking sediment around the islands are storms, wind-generated waves, boat wakes, and tidal currents all operating in a regime of accelerated sea-level rise. Locally, factors such as sediment composition, bluff stratigraphy, surface flow processes, and geotechnical properties, may influence erosion susceptibility. Analyses of individual bluffs revealed inconsistencies in their height and length, as well as in the dominant mechanism causing their retreat. The drumlin bluffs erode by means of two distinct morphologic processes; (1) planar slopes undercut by wave action, which result in episodic slumping events and (2) rilled or gullied slopes caused predominantly by rain splash. Factors controlling the process of erosion were identified and compared to better understand how slopes with different morphologies relate to one another as well as to the overall evolution of the islands through time.

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INTRODUCTION

The Boston Harbor Islands are a recent addition to the National Park System, established by Congress in 1996. The purpose of the National Park Area designation is to preserve and protect the drumlin island system including their associated natural and cultural resources, while enhancing public understanding and appreciation through public access (NPS, 2000). If access to the islands is expected to increase, it is imperative for island managers to identify the areas that will be most susceptible to erosion. This study identifies the primary regional and local processes responsible for the formation and continual erosion of bluffs along section of the island drumlins. The results will be used for resource management, engineering purposes, and may also serve as a foundation for future physical process research.

From above, the islands within Boston Harbor look like a scattered array of lobate hills, often connected together by thin, neck-shaped bands of sediment. The hills are drumlin deposits, evidence of the widespread glaciation that once buried Massachusetts beneath a thick sheet of ice. Within the harbor, the drumlins have been partially submerged by rising sea-level producing bluffs that intersect the smoothed drumlin topography. Comparison of the bluffs not only indicated differences in their heights and lengths but also illustrated that they do not retreat by a consistent morphologic process. The overall objectives of this paper are to; (1) Identify the factors controlling erosion as well as their influence on the dominant slope morphology and, (2) Create a theoretical model describing bluff evolution that accounts for the observed variations in bluff height, length, and morphology.

STUDY AREA

Physical Setting

The Boston Harbor Islands consist of one or more drumlins linked together by bars of sand and/or gravel often referred to as tombolos (Farquhar, 1967). These islands represent the only example of a drumlin archipelago found within the United States (Figure 1). The Harbor Islands lie within the Boston Basin, a structural depression which formed during active tectonism in the Paleozoic, and was later modified by Pleistocene glaciation (LaForge, 1932).

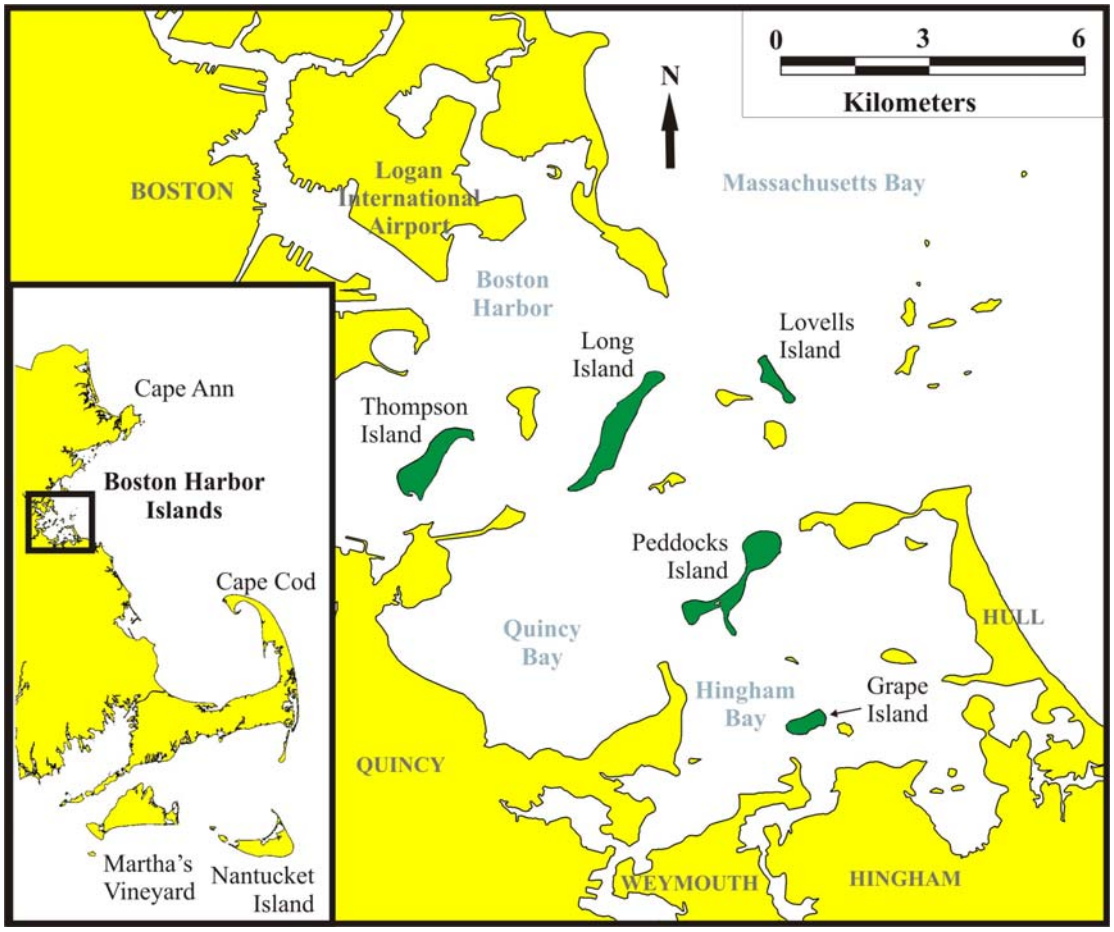


Figure 1. Location Map of Boston Harbor Island, Massachusetts. The five islands shaded green are the focus of this study.

During the Pleistocene, ice extended south in the northern hemisphere, across New England and through the Boston area. During this Epoch, there were multiple stages of

glacial advance with the most recent stage, the Wisconsinan, playing a major role in the shape of the present landscape. The drumlins that make up many of the islands within Boston Harbor are composed of two distinct till units, with the lower interpreted as a pre-Wisconsin till, and the upper attributed to late Wisconsin glaciation (Newman and Mickelson, 1994). Although the exact process of drumlin formation is still debated, the streamlined deposits consist of unstratified gravel, sand, silt and clay, scoured from the region by the overriding ice (Newman and Mickelson, 1994; Knebel et. al., 1992; Rosen et al., 1990). As the Laurentide Ice Sheet melted, water returned to the oceans producing a rise in sea-level during the Holocene, which intersected and began eroding the drumlin deposits within Boston Harbor. During the Holocene Transgression the Atlantic Ocean inundated the area (7,000 - 5,000 yr BP) and waves began carving into the till deposits, forming bluffs or scarps (FitzGerald et al, 1993). Bluff erosion delivered sediment to the beach where it was transported and re-deposited by wave action. Fingerlike bars extended off the downdrift end of drumlin headlands eventually linking drumlins together, forming transgressive barrier beaches. As these drumlin anchors continue to erode, the bluffs steady retreat landward.

Hydrographic Regime

The mean tidal range for Boston Harbor is 2 meters, making it a mesotidal environment according to Hayes' (1979) classification scheme. The mean annual wave height at the National Oceanographic and Atmospheric Association (NOAA) data buoy, located in 55 meters of water just outside the harbor, is 0.7m and has the lowest monthly average (0.4m) in July and the highest (1.2m) in April (FitzGerald, et al., 1993). The average wave period is 7.6-11.5 seconds, with dominant waves approaching from the northeast at an average velocity of 14.3 knots/hour (7.355 m/s) (FitzGerald, et al., 1993). The majority of the drumlin islands however, have lower wave energies than the values recorded at the NOAA buoy because they are enclosed within the harbor and sheltered from open ocean conditions. A wind rose depicting annual wind conditions at Logan Airport characterizes the wind climate within the study area (Figure 2). The prevailing winds, determined from the wind rose, blow from the west throughout the majority of the year. Of the total wind field, 51.1% have a westerly component, compared to 25.9% with

an easterly component (Riegler, 1981). The strongest or dominant winds however, are attributed to storms that blow in from the northeast. A gale summary by the U.S. weather bureau for a 75 year period, determined that of the 160 gales that occurred, 50% were from the northeast and 67% were from easterly quadrants (Riegler, 1981).

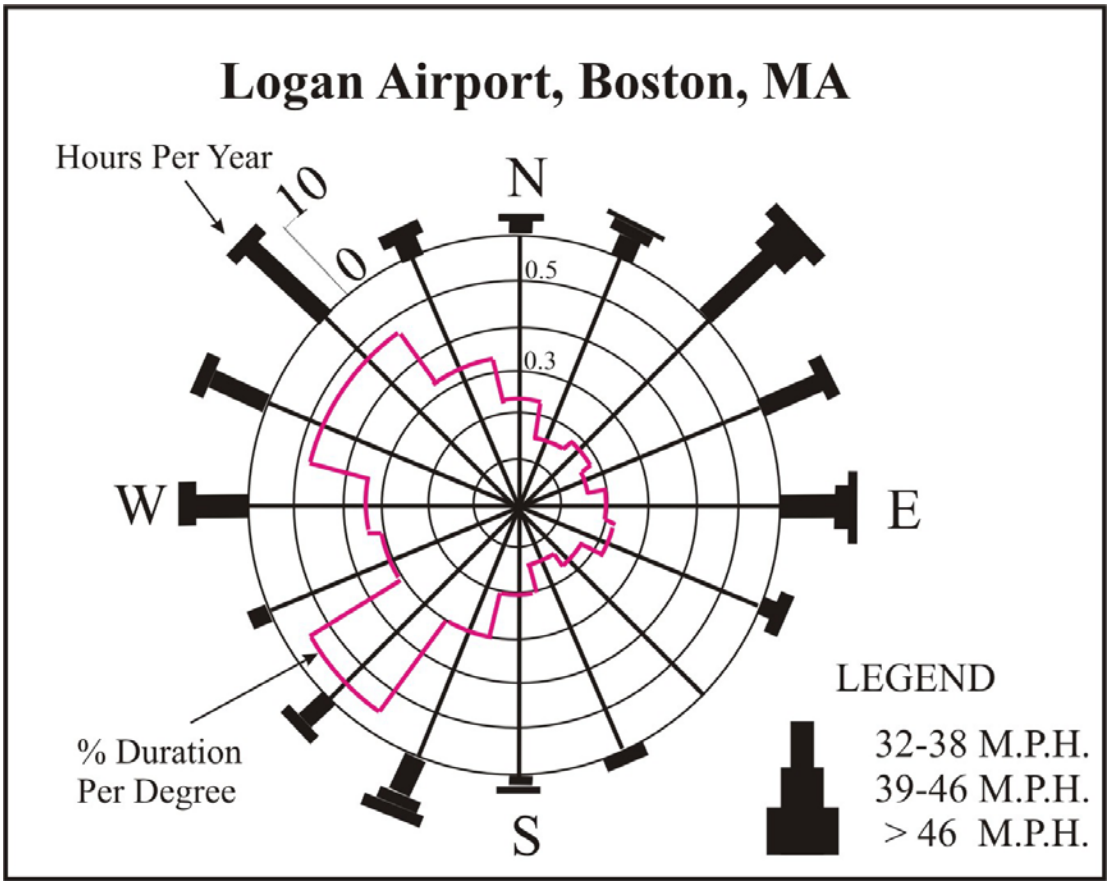


Figure 2. Wind Rose for Logan Airport, Boston Massachusetts (redrawn from U.S. Army Corps. of Engineers, 1976)

METHODS

To determine the extent and exposure of drumlin bluffs, surficial geology maps were used in conjunction with aerial photographs and field mapping. Previous studies have produced papers mapping out both the distribution and axial trend of the drumlins within Boston Harbor (Newman & Mickelson, 1994; Skehan, 1979, LaForge, 1932). These maps were used in conjunction with recent (1995) aerial photographs to locate the size and orientation of each drumlin and were later ground-truthed with field visits to the

islands. The influence of regional processes, such as storm wave attack, local waves, and boat wakes were determined by analysis of historical aerial photographs, wind data, and theoretical significant wave height calculations; S-M-B (Sverdrup, Munk, and Bretschneider) methods (Komar, 1998).

Aerial Photograph Analysis

Historical aerial photographs were used to identify long-term sedimentation trends and estimate retreat rates that could quantify the modification of island geomorphology. The 1995 shoreline was digitized from black and white, digital orthophotographs downloaded from the Massachusetts Geographic Information System website, (www.state.ma.us/ mgis.massgis.htm). The images have assigned spatial coordinates at a 1-meter/pixel resolution, a high level of geographic accuracy suitable for referencing the historic digitized images. Paper copies of the remaining aerial photographs were converted to digital format and georeferenced to the same coordinate system within a Geographic Information System (ArcView GIS). Advances in technology have greatly improved the resolution of photographs taken at high altitudes. The photographs from 1938 are of a poorer resolution than the 1995 digital orthophotographs. The process of georeferencing the photographs involves visually matching landmarks such as buildings or roads, between the unaligned image and the 1995 orthophotograph. ArcView's Image Analyst™ extension was used to establish a series of points linking the unreferenced image to the orthophotograph's coordinate system. The program manipulates the scanned photograph lining up designated links with corresponding points on the orthophotograph. Distances between points on the orthophotograph are then compared to distances between links on the scanned image to calculate the accuracy of alignment, displayed as a root mean square error.

A detailed historical analysis of the five islands (Thompson, Long, Lovells, Peddocks, and Grape Islands) was made using vertical aerial photographs covering the past sixty years. Once the photographs for a specific year were digitally aligned, shoreline positions were digitized to create simple polygon shapes using an ArcView extension called "BeachTools.™" The extension was created by the United States Army Corps of

Engineers (USACE) and was designed to extract shoreline positions from aerial imagery to assist in the study of historical shoreline change (Hoeke, et. al., 2001). Polygons for multiple years were compared to identify areas of the islands that are actively eroding. The wet/dry line has been used as a standard estimation of high the high tide line (Dolan, et.al., 1980, Smith & Zarillo, 1990). BeachTools™ has incorporated a methodology of using this in conjunction with the vegetation line, which may be a less variable indicator of long-term shoreline change (Hoeke, et.al, 2001). Tonal differences of raw pixels are generally small between wet and dry areas of the beach, but the BeachTools™ extension enables the user to maximize the contrast between these two areas. The user can enhance the viewed image by adjusting the histogram, which is a graphic representation of the number of pixels assigned to each individual value (color) that compose an image. The range of these raw values is spread out over the 256 bins (shades of gray) that can be used for display. To maximize the contrast between values in the brighter end of the spectrum (where the wet/dry line of the beach falls), the display can be manipulated to shift a larger range of bins over the pixel values that represent the bright beach area. The result is an image that has highly sensitive variation along the shoreline segments of the islands, enabling the user to easily determine tonal changes along the shore (Figure 3). The constructed polygon shapes use the wet/dry line as the ocean facing side and the vegetation line as the landward side, enclosing an area of the shoreline around each island. These polygons can then be used to study the historical shoreline change of specific beach. Coverage of the islands existed as far back as 1938 and extended through 1993 in approximately 30 year increments, except for Lovells Island, which did not have coverage prior to 1969. The polygons constructed from the aerial photographs were overlapped and viewed together, to identify shorelines segments that have changed significantly with time.

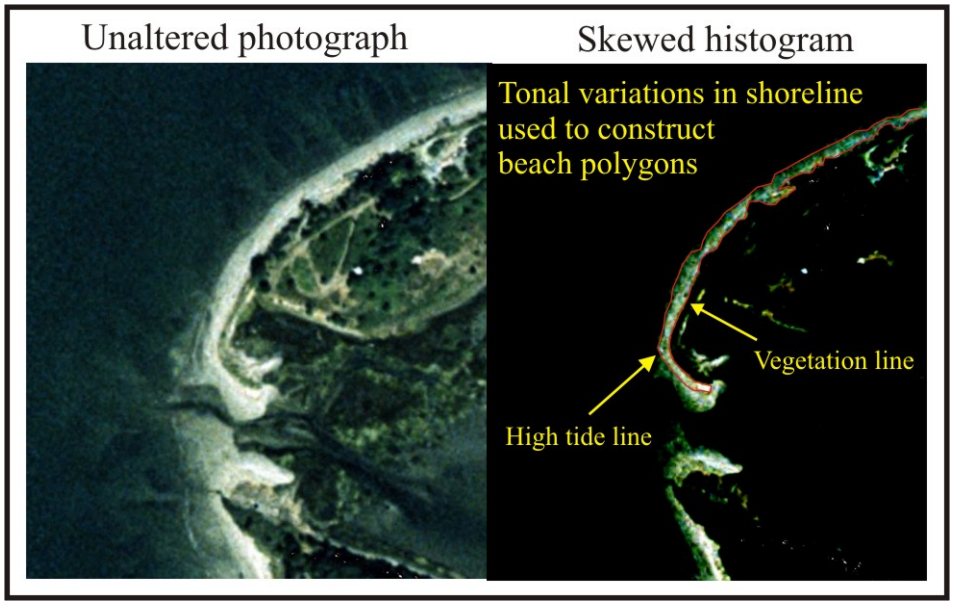


Figure 3. BeachTools™ histogram manipulation, accentuating tonal variation along beach.

Once the polygon shapes were created, they were used to estimate how much an individual bluff has retreated between 1938 and 1995 (57 years). The distance between both wet/dry and vegetation lines were measured along the length of each exposure perpendicular to the shoreline at 50 meters intervals. The measurements were first plotted to assure a normal sample distribution and then averaged to obtain a mean value of shoreline retreat. The mean was taken to be an intermediate estimate of retreat between the highly variable wet/dry line and the more consistent vegetation line. Retreat rates were estimated by dividing the number of years between photographs by the mean retreat length. The standard deviation was calculated to illustrate variability along the bluff and was also used to calculate confidence intervals using the t-distribution. The small-sample confidence interval was calculated using:

$$\bar{x} \pm t_{\alpha/2,n-1} \frac{s}{\sqrt{n}}$$

Where t is a value obtained from established small-sample statistics tests based upon the confidence percentage and found in the appendix of any standard statistics text book, α is the percent of confidence, n is the number of samples in the population, and s is the mean.

Historic Coastal Charts and Hydrographic Chart Data

Hydrographic and coastal charts dating from the early 1800's through the early 1900's were compared to illustrate an earlier time period of shoreline change on each of the selected islands. Data however was not available for Grape Island. Line tracings of mean low water, mean high water and features such as buildings, roads and piers were recorded on transparent sheets of acetate (Appendix G-J). Latitude and longitude crosses were recorded, and the location of roads and other human structures served as a double check, enabling comparison with the beach polygons constructed from the aerial photographs. The charts were re-sized and aligned by a student of Dr. Peter Rosen's at Northeastern University, and the acetate overlays were borrowed for use in this study. The process of overlaying the acetate sheets and the beach polygons was done in a computer assisted drawing program that enabled the top image to be rendered transparent for accurate alignment of latitude/longitude crosses, roads and buildings. This process is not exact however, and the placement of shoreline traces from the hydrographic charts is only approximate. The oldest shoreline positions based upon the 1944 hydrographic chart line up with the beach polygons from 1938, providing confidence in the accuracy of the alignment methods. Mean high water lines for each year were then digitally traced and added to the shoreline change map to further illustrate the evolution of the islands through time. Paper copies of other coastal charts not used in the construction of the acetate overlays were scanned into digital format and placed in sequence to produce a detailed visual of the more dynamic sections of shoreline evolution (Appendix K-O). Attempts to geo-reference these charts were unsuccessful due to the poor resolution of some and the lack of reference points on others.

Theoretical Wave Height Calculations

To better assess the potential impact of waves produced by locally-generated winds, significant wave height calculations were made for a number of locations on each island. Shorelines subject to severe wave action from ocean waves were not included because they have unlimited fetch lengths and therefore could not be calculated. Significant wave height is defined as the average height of the one-third highest waves. The quantity is estimated using the calculated root-mean-square height of the observed waves or:

$$H_{rms} = \sqrt{\frac{1}{N}\sum_{j=1}^{N} H_j^2}$$

Where N is the total number of observed waves, and H is their heights (Baum, 2001). The significant wave height is estimated using:

$$H_s \approx \sqrt{2} H_{rms}$$

A method of wave forecasting developed by Sverdrup, Munk and Bretschneider (S-M-B methods) empirically predicts both significant wave heights and periods from a known set of conditions, using a graph of all the available data such as wind velocity, fetch distance, and storm duration. The chart, which represents the relationship between significant wave height, wind speed, and its growth with increasing fetch distances, enables prediction of significant wave heights and periods from known fetch lengths and wind speeds (Komar, 1998). Wind direction exposures were chosen for locations that were fronted by expanses of open water greater than 1.5 kilometers. Fetch lengths were measured from the 1995 orthophotographs within ArcView GIS. Wind speeds were arbitrarily selected as a representation of various weather conditions; frequent breezes (10 knots), annual storms (20 knots), and infrequent hurricanes or Nor'easters (40 knots). The known wind speed and fetch values were used to determine the significant wave height, period and minimum wind duration from a chart developed by the USACE (Appendix O). The calculations have been summarized in Table 1, which includes an averaged value for each of the wind conditions irrespective of orientation. Graphs depicting mean significant wave heights (Figure 9) and mean wind speeds (Figure 10) at the National Oceanographic and Atmospheric Association (NOAA) data buoy (number 44013) were obtained from the national data buoy web site (http://www.ndbc.noaa.gov/hmd.shtml). Data from these graphs were used to compare significant wave heights produced in open ocean conditions with theoretical significant wave heights calculated for the fetch-limited environment within Boston Harbor.

Fieldwork Data Collection

Bluff heights were measured from the highest point of the exposed scarp to the ground using a Pentax PCS-325 laser total station. The total station was mounted on a tripod and set up on the beach at the base of each scarp. It measured both the vertical and horizontal

distance between the tripod and the prism, which was placed at the highest point of the exposed scarp. The total station was also used to collect profile data for bluffs that had extensive erosion within the study. Horizontal and vertical distances were recorded for a series of points moving along a line perpendicular to the eroding scarp. The data points were entered into a spreadsheet database and normalized to height before they were graphed. In cases where the tripod was not within the direct line of the profile, trigonometric manipulations using the law of cosines were done to correct the data. The law of cosines states that:

$$a^2 = b^2 + c^2 - 2bc * \cos(a)$$

Where *b* and *c* are the horizontal distances from the tripod to two points on the profile line and *a* is the horizontal distance between *b* and *c*. The vertical distances are consistent, regardless of where the tripod is placed and therefore do not need to be corrected. The data for all profiles is available in Appendix A-F.

The dominant mechanism removing sediment from the drumlin scarp was identified by a visual inspection of the eroding bluff. Pictures of the scarp were taken to document the morphology of the exposure and can be found referenced to their location on the shoreline change maps created for each island (Figures 8-11).

RESULTS

Upon completion of both lab and fieldwork, two overall trends were identified that describe the nature of bluff retreat: 1) The largest amounts of shoreline retreat are along shoreline segments directly exposed to northeast storms; and 2) Bluffs facing northwest are at greater heights than bluffs forming on the southeast side of the same drumlin.

Comparisons of local wave energies with open ocean conditions indicate that the northeast storms are the most powerful factor influencing erosion. Storm winds lead to the production of the greatest incoming wave energies and all shorelines with direct northeast exposures have high bluffs with gullied slope morphologies. Bluffs exposed to

northeast waves along Long, Lovells and Peddocks Island have some of the greatest bluff heights within the study area, all of which retreat due to rill and gully processes.

Drumlins that have both northwest and southeast exposures experience greater bluff heights on the shorelines that face the northwest. The orientation of the drumlins within Boston Harbor places the topographic crest of the deposit closer to the northwest shoreline. Both exposures have long fetch lengths that would enable the generation of comparable wave heights under the same wind conditions (Table 1). The northwest bluffs however face into the direction of the prevailing winds, and bluffs facing that orientation experience a higher frequency of direct wave attack than their southeast bluff counterpart.

Location	Wind Direction	Fetch[1] (statute miles)	(km)	Wind Speed[2] (knots)	(mi/hr)	(m/sec)	Significant Wave Height[3] (feet)	(meters)	Peak Spectral Period[4] (s)
Thompson Island	NE	2.86	4.61	10	11.51	5.14	0.55	0.17	1.8
				20	23.02	10.29	1.2	0.37	2.25
				40	46.03	20.58	2.3	0.70	2.8
	NW	1.88	3.03	10	11.51	5.14	0.45	0.14	1.63
				20	23.02	10.29	0.9	0.27	1.97
				40	46.03	20.58	1.9	0.58	2.5
	SW	1.08	1.74	10	11.51	5.14	0.35	0.11	1.35
				20	23.02	10.29	0.7	0.21	1.65
				40	46.03	20.58	1.45	0.44	2
Long Island	NW	2.53	4.07	10	11.51	5.14	0.4	0.12	1.77
				20	23.02	10.29	1.13	0.34	2.2
				40	46.03	20.58	2.25	0.69	2.75
	SE	2.02	3.25	10	11.51	5.14	0.49	0.15	1.67
				20	23.02	10.29	0.95	0.29	2.15
				40	46.03	20.58	2	0.61	2.6
Lovell Island	NW	4.01	6.45	10	11.51	5.14	0.7	0.21	2.1
				20	23.02	10.29	1.38	0.42	2.6
				40	46.03	20.58	2.75	0.84	3.25
Peddocks Island	W	3.59	5.78	10	11.51	5.14	0.67	0.20	2
				20	23.02	10.29	1.3	0.40	2.45
				40	46.03	20.58	2.7	0.82	3.15
	SE	3.05	4.90	10	11.51	5.14	0.65	0.20	1.88
				20	23.02	10.29	1.23	0.37	2.4
				40	46.03	20.58	2.48	0.76	3.15
Grape Island	NE	2.17	3.49	10	11.51	5.14	0.5	0.15	1.6
				20	23.02	10.29	1.07	0.33	2.1
				40	46.03	20.58	2.48	0.76	2.95
	W	1.21	1.95	10	11.51	5.14	0.4	0.12	1.4
				20	23.02	10.29	0.75	0.23	1.7
				40	46.03	20.58	1.55	0.47	2.15
Average Wind Speed		0.16	0.32	0.67					

[1] Fetch lengths measured within ArcView GIS from 1995 Orthophotographs, available at www.state.ma.us/mgis/massgis.
[2] Wind speeds were chosen to represent various weather conditions (frequent breezes, annual storm, hurricane/Nor' Easter.
[3] Significant Wave Height and Peak Spectral Period were determined through S-M-B methods (Komar, 1998)

Table 1. Significant wave height calculations for locally-generated winds at various exposures. Calculations are based on wind speed and fetch.

Thompson Island

North Head Drumlin

Thompson Island is sheltered from the open ocean by a series of islands that extend eastward into Massachusetts Bay. The drumlin deposit that makes up the northern half of the island extends for 900 meters along the northwest coast, from the pier to the curve at the top end of the island. Accumulation of sediment on the northeastern side of the pier indicates that longshore currents are transporting sediment towards the southwest. The pier acts as a barrier that attenuates the current and results in updrift accretion. Just to the north lies President Roads, a deep water passageway for large ships, which may enable large swells to reach the island through this channel during storm events. These swells along with locally-produced waves have carved into the bluffs, producing wave-notched slopes along the northern side of the island. A well-developed, 0.15 m mussel berm sits at the base of the 8-10 meter bluffs, indicating the landward extent of wave energy during recent storm events. The continuous bluff has a planer slope with a well-developed wave notch at the base, interrupted only in areas where recent slump events have occurred (Figure 4). Moving north along the drumlin, the shoreline bends into a direction perpendicular to the northerly winds, and there is evidence of several recent slump events with piles of loose sediment on the beach and fresh scars of bare slope on the bluff. The base of the slope is sheltered from direct wave attack by large mounds of slumped sediment. Long lengths of open water fronting the northernmost part of Thompson Island, are capable of delivering 0.37 meter waves (Table 1) during 10 knot winds from the north. This condition may explain the placement of protective rip-rap along the slope base. The bluffs behind the rip-rap average about 10 meters in height and have been estimated to retreat at a rate of 0.21 meters/year based upon aerial photograph analysis (Table 2).

The rip-rap that protects the north side of the island continues around the tip to the south-facing shoreline. This shoreline faces southeast, and is sheltered from the prevailing winds from the west. Wave refraction around North Spit produces longshore currents that also transport sediment to the southwest. Opposing currents converge at the southeastern end forming the South Cuspate Spit, as identified by Rosen and Leach (1987) (Figure 4). Bluff heights are much lower along this side of the drumlin, reaching a maximum height of only 3 meters. Not only has the southeast exposure experienced a

reduced wave climate, but the bluff has formed on the more moderately sloping side of the drumlin deposit. The short, planar slope retreats at an average rate of 0.06 meters/year. This side of the island is farther from the topographic crest of the drumlin and therefore requires a larger amount of shoreline retreat to result in an increase in bluff height.

Table 2. Mean retreat rates and confidence intervals of shoreline change on Thompson, Long, Lovells, Peddocks, and Grape Islands.

Table 2. Mean value of retreat (meters), calculated rate (meters/year) and statistically derived confidence intervals (meters) for shoreline change on Thompson, Long, Lovells, Peddocks, and Grape Islands. Mean retreat rate determined from 1938 and 1995 beach polygons (Figures 4-8). Standard deviation indicates amount of variability between measurements along the bluff length. Root mean square (RMS) value demonstrates accuracy in alignment of 1938 aerial photograph and can be found next to the name of each island.

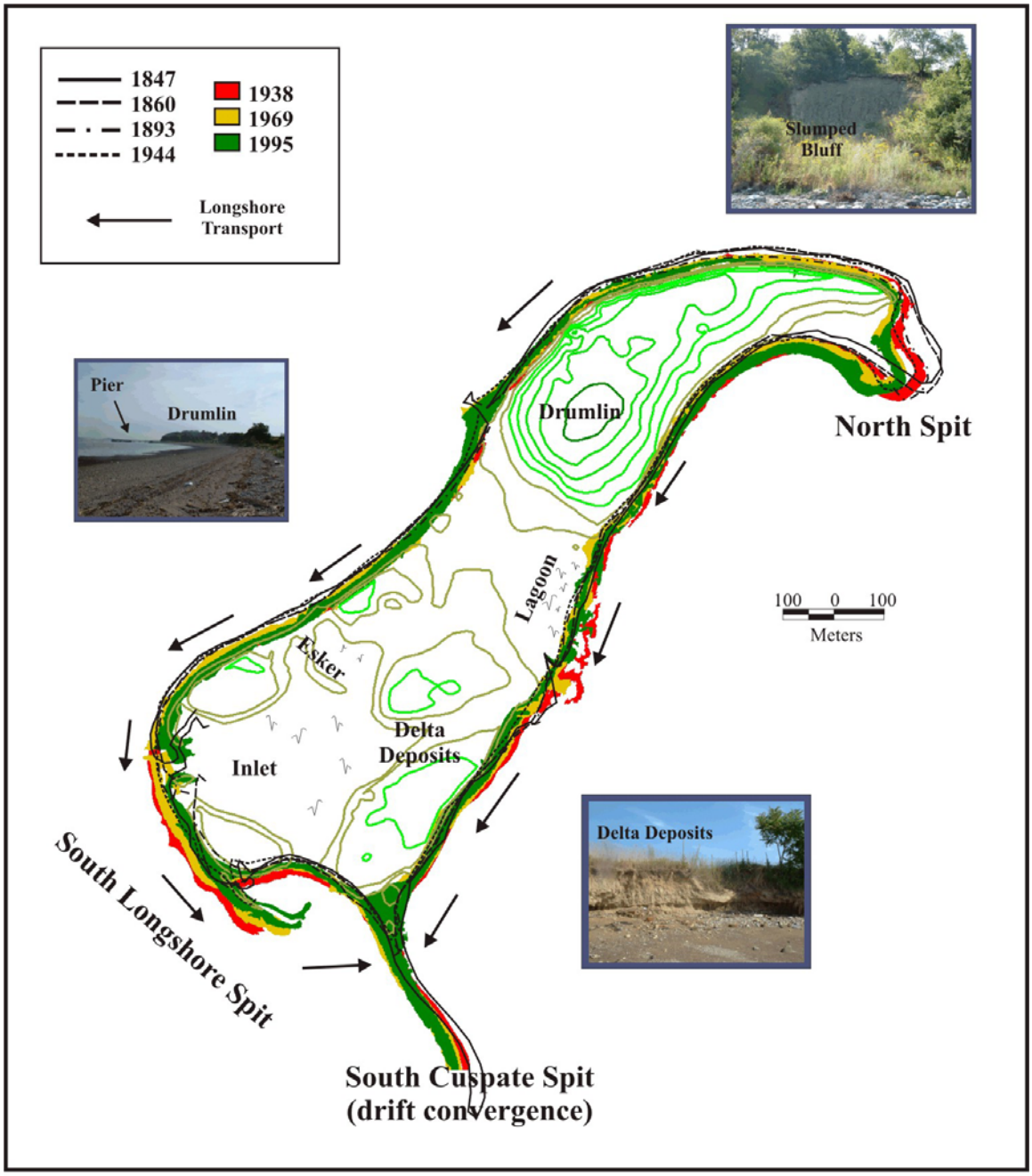


Figure 4. Map of Thompson Island Shoreline Change. Lines mark estimated shoreline positions from hydrographic sheet data. Polygons outline beach from vegetation line to high tide position traced from georeferenced aerial photographs. Longshore transport directions based upon fieldwork observations and aerial photograph analysis.

Long Island

East Head Drumlin

The northeastern end of Long Island is made up of a drumlin deposit, which was fortified with a granite seawall in 1870. Prior to construction of the seawall, the drumlin was exposed to direct wave attack during storms from the northeast. These waves carved deep into the hill, producing an 18 meter bluff along the northwest side. Although erosion by wave attack has been successfully thwarted by the seawall, the 650 meter long bluff is still impacted by rain splash. The development of rills and gullies suggests that erosion still occurs and is associated with rainfall events. The southern side of the drumlin is currently sheltered from wave attack by accretionary deposits of sand and gravel. Prior to deposition however, this side of the drumlin was actively eroding, leaving behind evidence of former wave-cut bluffs.

Middle Head Drumlinoid (3 drumlins)

The midsection of Long Island is made up of three drumlins and has exposed bluffs on both the northwest and southeast sides of the island. The shoreline is fronted by a shingle beach, and protected on both sides by large blocks of rip-rap. The first drumlin, middle-north, has noticeably different bluff types on adjacent sides of the pier located on the northwest side of the island. The bluff extends into the central part of the island, but is not currently acted upon by wave action, similar to the inactive bluffs on the interior part of North Head. North of the pier, the 300 meter long bluff ranges from 3 to 6 meters in height and has slight indications of a wave notch at the base of the slope. The storm mussel berm does not lie at the base of the slope, as seen at most other shoreline bluffs, but stands approximately 0.5-0.75 meters seaward. Rates of shoreline change from aerial photograph analysis indicate an accretion rate of 0.14 meters/year (Table 2). Accumulation of sediment on the northeastern side of the pier indicates that the direction of longshore transport is to the southwest. Immediately south, and downdrift from the pier, the 500 meter bluff reaches heights of 21 meters and has retreated at a rate of 0.12 meters/year. This bluff is deeply incised with a network of rills and gullies (Figure 5). This bluff is dramatically different from the short, planar bluff seen north of the pier.

The southeastern side of the middle-north drumlin is a 725 meter long bluff with heights of 3 meters along the drumlin flanks that climb to heights of 12 to 14 meters at the crest.

Along the shorter sides the slope is smooth and erosion occurs through wave notching and slumping processes. Many areas along the sloping sides are well vegetated and have little indication of recent slumping. Recent erosion is restricted to the highest section of bluff which has retreated at an approximate rate of 0.42 meters/year. At the crest of the drumlin deposit the slope morphology changes. The central portion of the bluff is incised by multiple rills and gullies and does not have the planar slope morphology seen along the tapered sides of the exposure.

The topographic crest of the central drumlin of the middle drumlinoid complex is located slightly southeast from the drumlin to the north. Extending along the northwest shore for 350 meters, the planar slope has an almost continuous wave-cut notch at the base. Ranging in height from 6 to 9 meters the bluff is retreating at an average rate of 0.18 meters/year. The southeast exposure is 250 meters long and has a significantly higher maximum bluff height of 18 meters. The slope is incised with rills and gullies and has been eroding at an average rate of 0.35 meters/year. This is the only bluff of the study that had an older stage of bluff evolution along the southeast exposure, when both southeast and northwest exposures were simultaneously eroding.

The northwestern exposure of the middle south drumlin has bluff heights of 6 to 9 meters, and extends for 185 meters. The planar slope is undercut by wave attack and erodes due to slumping processes at an average retreat rate of 0.21 meters/year. On the opposite side of the drumlin, the 150 meter long bluff faces southeast and ranges from 6 to 9 meters in height. Similar in appearance to its northwest counterpart, the slope is dominated by wave notching and slumping and retreats at an average rate of 0.30 meters/year. Sediment is being transported to the southwest in longshore currents along the southeastern side of the island, just as they are on the northwest. With no man-made structures interfering with the longshore currents along this side of the middle drumlinoid complex, there are no easily identifiable accumulations of sediment indicating the direction of longshore transport. Sediment is accreting at the southernmost end of the middle south drumlin. Comparison of coastal charts and aerial photographs indicate that

this accumulation of sediment is migrating towards the southwest, which agrees with the proposed direction of longshore transport (Figure 5).

West Head Drumlin

The west end of Long Island was connected to Moon Island by a bridge in 1952. North of the bridge, the bluff extends for 150 meters and reaches a maximum height of 15 meters. Facing the northwest, the gullied slope has retreated at an average rate of 0.33 meters/year. The 200 meter long bluff south of the bridge ranges in height from 6 to 9 meters. The planar slope has a southwest exposure characterized by slump scarp morphology and has an average retreat rate of 0.16 meters/year (Table 2).

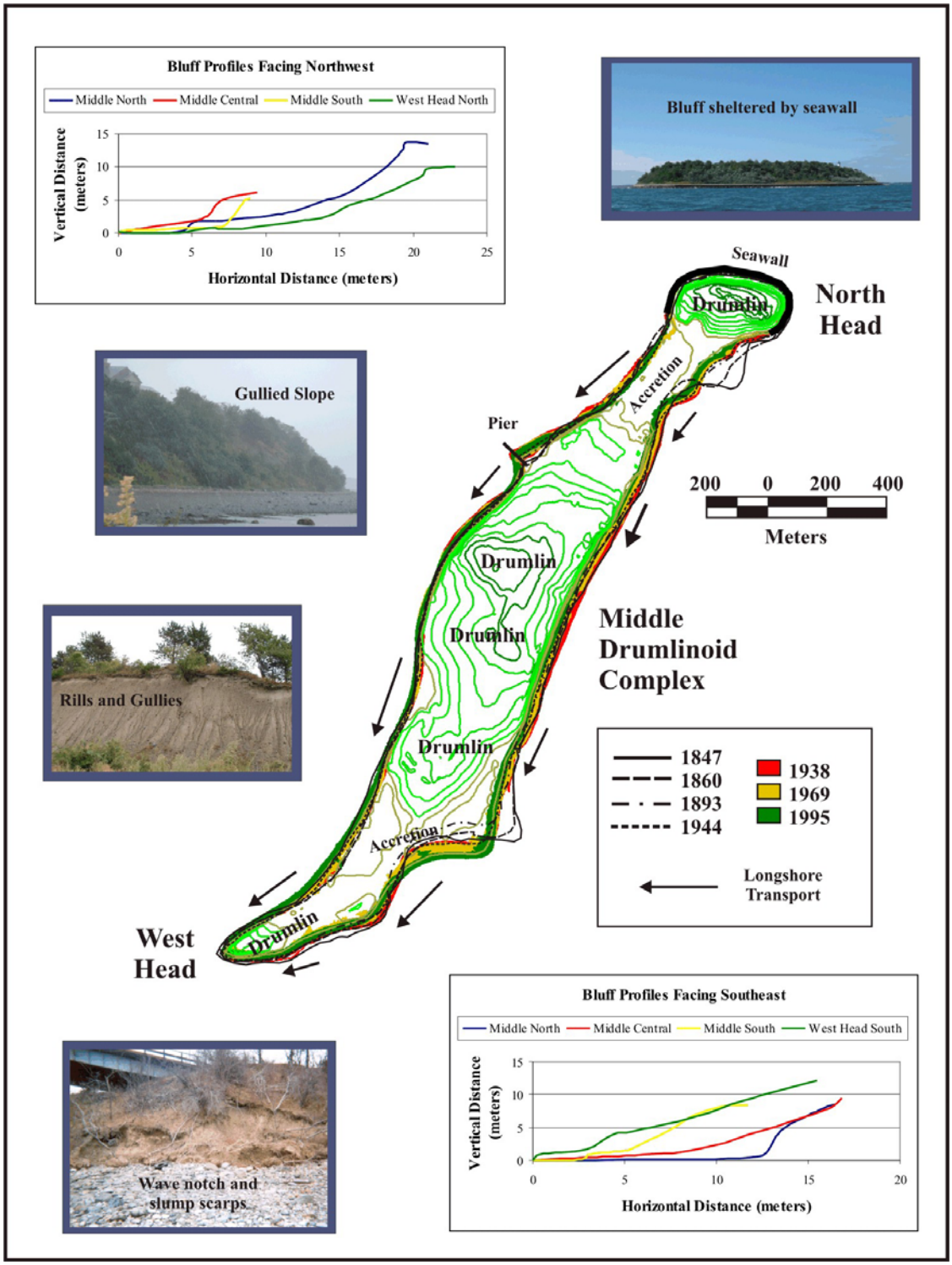


Figure 5. Long Island shoreline change. Lines mark estimated shoreline positions from hydrographic sheet data. Polygons outline beach from vegetation line to high tide position

Lovells Island

North Head Drumlin

A stone seawall protects remnants of the drumlin at the northern tip of Lovells Island. Visible in the 1857 coastal chart, the seawall must be at least 145 years old (Appendix G). The seawall was covered and reinforced with rip-rap which also extended to the south, protecting the entire east side of the island from ocean waves. The blocks of granite rip-rap have angular edges, which implies that the rip-rap was placed on the shore recently and high-energy ocean waves have not had time to wear down the sharp edges. The interior section of this drumlin was modified extensively during construction of underground bunkers in World War II and the exposed slopes have been sheltered from the natural effects of wave erosion for several decades. Due to these circumstances, classification of the bluffs through identification of slope processes and morphology is not possible.

Middle Head Drumlin

Due to protection from the seawall on the eastern and more exposed section of the drumlin, there are no actively eroding bluffs facing the ocean. The interior of the central drumlin was also modified extensively during World War II, when underground bunkers and excavated passageways were constructed. The western side of the island has a 75 meter-wide, 10 to 12 meter-high, steep-sided bluff (Figure 6). The most dramatic feature of this shoreline segment is the crumbling ruins of a buried passageway that protrudes out of the center of the bluff and extends landward into the heart of the drumlin. This section of the shoreline has only been exposed to wave attack in the past 50 years, and was previously fronted by a wide beach. Sediment likely came from Rams Head, which lies directly to the Northeast and protected the drumlin from wave attack until the sediment was worked off and along the shore (Appendix H). Presently the bluff stands exposed to the prevailing Northwesterlies and also experiences indirect wave attack due to refraction of ocean waves around the northern point of the island both of which produce longshore currents that transport sediment to the south. Wave refraction around the southern end of the island reverses the direction of longshore currents, and a cuspate beach lies at the point of their convergence. With an average retreat rate of 1.06 meters/year (Table 2) the slope has a few indications of rill development on its surface, but the primary mechanism removing sediment is slumping. Other portions of the drumlin to the south were exposed

to wave attack in the past forming bluffs, but are now overgrown with vegetation. The once active bluff is currently fronted by a wide accretionary deposit of sand, which shelters it from wave attack.

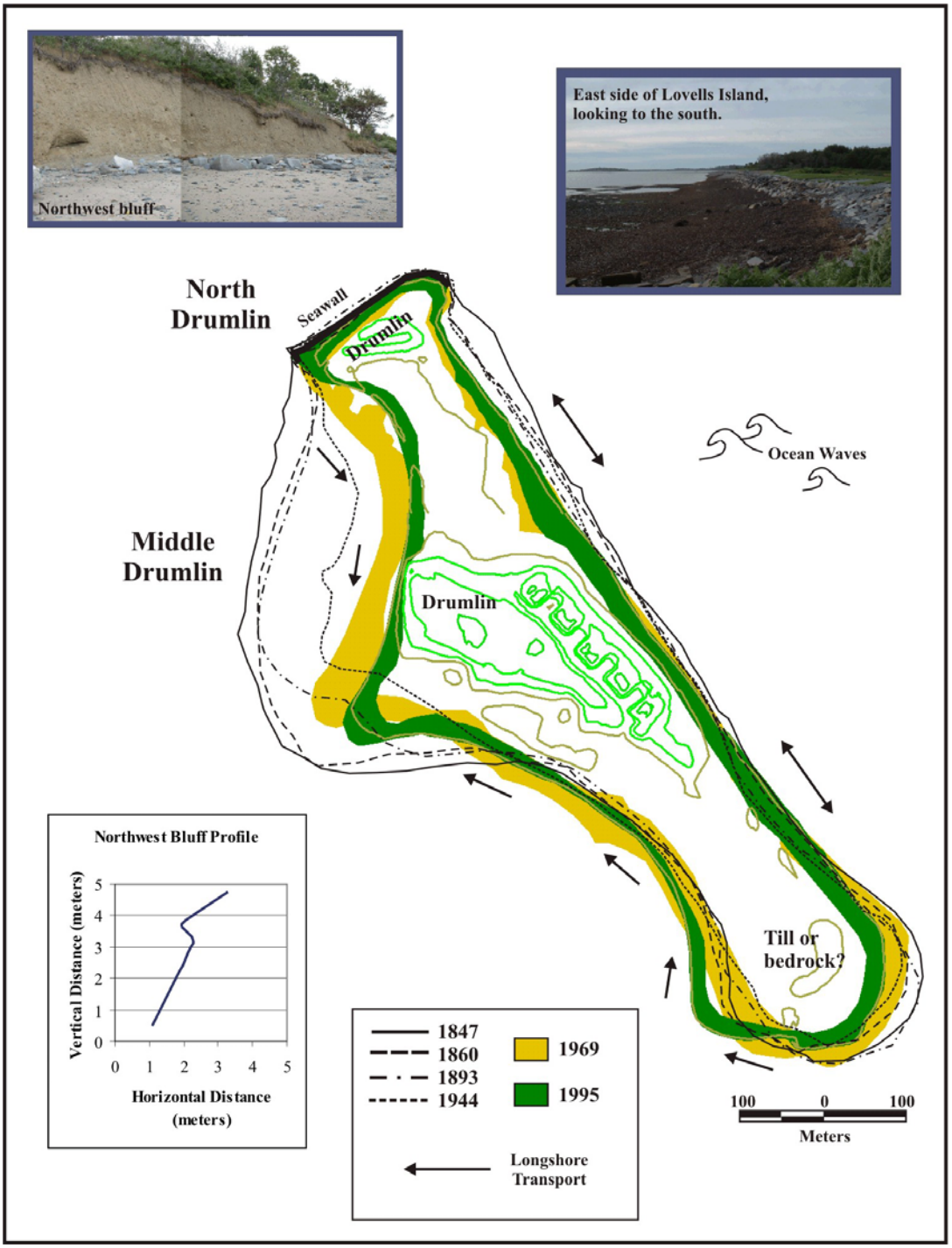


Figure 6. Lovells Island Shoreline Change. Lines mark estimated shoreline positions from hydrographic sheet data. Polygons outline beach from vegetation line to high tide position traced from georeferenced aerial photographs. Bluff profile measured along northwest side of middle drumlin, bulge is overhand at

top of slope. Longshore transport directions based upon fieldwork observations and aerial photograph analysis. Coverage was not available for 1938.

Peddocks Island

East Head Drumlins

East Head is made up of two drumlins and is located at the northeastern end of Peddocks Island. The bluff that defines the shoreline of the northernmost drumlin is over 700 meters long and wraps around the northwest and southeastern sides (Figure 7). The shoreline exposures along this drumlin are high, beginning at heights of 8 meters on either end of the exposure and increasing to a maximum height of 24 meters at the topographic crest of the drumlin. Segments of the bluff with shorter heights have planar slopes and erode due to wave notching and slumping. As bluff heights increase however, the primary process of sediment removal on the slope is through a deeply incised network of gullies. Vegetation can be found on the more stable ridge segments that separate the gullies. Water that is channelized and moved down the slope in a rainfall event contributes to an average retreat rate of 0.26 meters/year (Table 2).

The second drumlin making up East Head is sheltered by the first drumlin to the northeast. Bluffs on the northwest and southeast sides are quite different than the bluff seen on the first drumlin. Along the northeast coast, the 60 meter-long bluff reaches a maximum height of 6 meters and is not nearly as high as the scarps along the more exposed drumlin to the east. There are few indications of recent erosion along the northwestern bluff which has an average retreat rate of 0.05 meters/year (Table 2). The southeastern side of the drumlin has a significantly longer bluff that extends for 340 meters along the coast. The majority of the slope is covered with dense vegetation and therefore has an average retreat rate of only 0.06 meters/year. Discontinuous wave notches at the slope base are infrequently interrupted by a recent slump event. The bluffs along both sides have smooth or planar slopes and retreat by wave notch and slumping processes. Ocean waves are refracted around the tip of East Head and produce a longshore current that transports sediment to the southwest on both the north and south sides of the island. This sediment aids in maintaining the connective tombolos/bars that join the multiple drumlins making up Peddocks Island.

Middle Head Drumlin

The drumlin bluff on the northwestern side of Middle Head is 230 meters long and ranges from 6 to 10 meters in height. Having already retreated past the topographic crest of the drumlin, bluff heights will continue to diminish with erosion. Retreating at rates of 0.05 meters/year, the upper slope face has minor indications of rills and gullies but the absence of sediment at the base of the slope suggests that it is vulnerable to wave notch and slumping processes.

On the opposite side of the drumlin a bluff extends for 260 meters along the more sheltered southeast side of the island. Retreating at an average of 0.14 meters/year, the bluff is eroding primarily by slumping processes. The planar slope has been notched at the base due to wave action and does not exceed 6 meters in height.

West Head Drumlin

The bluff at the northwest side of West Head extends for 500 meters along the north-facing shore before it bends sharply to the south, extending for another 200 meters facing west. The bluff ranges from 6 to 12 meters in height with the greatest heights occurring at the northwest bend. Retreat rates of the north-facing bluff average 0.05 meters/year, while the western exposure has rates of 0.11 meters/year (Table 2). Wave notching and slumping processes dominate the slope morphology along the entire bluff with the exception of the bluff segment at the northwest bend. There, the dominant mechanism removing sediment from the slope appears to be a combination of slumping and gullying processes. The uppermost part of the slope is incised with rills, which are truncated by a recent slope failure towards the base.

Prince's Head Drumlin

Refraction of the Northwesterlies around the southern end of West Head converges with southwestern longshore currents producing the tombolo/bar that connects Prince's Head to Middle Head. Erosion on adjacent sides of the drumlin deposit that is Prince's Head have resulted in both bluffs arriving at the topographic crest of the drumlin simultaneously. The opposing bluffs extend to the south for 170 meters on the west and east sides of the drumlin. The west-facing bluff begins as a 0.25 meter scarp at the

northern end, and increases to a maximum height of 14 meters at the topographic crest of the drumlin. On the east side, the bluff only reaches a height of 12 meters. Both sides of the drumlin are primarily eroding due to a network of rills and gullies that become more deeply incised towards the southern end. Average retreat rates determined from aerial photograph analysis estimate a retreat rate of 0.23 meters/year for the western bluff and 0.13 meters/year for the eastern exposure (Table 2).

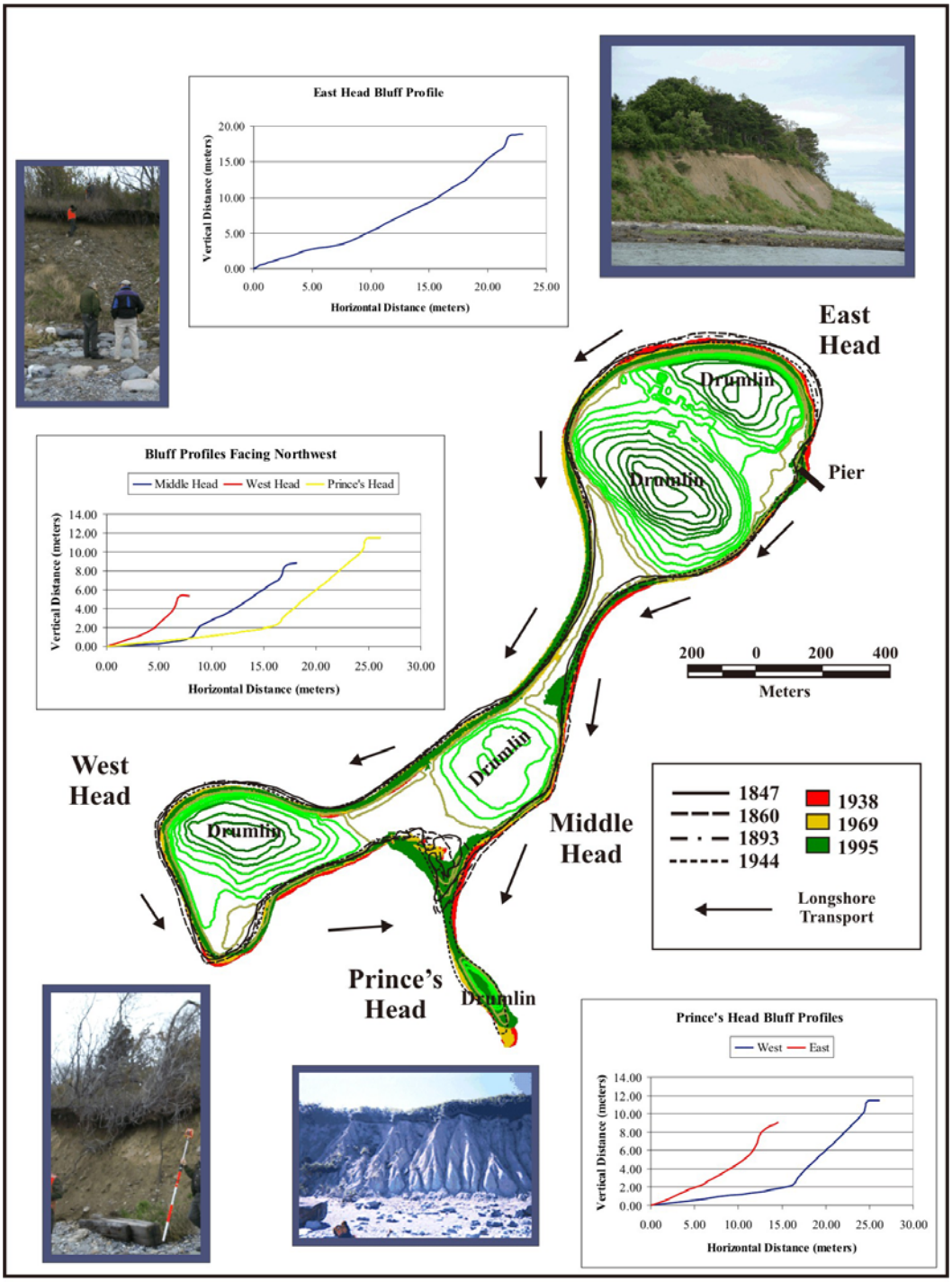


Figure 7 Peddocks Island shoreline change. Lines mark estimated shoreline positions from hydrographic sheet data. Polygons outline beach from vegetation line to high tide position traced from georeferenced aerial photographs. Longshore transport directions based upon fieldwork observations and aerial photograph analysis. Graphs illustrate bluff profiles for various exposures.

Grape Island

West Head Drumlin

Grape Island is made up of two drumlin deposits and is located in Hingham bay, near the mouth of the Weymouth River. A bluff along the western side of the island begins at the southern end, just north of a large gravel spit and extends over 450 meters to the northern side. Covered with dense vegetation, the bluff rarely exceeds 6 meters in height and is dominated by slump scarp morphology. Grape Island is sheltered from wind waves along the entire southern length. This side of the island is only separated from the mainland by approximately 500 meters of water and is flanked by a broad gravel beach. The short fetch lengths prevent winds from generating large waves. A commuter boat route passes just offshore from the southern side of Grape Island. Along the 250 meters facing west/southwest, the bluff is retreating at an average rate of 0.10 meters/year (Table 2) and has a greater frequency of recent slump events than the section of the bluff to the north. South of the gravel spit, the bluff continues for approximately 200 more meters and had an average annual retreat rate of 0.07 meters/year. The 200 meter section that faces north is retreating at an average rate of 0.07 meters/year and has occasional slump scarps interrupting the vegetated slope. The northern side of the island has longer fetch lengths and although it is sheltered from ocean, the bluffs face northeast and are vulnerable to Nor'easter storm waves.

East Head Drumlin

The morphology of the east-facing bluff is similar in appearance to bluff along the western drumlin. Beginning at the northern side of the island, the bluff extends around the side of the island for over 500 meters to the south. The north-facing part of the bluff reaches a maximum height of 10 meters and has a visible wave notch at its base. Currently active, the bluff has an average annual retreat rate of 0.09 meters/year. Moving to the east, the bluff height decreases to 3 meters and is sheltered from wave attack by a sequence of ridge and swale deposits identified as a cuspate foreland by Jones and Fisher (1990). These accretionary deposits extend to the southern side of the island sheltering the remainder of the once-active bluff from wave attack.

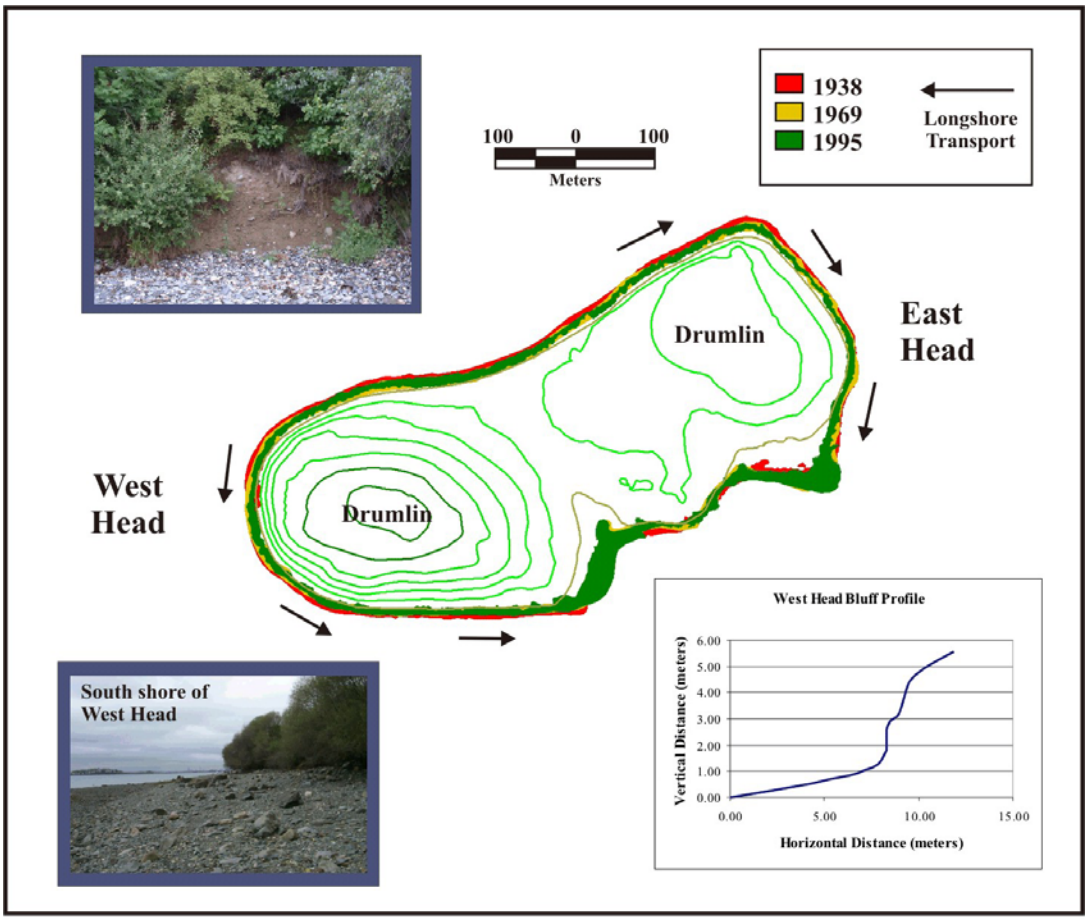


Figure 8. Grape Island shoreline change. Polygons outline beach from vegetation line to high tide position traced from georeferenced aerial photographs. Longshore transport directions based upon fieldwork observations and aerial photograph analysis. Hydrograph chart data was not available.

DISCUSSION

Regional Influences

Coastal storms have a significant impact on segments of island shorelines with direct northeast exposure, such as Lovells, Long, and the northern tip of Peddocks Island. These shoreline bluffs have some of the greatest heights when compared within the study area, and all slopes are deeply incised with rills and gullies. Northeast storms generate sustained, high-speed winds, which can produce wave heights in excess of 4.0 meters (Figure 9). Wave heights for islands enclosed within the harbor are limited by fetch, or the expanse of open water fronting the shorelines. Significant wave heights averaged for all orientations at each wind speed (breeze, storm, hurricane/ Nor'easter) are respectively:

0.157 meters (10 knot winds), 0.323 meters (20 knots), 0.667 meters (40 knots) (Table 1). Wind speeds at the NOAA data buoy averaged 10 knots for the month of June (Figure 10) The mean significant wave height for the buoy in June was 0.5 meters, a 0.343 meter difference from the mean calculated within the harbor. At greater wind speeds, the difference between significant wave heights of fetch-limited and open ocean conditions increases. This difference becomes more noticeable when comparing the mean significant wave heights for "annual storm" conditions (20 knots). Generating wave heights of 0.9 meters (Figure 9), the ocean winds only averaged speeds of 15 knots in December (Figure 10). The 0.323 meter significant wave heights averaged for 20 knot winds within the harbor (Table 1) are 0.577 meters smaller than waves produced in the ocean. In spite of having a 5 knot wind speed advantage, significant wave heights within the harbor were smaller due to fetch limitations.

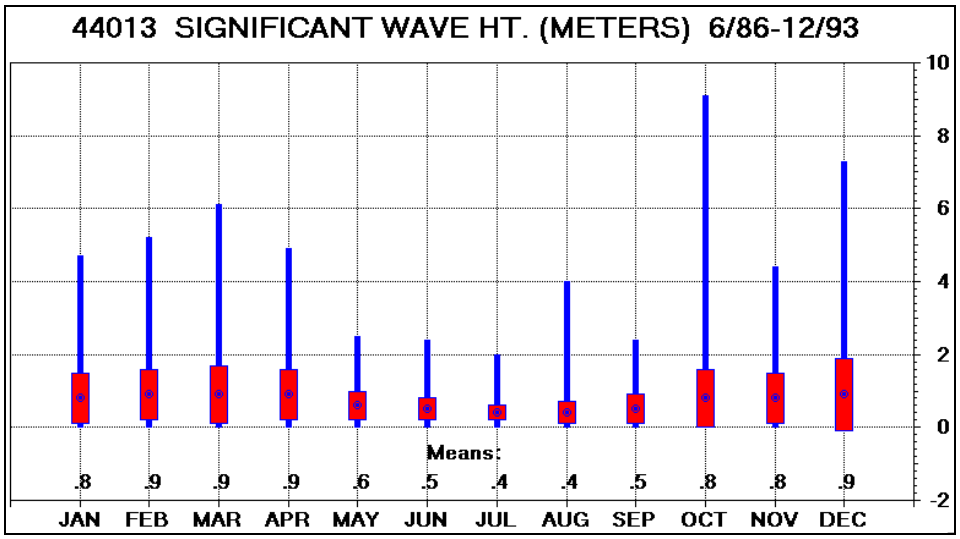


Figure 9. Significant wave heights for the NOAA data buoy, located in 55 meters of water just outside of Boston Harbor. Lines represent range of recorded wind speeds.

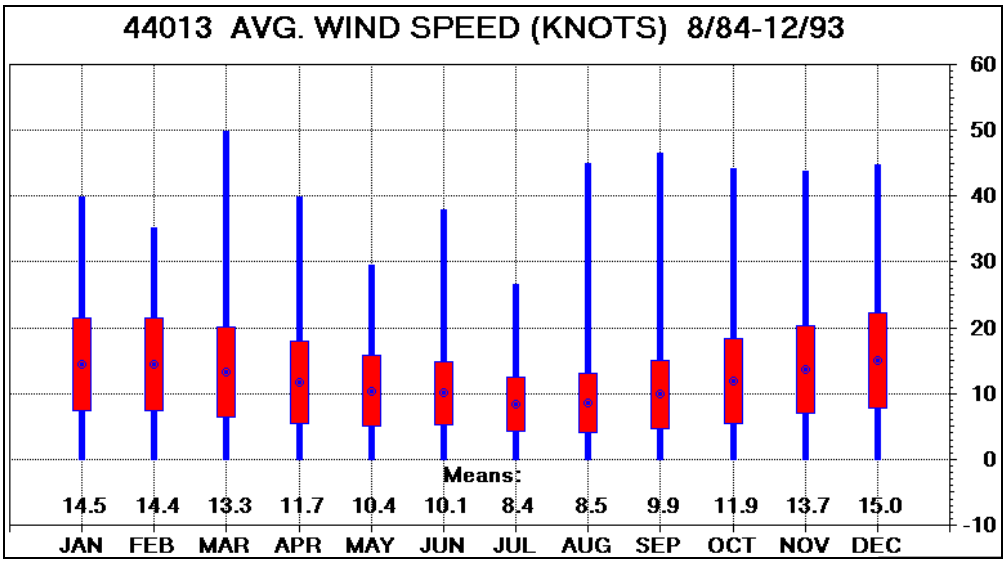


Figure 10. Wind speeds averaged by month for NOAA data buoy #44013.

Comparison of significant wave heights approaching the NOAA data buoy in an environment unlimited by fetch with theoretical wave heights calculated for some of the largest fetch lengths within the harbor clearly illustrate the powerful impact the northeast storms can have on the islands. Sediment has linked many drumlins in a northeast to southwest orientation, indicating the dominant direction of sediment transport, which in large part is due to the high wave energies from storm events. Comparison of early coastal charts and their respective shoreline change maps show migrating bulges of sediment along the southeastern sides of Long, Peddocks, and Grape Island, as well as the northwestern side of Lovells Island (Appendix G-J). The dominant direction of sediment movement along the shorelines of the islands is to the southwest.

During low wave energy conditions, when the prevailing winds blow out of the west, significant transport may occur as well. Although the average wave energies produced by the prevailing Westerlies are not as significant as those produced by storm waves, they are capable of transporting sediment alongshore. A study done at Thompson Island showed that the coarse beach material (the dominant sediment on all drumlin island beaches) is successfully transported along the shore during low wave energy conditions (Rosen & Brenninkmeyer, 1988). The study found that the coarse clasts collect at the breaker zone where an incoming wave expends enough energy to move the material.

Although one wave may only move a cobble a few millimeters, the prevailing winds blow for a significant portion of the year, and the resultant low energy waves are able to move the coarse material significant distances. These waves do not have as significant an impact as a storm event does on the eroding bluffs, but should be considered an influential process in the transport of sediment alongshore. Longshore transport reversals will not counteract the sediment movement from a single, powerful storm but may influence the transport of sediment away from a location where it can shelter an otherwise exposed bluff.

The orientation of the drumlin deposits was determined by the direction of ice movement across the area during the last period of glaciation. Drumlin deposits within the Boston area trend northwest/southeast, with the topographic crest of the drumlin lying closer to the northwest end. Drumlins that are sheltered from ocean waves by an adjacent drumlin to the east tend to possess eroding bluffs on both northwest and southeast ends. Several examples can be found on Long Island, as well as Thompson and Peddocks Islands (Figures 4, 5 & 7)). Among all drumlins with these two exposures, the northwest bluffs tend to be at a greater height than the southeast counterpart. The northwest bluffs not only lie closer to the topographic crest of the deposit, but face into the prevailing northwesterlies, and experience the highest frequency of direct winds throughout a given year (Figure 2). Although these winds are not as powerful as those generated by a storm, the northwest exposures tend to have long fetch lengths when compared to other orientations within the harbor. With a high frequency of direct winds and long fetch lengths, the northwest bluffs experience greater wave energy than the southeast sections. Higher wave energies imply that greater amounts of erosion have taken place along the northwest sections of shore. The northwestern bluffs have been able to cut further into the drumlin than on the southeast. Due to the proximity of the topographic crest on the northwest side, short lengths of shoreline retreat result in large changes in bluff height on the more tapered southeast side of the drumlin, a similar length of shoreline retreat would not produce the same change in bluff height. This in conjunction with the differences in wave energy for each exposure explains why the northwest bluffs tend to be at greater heights than those found on the southeast.

One exception to this overall trend was found on Long Island. The middle drumlin of the central drumlinoid complex has a greater bluff height on its southeast exposure than it does along the northwest bluff (Figure 5). Since wave energy is no different here than at the other exposures adjacent to the northeast and southwest, the main factor influencing bluff height must be related to the position of the drumlin with respect to the adjacent deposits. This drumlin is offset to the south from the drumlin adjacent to the northeast. This offset produced a small indentation in the northwest-facing shoreline which has been filled in with sediment transported to the southwest in longshore currents. This pocket of sediment shelters the base of the bluff from wave attack, attenuating the influence of the Westerlies on shoreline retreat. Due to the offset seen on the northwest side of the drumlin, it is expected that initially the southeast shoreline protruded out between the drumlins adjacent to the north and south. The shoreline on the southeast side is currently linear , which indicates that the central drumlin has cut further into the tapered side of the drumlin reaching bluff heights that are greater than what is seen on the northwest side of the island.

Local Factors of Erosion

Studies done on the geotechnical properties of drumlin sediment indicate that the composition of material may play a role in the resistance of an area to erosion (Jones and Fisher, 1991). Bluffs that have a high clay-sand ratio may be more resistant to erosion than segments of shore that are made up of re-deposited sediment whose clay fraction has been transported offshore. The majority of the Boston Harbor Island beaches are composed of sediment coarser than sand (Jones, et. al., 1991, Jones & Fisher, 1990, Newman et. al., 1990, Rosen, 1984). The stratigraphy of the two tills that form the drumlin deposits throughout the harbor have been described as a uniform clay matrix with entrained cobbles and boulders (Newman et. al., 1990).

On the northeastern exposure of Peddocks Island there is a slope inflection point that appears to lie at the boundary between the two tills. The change in slope gradient may reflect a difference in shear strength between the two tills. A prior stratigraphic study on

the two tills concluded that the lower till was deposited prior to the upper till and was exposed to a period of weathering before the second period of deposition (Newman et al., 1990). The more weathered lower till may be less resistant to erosion. Bluff exposures that contain both tills may be more susceptible to undermining due to a weaker basal unit.

The Boston Harbor Islands are not entirely made up of drumlin deposits. Sediment has been re-deposited connecting headlands together and oftentimes enclosing low-lying marsh areas. Till deposits not in drumlin form can be found at the southern end of Thompson Island adjacent to a sinuous esker. The southernmost end of West Head on Peddocks Island is noticeably stratified, potentially deposited as outwash during glacial retreat (Figure 7). Sediment is anchored to either bedrock or till deposits on the southern end of Lovells Island. Although these areas will evolve in a manner different from the behavior of the drumlin bluffs, they are strongly influenced by sediment the headlands provide.

Boat wakes are another locally influential factor contributing to shoreline retreat. Many of the actively eroding shorelines are adjacent to commuter ferry routes, which pass through the harbor several times an hour. The boats displace a significant amount of water especially as they initially accelerate, generating a large set of waves that may potentially reach the base of adjacent bluffs during high tide. Bluffs that retreat by wave notch and slumping processes will be noticeably impacted by a wave breaking at its base. If a slope base is sheltered by slumped sediment, the incoming wakes will simply speed up the process of transporting the sediment alongshore reducing the amount of time the bluff is sheltered. The frequency of slump events along the southwestern shore of Grape Island may suggest that these wakes play a role in bluff erosion. Exposures along the western edges of Peddocks and Long Island are also exposed to waves generated by passing commuter boats. This project has aimed at establishing an understanding of how the bluffs have evolved naturally. The various factors influencing shoreline retreat have been identified but a more focused study specifically on the impact of boat wakes is beyond the scope of this study. A project is currently underway that will attempt to

assess the impact of boat wakes on adjacent shorelines and quantify the influence it has when related to the other factors contributing to shoreline retreat.

Importance of Bluff Height

Prior field studies (Sunamura, 1977 and Pinet et. al, 1998) have observed the correlation between bluff height and the volume of sediment slumped during a given event. Larger bluffs are made up of greater amounts of material and can shed more sediment. Slumped sediment shelters the base of the bluff from wave attack, which then attacks the sediment moving it away from the bluff through longshore currents. As a bluff cuts further back into the drumlin deposit, larger and larger amounts of sediment are delivered to the base. Higher bluffs produce slumps with greater sediment volumes, which will increase the lag time between successive slope failures. Rills that form on low bluffs are quickly erased by frequent slump events, and the dominant slope morphology is characterized by planar slopes with wave-notched bases. As bluff heights climb and the base is sheltered for longer periods of time, rills are able to evolve into deep gullies altering the dominant slope morphology.

To better illustrate this concept bluff orientations were plotted against the maximum bluff height for each exposure. Field observations enabled identification of the dominant slope morphology and each bluff was plotted with respect to the primary mechanism responsible for its retreat (Figure 11). A few of the bluffs within the study exhibited characteristics of both slope morphologies making it difficult to assign a preferential process and were instead reported as transition bluffs. When bluff heights exceed 10 meters there is a change in the dominant slope morphology, regardless of bluff exposure. Therefore the interplay between the two mechanisms involved in bluff retreat depends primarily upon the sediment supply delivered to the beach, which is directly controlled by bluff height.

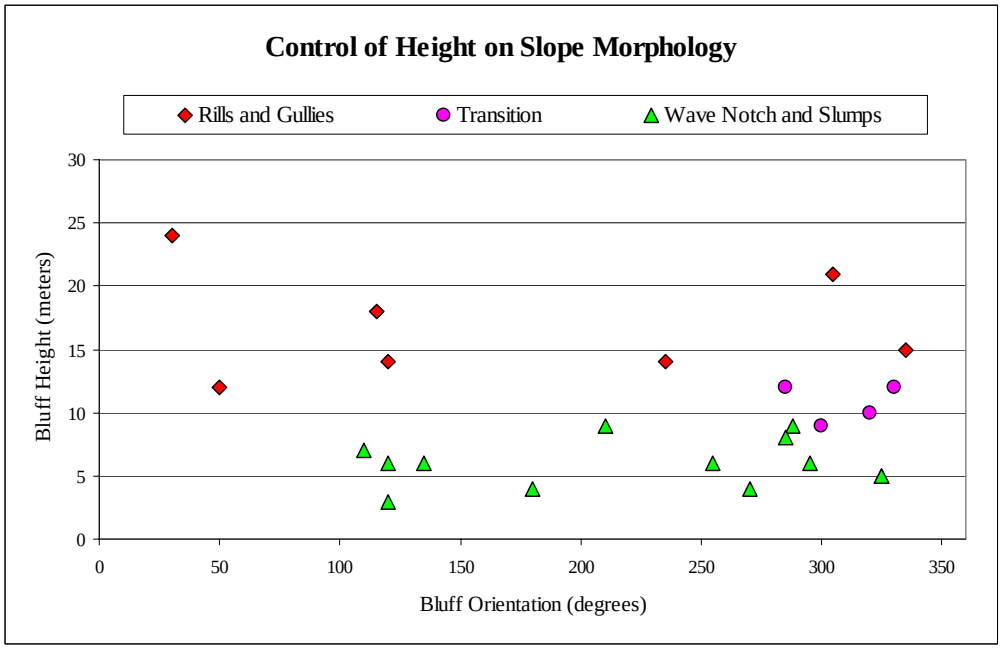


Figure 11. Bluff orientation in degrees (with zero equal to North) with respect to dominant slope morphology at maximum bluff height of each exposure.

Model of Bluff Evolution

As a result of these observations, a model of bluff evolution was constructed for bluffs based upon features such as bluff height, slope morphology, and the orientation of the bluff with respect to the long axis of the drumlin and the topographic crest. The four stages of evolution were depicted for bluffs forming both perpendicular and parallel to the long axis of the drumlin, as is observed within Boston Harbor.

The young stage of bluff evolution represents the initiation of wave attack on the drumlin. Bluffs are characterized by slopes that are less than 10 meters tall with a slope morphology dominated by wave notching and slumping processes (Figure 12a). As wave attack continues, slope failure pushes the slope face further into the drumlin increasing bluff heights as well as the volume of sediment delivered to the slope base during a slump event. As bluff heights exceed 10 meters, the volume of slumped sediment at the bluff base is large enough to protect the slope from wave and marks the transition to the mature stage of evolution (Figure 12b). Although protected from waves, the fresh, planar scarp lacks vegetation and is vulnerable to storm erosion in the form of rain splash and surface

runoff. Rain drops converge into small rills on the slope surface which deepen and widen into gullies with each successive storm. Sediment that is removed from the slope during rainfall events is re-deposited at the base of the slope adding to the slumped sediment that initially sheltered the bluff from wave attack. With continual storm-influenced erosion, the bluff crosses the topographic crest of the drumlin and enters the old stage of bluff evolution. Bluff heights begin to decrease while wave attack transports away sediment piled at the base of the bluff (Figure 12c). Decreasing bluff heights deliver less sediment to the base of the bluff and waves transporting sediment away outpace the storm-eroded sediment which used to sufficiently replace the amount removed by longshore currents. The base of the bluff is again vulnerable to wave attack, which leads to slope instability and slumping. Slump events quickly return the gullied slope to a planar morphology and indicate passage into the terminal stage of bluff evolution. During this final stage, the remaining segment of drumlin is completely winnowed away by wave attack (Figure 12d).

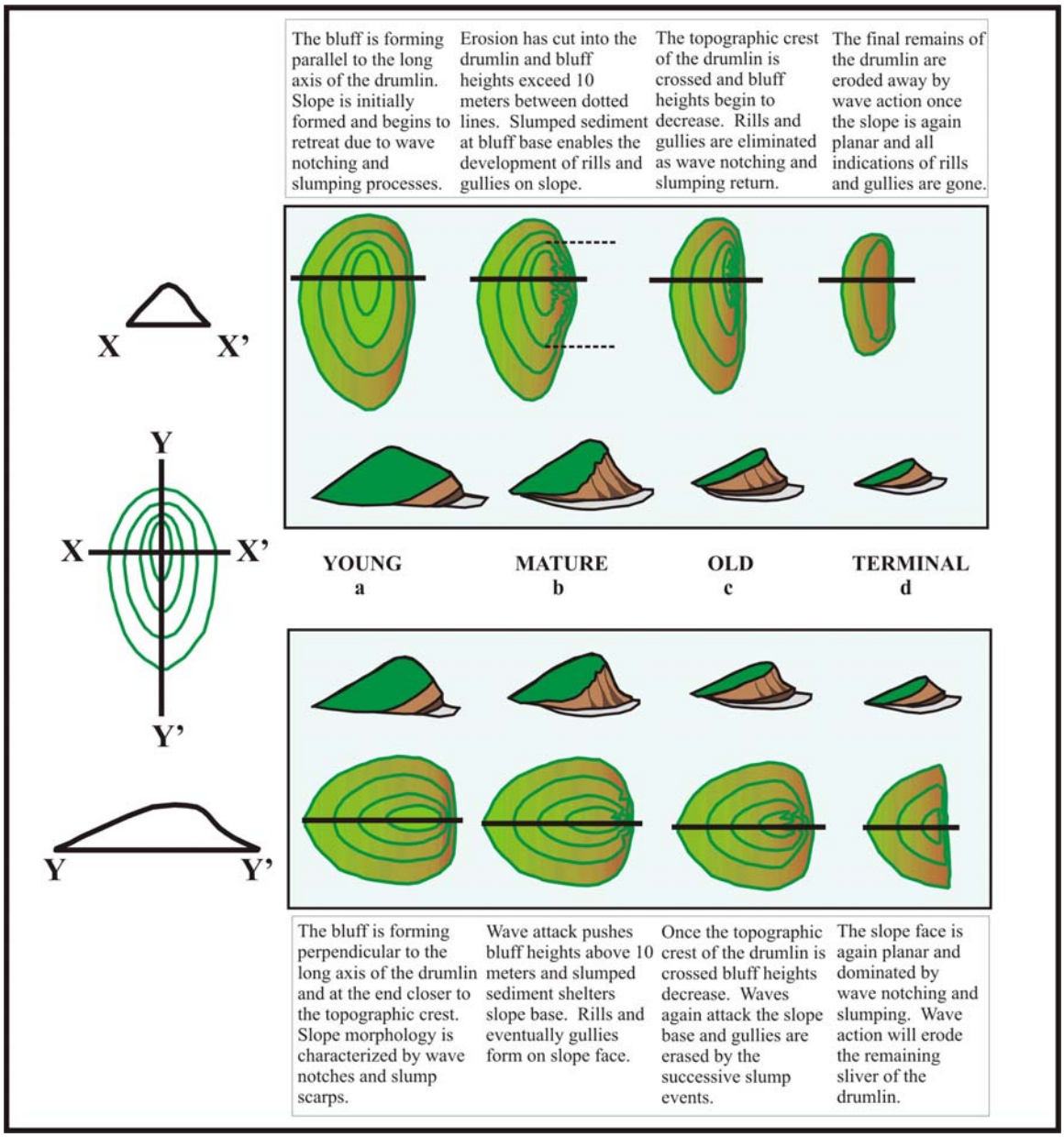


Figure 12. Theoretical model of drumlin bluff evolution. Transects illustrate the four stages of evolution for bluffs forming parallel (Y-Y') and perpendicular (Z-Z') to long axis of drumlin. Dotted lines are drawn to illustrate the area that demonstrates that type of behavior.

The drumlin topography that defines the harbor islands has primarily been influenced by wave attack since the region was inundated by post-glacial sea-level rise. Initially producing a shoreline transgression, rising sea-level cut into the exposed drumlins creating beaches fronted by low bluffs (Colgan and Rosen, 2001 and Jones and Fisher, 1991). Drumlin headlands with ocean exposures were extensively eroded, providing

sediment sources for the accretionary beaches that link drumlins together (Farquhar, 1967). As erosion continued, scarps cut further into the drumlin producing bluffs of greater height fronted by boulder retreat lags in areas where drumlin bluffs once stood. Sand and fine gravel deposits were moved by longshore transport processes and re-deposited in the sheltered area behind the headland. These areas are where waves converge as they refract around the headlands, creating areas of accretion that build out towards downdrift drumlin deposits. This sediment extended spits and enclosed embayments or low-lying salt marsh areas between headlands. The earlier stages of bluff erosion are dominated by slumping, which is evidenced by frequent wave notching of the slope base (Figure 13a). As the bluff retreats further into the drumlin, the volume of sediment delivered to the beach in a given slump event increases. This sediment is able to shelters the slope base from wave attack until longshore currents transport the sediment away from the area. When bluff heights erode far enough into the drumlin to exceed 10 meter heights, the volume of sediment in a single slump event is large enough to shelter the base of the bluff from wave attack allowing overland processes such as rain splash to alter the dominant process of sediment removal. Rill networks develop and are able to evolve into deeply entrenched gullies, indicating the influence of rain runoff processes (Figure 13b).

Wave notching and slumping processes **Development of rills and gullies**

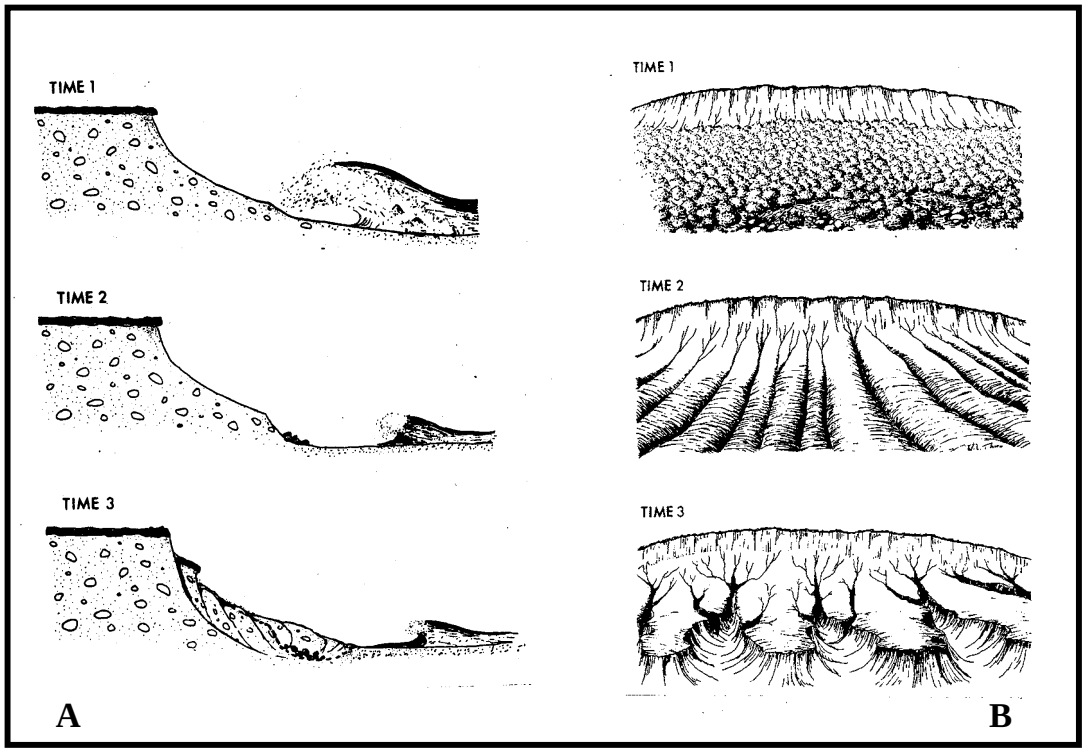


Figure 13. Time sequence of slope erosion processes. A) Wave action undermines base resulting in slope failure. B) Rain and groundwater runoff incise slope with rills that mature into a characteristic gullied morphology. (Figure adapted from FitzGerald et al., 1979)

The drumlins within Boston Harbor have multiple exposures eroding simultaneously on a single deposit. Scarps are aligned both perpendicular and parallel to the long axis and often erode contemporaneously from both ends. The height of the bluffs will still vary in a predictable fashion under the influence of erosion, but the length of bluff may not progress uniformly through each stage of the model. The characteristics and style of retreat are strongly influenced by the height of the bluff and pass through the individual stages of evolution outlined in the model above (Figure 12).

The northwest/southeast orientation of the drumlin deposits reflects the direction of ice movement during their time of deposition during the last glaciation. Drumlins bluffs oriented parallel to the long axis can be found at the northern ends of Long, and Peddocks Island which are also exposed to some of the greatest wave heights among bluffs within the study. East Head drumlin on Peddocks Island is oriented parallel to the long axis and

has passed from the young to mature stage of bluff evolution (Figure 7). While the central portion has already evolved into the mature stage, the long, tapered sides of the deposit are still dominated by wave notching and slumping processes and remain in the young stage of evolution.

All of the northwest exposures facing are located in close proximity to the topographical crest of the drumlin. As erosion cuts into the drumlin, bluffs will experience greater increases in height over shorter distances than what bluffs experience on the southeast side of the drumlin. With the exception of the middle drumlin on Long Island, comparisons of all drumlins with dual exposures indicate that bluffs facing northwest are at a later stage of the evolutionary cycle than their southeast counterpart. The southeast bluff of the middle drumlin is at a later stage of evolution than the northwest-facing bluff because the slightly southeast position of the drumlin allowed sediment to build up in front of the northwestern bluff sheltering it from continual wave attack. Erosion on the southeast side of the drumlin was intensified due to this southeast offset and resulted in a focusing of wave attack that eventually flattened the shoreline into its present, linear form.

Hierarchical Classification and Bluff Characteristics

The main organizational concept and classification scheme was influenced by a prior study done by Pinet, McClellen and Moore (1998). The multiple factors influencing erosion on the drumlin were classified according to the scale at which they operate within the system. This provided a way in which to systematically account for all potential variables influencing erosion.

To identify the role each potential erosive process plays in the overall response of shoreline retreat, a hierarchy was constructed to classify factors based upon the scale at which they operate within the system (Figure 14). With these factors identified, individual slope characteristics could be used to classify the bluffs according to their style of retreat and ultimately determine their stage in bluff evolution.

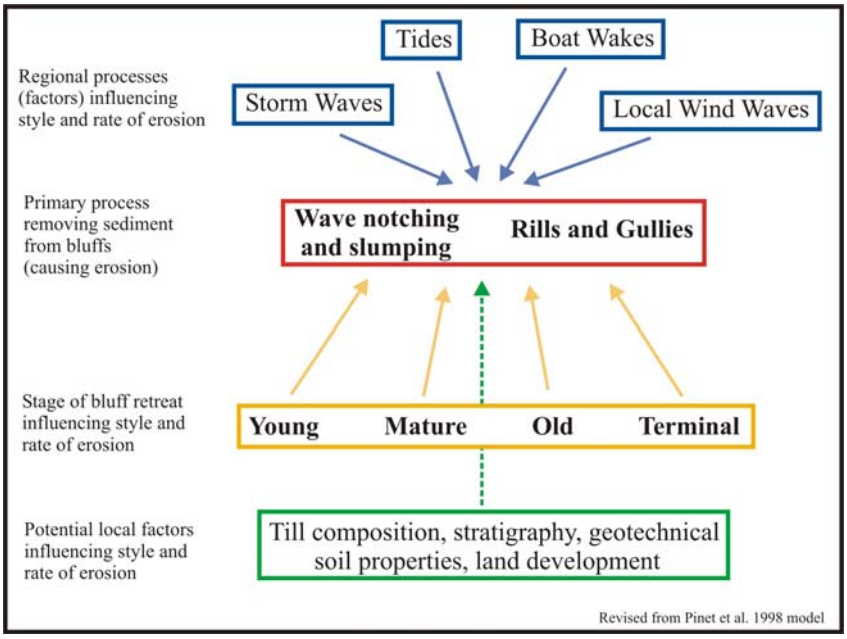


Figure 14. Hierarchical classification of geomorphic factors.

The prior study was done along the southern coast of Lake Ontario. Drumlins were oriented north/south and bluffs formed perpendicular to the long axis of the deposit, at the end closest to the topographic crest. Their simplistic model categorized bluffs according to their slope morphology, based upon the restricted set of conditions under which they formed. The conceptual model created in this study describes drumlin bluff evolution for a variety of exposures not only according to slope morphology, but with respect to the long axis and topographic crest of the deposit. Both of these factors have an influence in bluff height which is the primary control on slope morphology. With a continual rise in sea-level, the relative location of bluff base will climb steadily up the side of the bluff. The rate of sea-level rise in Boston Harbor has been estimated as 2.65 mm/year, and occurs on a much smaller scale than the other factors influencing erosion (Zervas, 2001). Although this may seem insignificant on a yearly scale, when considering the evolution of the islands over a longer period of time, its importance becomes more apparent. For the 57 years of aerial photograph coverage (1938-1995) sea-level rose 0.2 meters (0.5 feet). As sea level rise continues to submerge the drumlin the overall height of the deposit decreases. Once bluff heights no longer exceed 10 meters bluffs will no longer have multiple stages of evolution characterized by distinct

slope morphologies. Low bluff heights will restrict the volume of available sediment and the exposed bluffs will retain a slope morphology dominated by wave notching and slumping processes.

CONCLUSIONS

Characterizing the erosion factors within a hierarchy enables the numerous variables to be separated upon their scale of influence. The conceptual model was a useful tool that aided not only in an explanation in the different slope morphologies but helped tie together all of the factors contributing to erosion at a specific site. This model is not limited to the drumlins that make up the Boston Harbor Islands, the way that the Lake Ontario model was, because it accounts for bluffs formation under a variety of conditions.

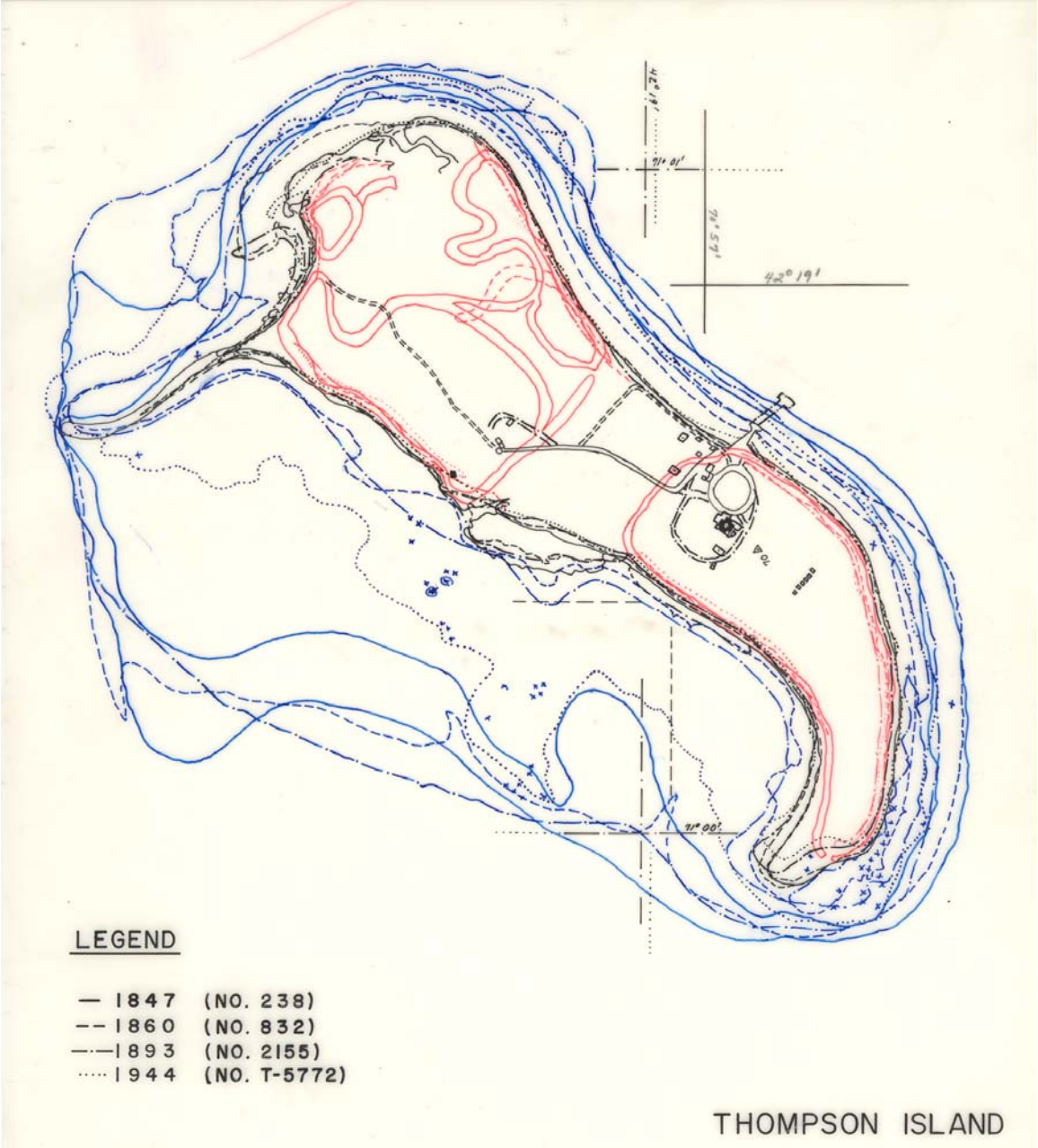
The numerous factors controlling the process of erosion along the drumlin bluffs within Boston Harbor are storm and locally-generated winds, geotechnical soil properties, and boat wakes. The most powerful force are winds produced during northeast storms (Nor'easters), which are capable of generating large waves in an environment not limited by fetch. Drumlins that are directly exposed to the open ocean possess mature bluffs that have eroded significant portions of the total drumlin deposit. Bluff exposures sheltered from northeast wave are shaped under the influence of local winds. Bluffs along the northwest sides of drumlins range between young and old stages of evolution, but are invariably at later stages of evolution than the corresponding bluff on the southeast side of the drumlin. The consistent northwest/southeast orientation of the deposits places the topographic crest of the drumlin within closer proximity to the northwest shorelines. This fact in conjunction with a higher frequency of strong winds blowing from the northwest than compared to the southeast has consistently resulted in the presence of older stage bluffs along the northwest exposures. Differences in the composition of the till may produce variations in slope morphology on a local scale. This accounts for the dynamic shorelines along the southern part of Thompson Island, as well as the southwestern end of West Head on Peddocks Island. The influence of boat wakes on

different stages of bluff evolution is worthy of further investigation. Many of the bluffs adjacent to the commuter boat routes are well protected from northeast winds and have small fetch lengths that limit the height of locally generated waves. The impact of boat wakes on these shores during high tide may result in waves reaching the base of the bluff. This would increase the frequency of slope failures and ultimately produce a rise in the rate of shoreline recession.

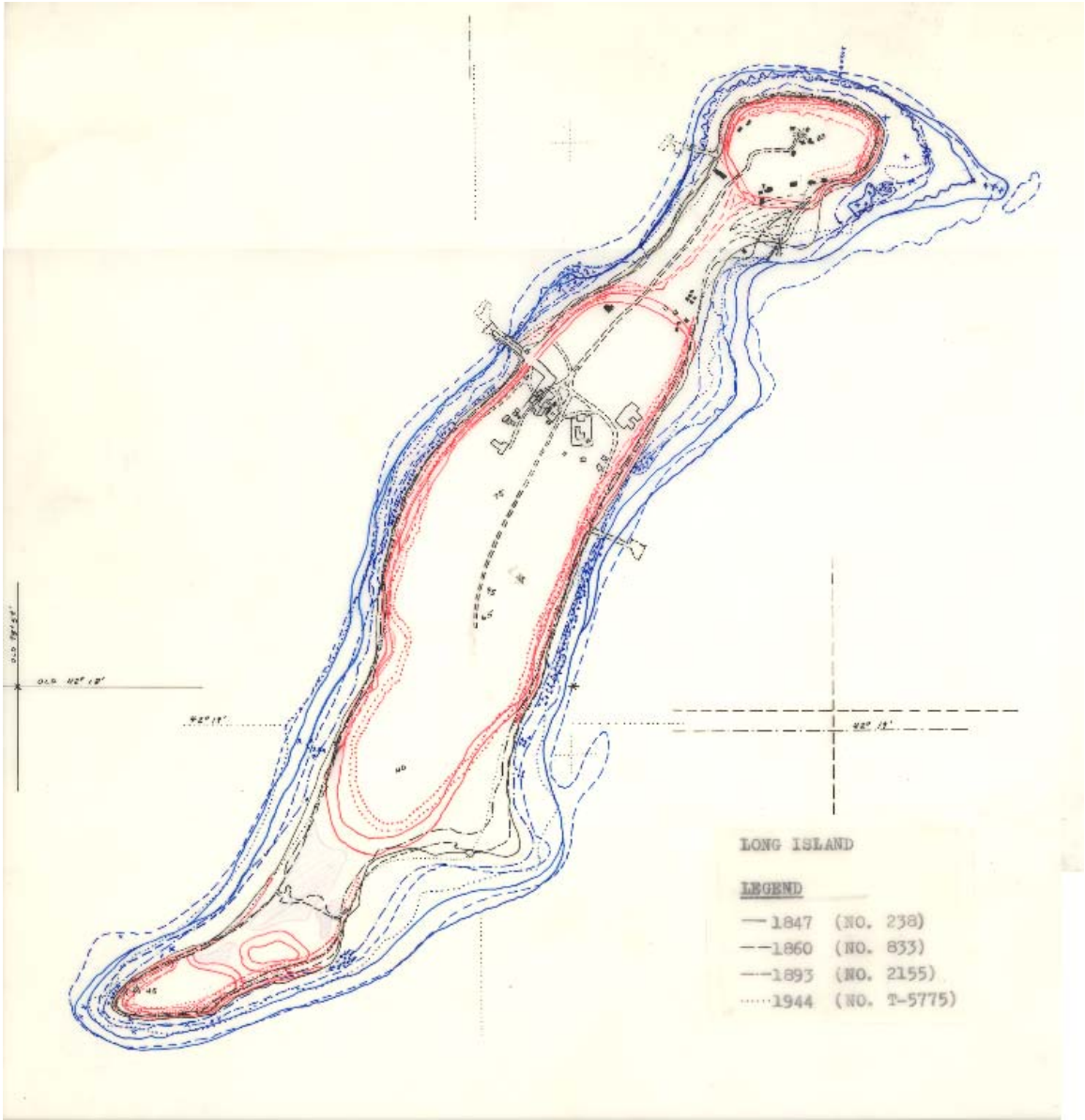
The variations in bluff characteristics throughout Boston Harbor have been explained through development of a theoretical model describing drumlin bluff evolution. Drumlin headlands evolve in a predictable manner and by classifying the factors responsible for erosion within a hierarchy, the overall impact of an individual process can be determined. The continual rise in sea-level will have a great impact on all of the Nation's shorelines. A better understanding of the role individual processes play, especially those that may be reduced or minimized by humankind, will ensure the protection of unique coastal areas such as the drumlins that comprise the Boston Harbor Island National Park Area.

APPENDIX

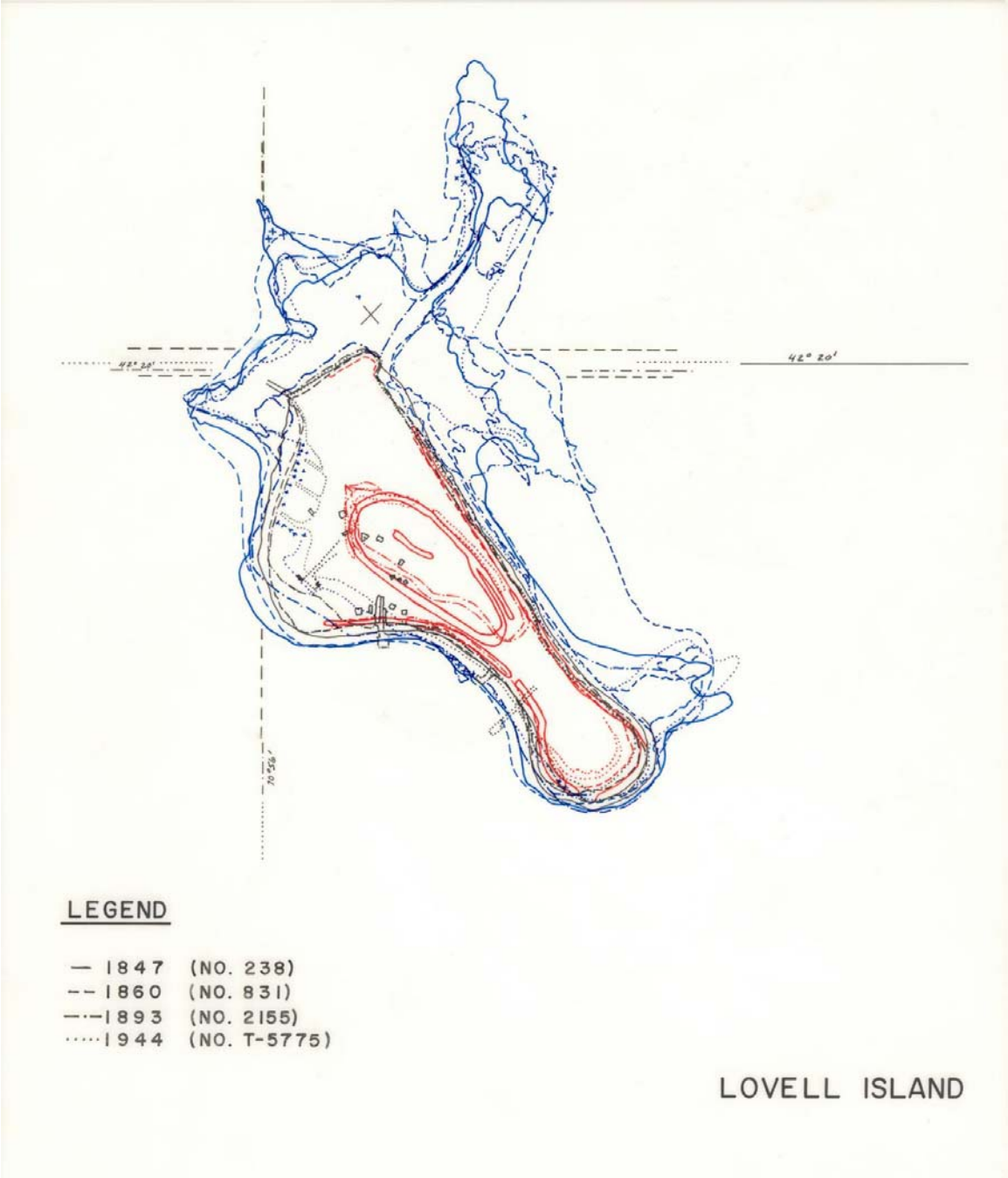
Raw data used in bluff profiles



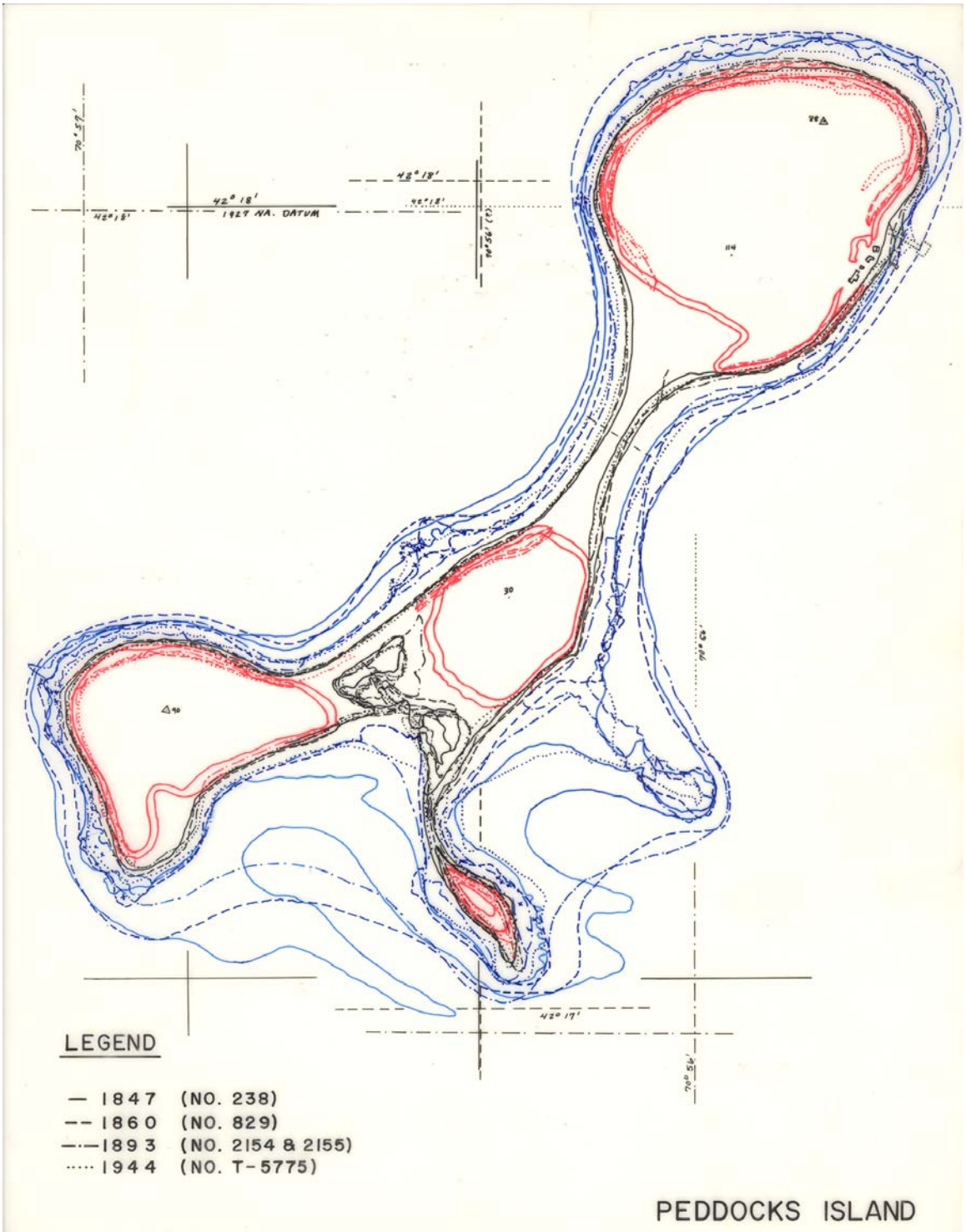
Appendix B. Mylar tracings of hydrographic sheet and historic coastal charts of Thompson Island. Red lines are used as control points along with buildings and latitude/longitude marks. Black lines mark location of mean high water for respective years, and blue lines mark location of mean low water.



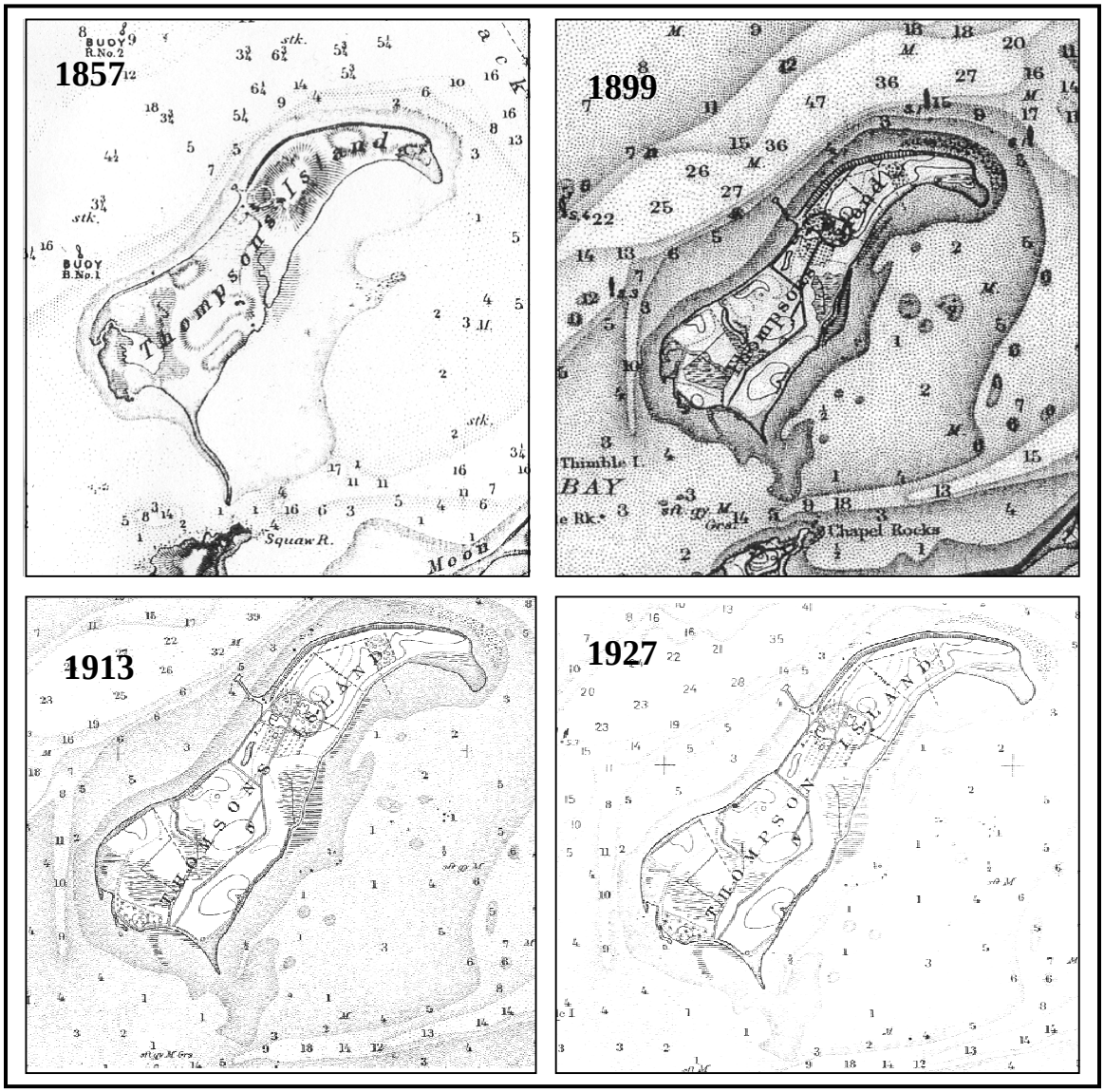
Appendix C. Mylar tracings of hydrographic sheet and historic coastal charts of Long Island.



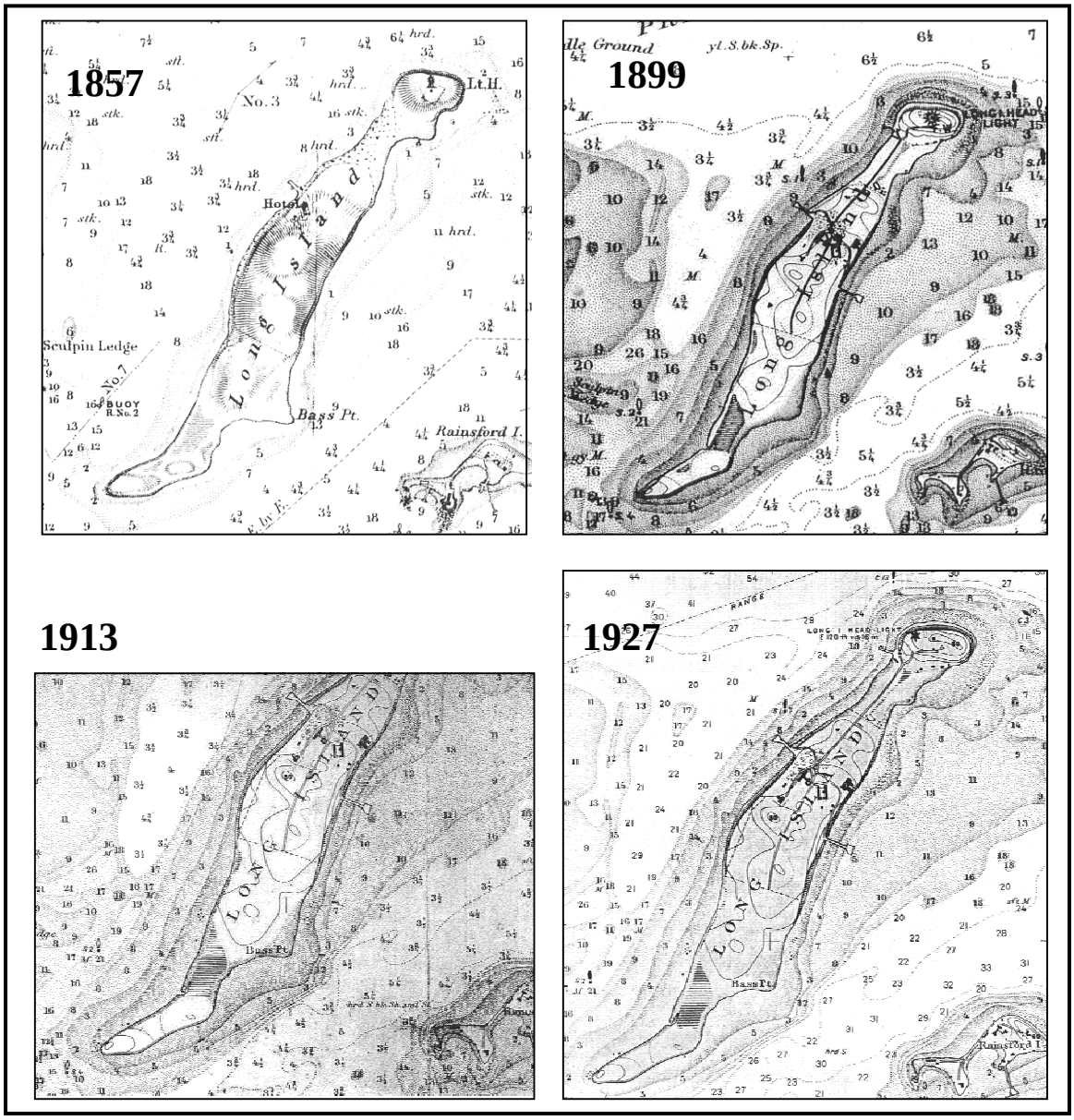
Appendix D. Mylar tracings of hydrographic sheet and historic coastal charts of Lovells Island



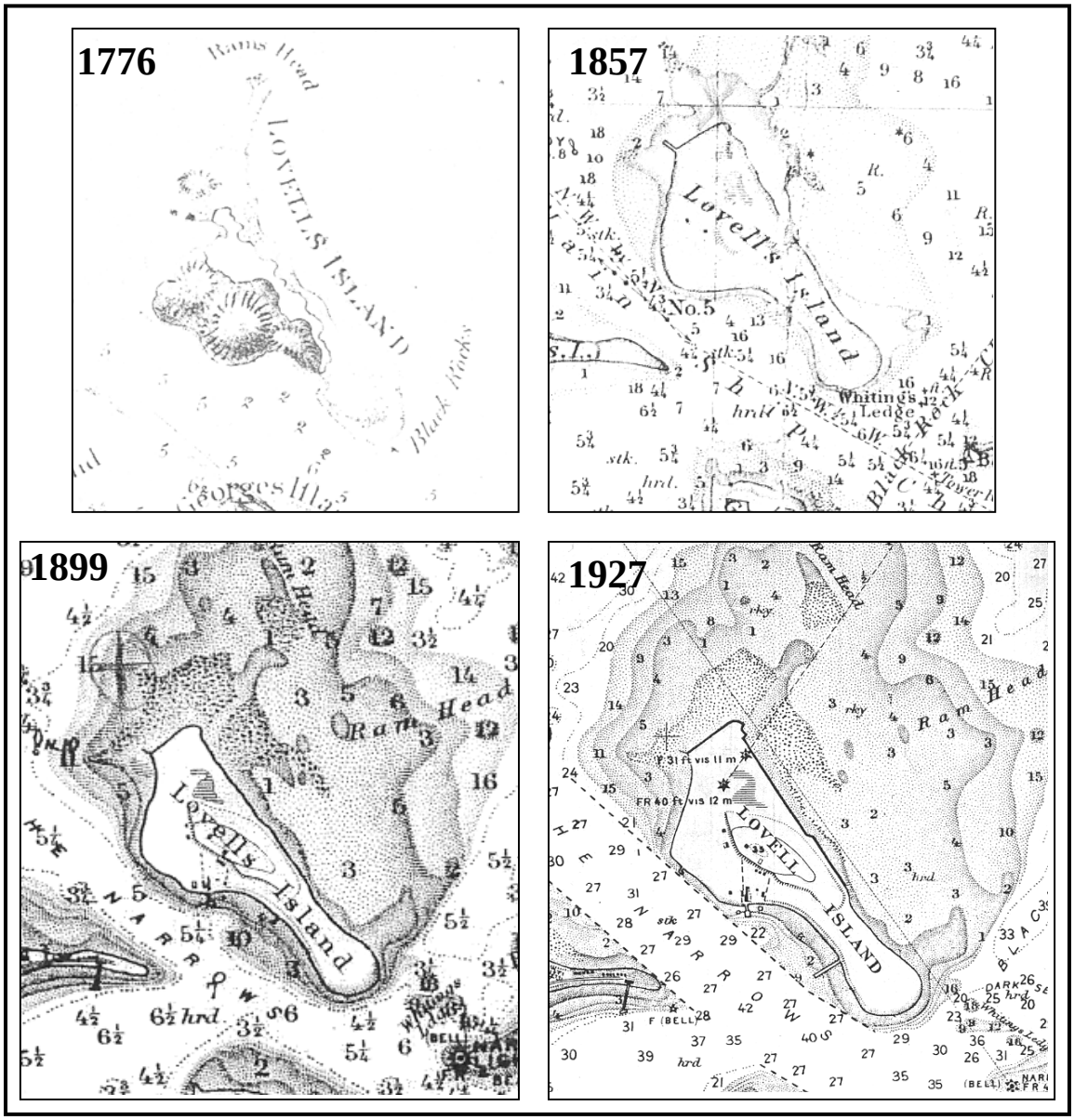
Appendix E. Mylar tracings of hydrographic sheet and historic coastal charts of Peddocks Island.



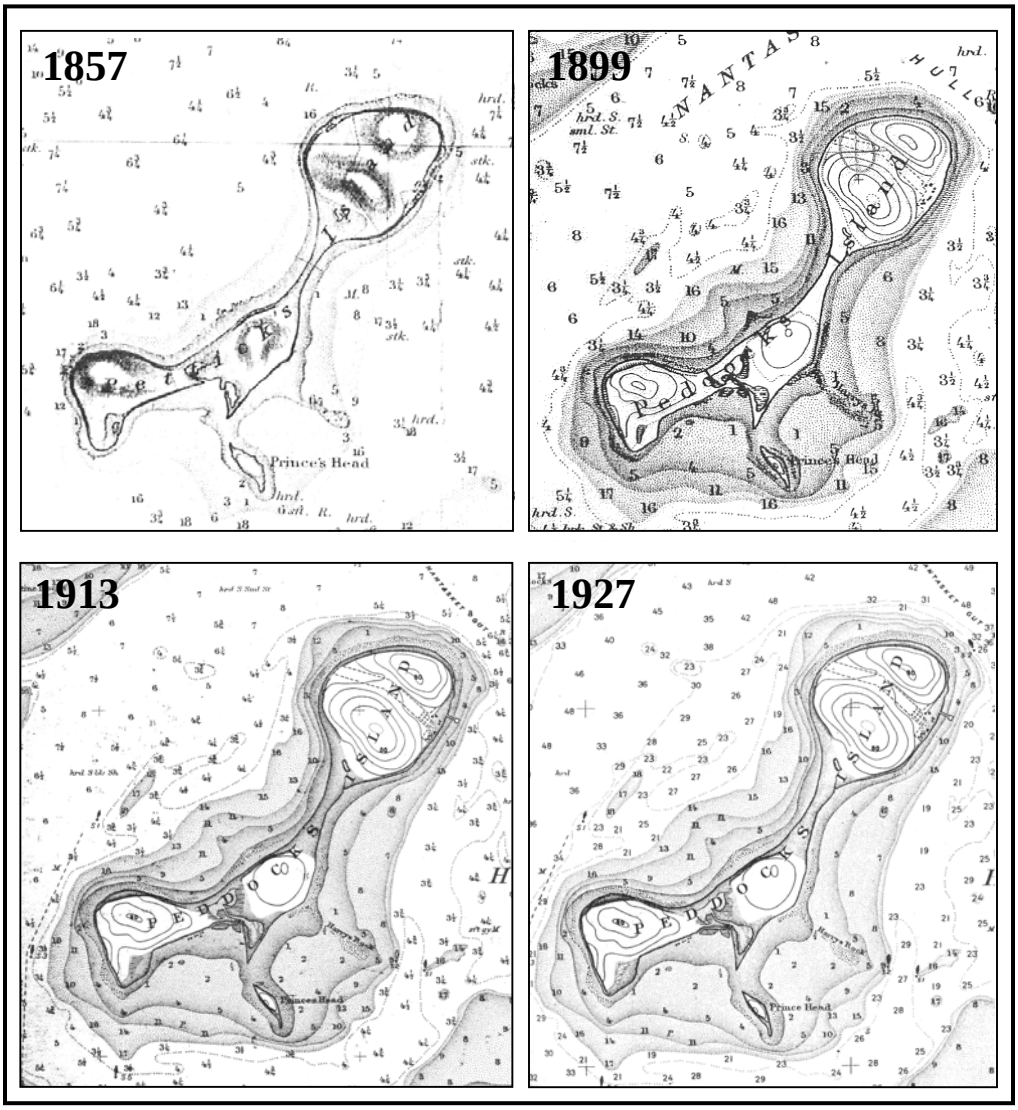
Appendix F. Coastal chart sequence for Thompson Island. Charts were scanned, cropped, and re-sized to create a visually similar series through time.



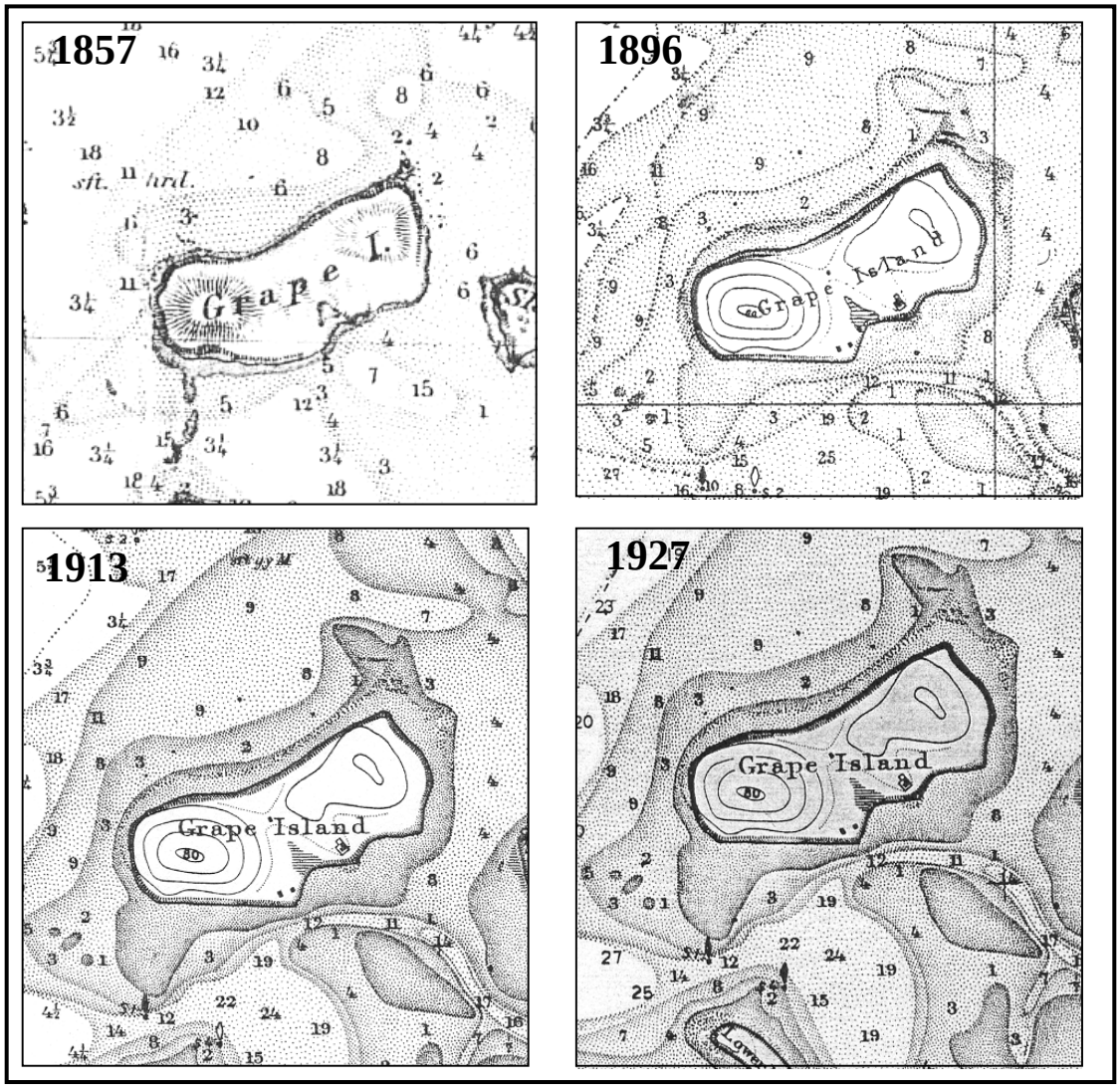
Appendix G. Coastal chart sequence for Long Island. The northernmost extent of Long Island did not appear on the 1913 map, hence the reason it is cropped.



Appendix H. Coastal chart sequence for Lovells Island. The 1776 map was not a hydrographic chart, however it was included to illustrate the earliest stages of the island's development.



Appendix I. Coastal chart sequence for Peddocks Island.



Appendix J. Coastal chart sequence for Grape Island.

See attached

Appendix K. A nomogram for the significant wave height and period of waves generated by a wind-stress factor U_A and fetch (from Komar, 1998).

BIBLIOGRAPHY

Bates, R.L., and Jackson, J.A. (eds.),1984. Dictionary of Geological Terms, third edition. New York, Bantam Doubleday Dell Publishing Group, Inc., 571p.

Caldwell, D.W., 1984. Surficial geology and archaeology on Thompson Island, Boston Harbor, Massachusetts. *In* Hanson, L. (ed.), *Geology of the Coastal Lowlands, Boston MA to Kennebunk, ME,* New England Intercollegiate Geological Conference, pp. 402-416.

Colgan P.M., and Rosen, P.S., 2001. Quaternary Environments and History of Boston Harbor, Massachusetts. *In:* West, D.P., and Bailey, R.H. (eds.), *Guidebook for Geological Field Trips in New England.* 2001 Annual Meeting of the Geological Society of America, Boston Massachusetts. pp. I1-I20.

Dolan, R.B., Hayden, B., May, P., and May, S., 1980. The reliability of shoreline change measured from aerial photographs. *Shore and Beach*, v. 48, pp.22-29.

Farquhar, O.C., 1967. Tombolos around Massachusetts Bay. *Economic Geology in Massachusetts*, University of Massachusetts Graduate School Publications, pp. 559-565.

FitzGerald, D.M., D'Amore, D., Levin, D., and Oates, L., 1979. Yirrell Beach Coastal Processes Study: Winthrop, Massachusetts. *Technical Report No. 1.* Coastal Environmental Research Group, Department of Geology, Boston University, Boston, Massachusetts.

FitzGerald, D.M., van Heteren, S., Rosen, P.S., 1993. Distribution, Morphology, Evolution, and Stratigraphy of Barriers Along the New England Coast. Technical Report No. 16.

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

Hoeke, R.K., Zarillo, G.A., and Synder, M., 2001. A GIS Based Tool for Extracting Shoreline Positions from Aerial Imagery (BeachTools). Coastal Engineering Technical Note CETN-IV-__, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Johnson, D.W., 1925. New England and Acadian shoreline: New York, John Wiley and Sons, 584p.

Jones, J.R., Cameron, B., and Fisher, J. J., 1993. Analysis of cliff retreat and shoreline

erosion: Thompson Island, Massachusetts, U.S.A. *Journal of Coastal Research*, v.9, n.1, pp.87-96.

Jones, J.R., and Cameron, B., Fisher, J.J., 1991. Photogrammetric Analysis of Shoreline Change for Islands Within Middle Boston Harbor, Massachusetts; 1938-1977. *Northeastern Geology*, v.13, n.1, pp.3-10.

Jones, J.R., and Fisher, J.J., 1990. Environmental factors affecting prehistoric shellfish utilization; Grape Island, Boston Harbor, Massachusetts. *In:* Lasca, N.P., and Donahue, J., (eds.), *Archaeological geology of North America: Boulder, Colorado, Geological Society of America, Centennial Special Volume 4*, pp.137-146.

Knebel, H.J., Rendigs, R.R., Oldale, R.N., and Bothner, M.H., 1992. Sedimentary Framework of Boston Harbor, Massachusetts. *In*: *Quaternary Coasts of the United States: Marine and Lacustrine Systems*, SEPM Special Publication No. 48., pp.35-43.

Komar, Paul, 1998. Beach Processes and Sedimentation, Second Edition. Prentice Hall, Upper Saddle River, New Jersey. 544pp.

Luedtke, B.E. and P.S. Rosen, 1993. Archaeological Geology on Long Island, Boston Harbor, p. T-1 – T-15, I*n: Field Trip Guidebook for the Northeastern United States*, Geological Society of America, Boston, MA, Volume 2.

National Park Service Bulletin, 2000. Boston Harbor Islands, A National Park Area, Draft General Management Plan and Draft Environmental Impact Statement. Boston Support Office of the Northeast Region, National Park Service for the Boston Harbor Islands Partnership.

Newman, W.A., and Mickelson, D.M., 1994. Genesis of Boston Harbor drumlins, Massachusetts. *Sedimentary Geology*, v.91, pp.333-343.

Pinet, P.R., McClennen, C.E., and Moore, L.J., 1998. Resolving environmental complexity: A geologic appraisal of process-response elements and scale as controls of shoreline erosion along southeastern Lake Ontario, New York. *In*: Welby, C.W., and Gowan, M.E. (eds.), *A Paradox of Power: Voices of Warning and Reason in the Geosciences:* Boulder, Colorado, Geological Society of America Reviews in Engineering Geology, v.12, pp.9-21.

Riegler, P.W., 1981. An aerial photogrammetric study of erosion and accretion, Boston Harbor Islands, Massachusetts. Master's Thesis, University of Rhode Island.

Rosen, P.S., and Brenninkmeyer, B.M., 1989. Transport of coarse material in low energy beach environments. In: Magoon, O.T., Converse, H., Miner, D., Tobin, L.T.,

Clark, D. (eds.), Proceedings of the Symposium on Coastal and Ocean Management, v.6, p.1724-1737.

Rosen, P.S., 1984. Gravel Spit Processes, Thompson Island, Boston Harbor, Massachusetts. *In*: Hanson, L (ed.), *Geology of the Coastal Lowlands, Boston, MA to Kennebunk, ME,* New England Intercollegiate Geological Conference, pp. 25-38.

Rosen, P.S., and Leach, K., 1987. Sediment Accumulation Forms, Thompson Island, Boston Harbor, Massachusetts. *In:* FitzGerald, D.M., and Rosen, P.S. (eds.), *Glaciated Coasts*, Academic Press. pp.233-250.

Smith, G.L., and Zarillo, 1990. Calculating long-term shoreline recession rates using aerial photographic and beach profiling techniques. *Journal of Coastal Research*, v.6, pp.1110-1120.

Sunamura, T., 1977. A relationship between wave-induced cliff erosion and erosive force of waves. *Journal of Geology*, v. 85, p. 613-618.

Zervas, Chris, 2001. Sea Level Variations of the United States 1854-1999. *National Oceanic and Atmospheric Administration* (NOAA) *Technical Report,* National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) 201 p.